Final Hydrogeological Report

Volume I
Report

FRESH KILLS

Leachate Mitigation System Project

November 26, 1

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INTERNATIONAL TECHNOLOGY CORPORATION

FRESH KILLS

CONTRACT No. 901 - 9260

Leachate Mitigation System Project IT PROJECT No. 529363

Final Hydrogeological Report

Volume I
Report

Date: November 26, 1993
Document No. 529363 - 01814

Submitted to:

NEW YORK STATE
DEPARTMENT OF ENVIRONMENTAL CONSERVATION

In Compliance With the Order on Consent:
NYSDEC Case No. D2-9001-89-03, Appendix A - 6

Prepared for:

CITY OF NEW YORK
DEPARTMENT OF SANITATION
NEW YORK, NEW YORK

Prepared by

INTERNATIONAL TECHNOLOGY CORPORATION

With

Wehran EnviroTech

O'BRIEN & GERE

EXECUTIVE SUMMARY

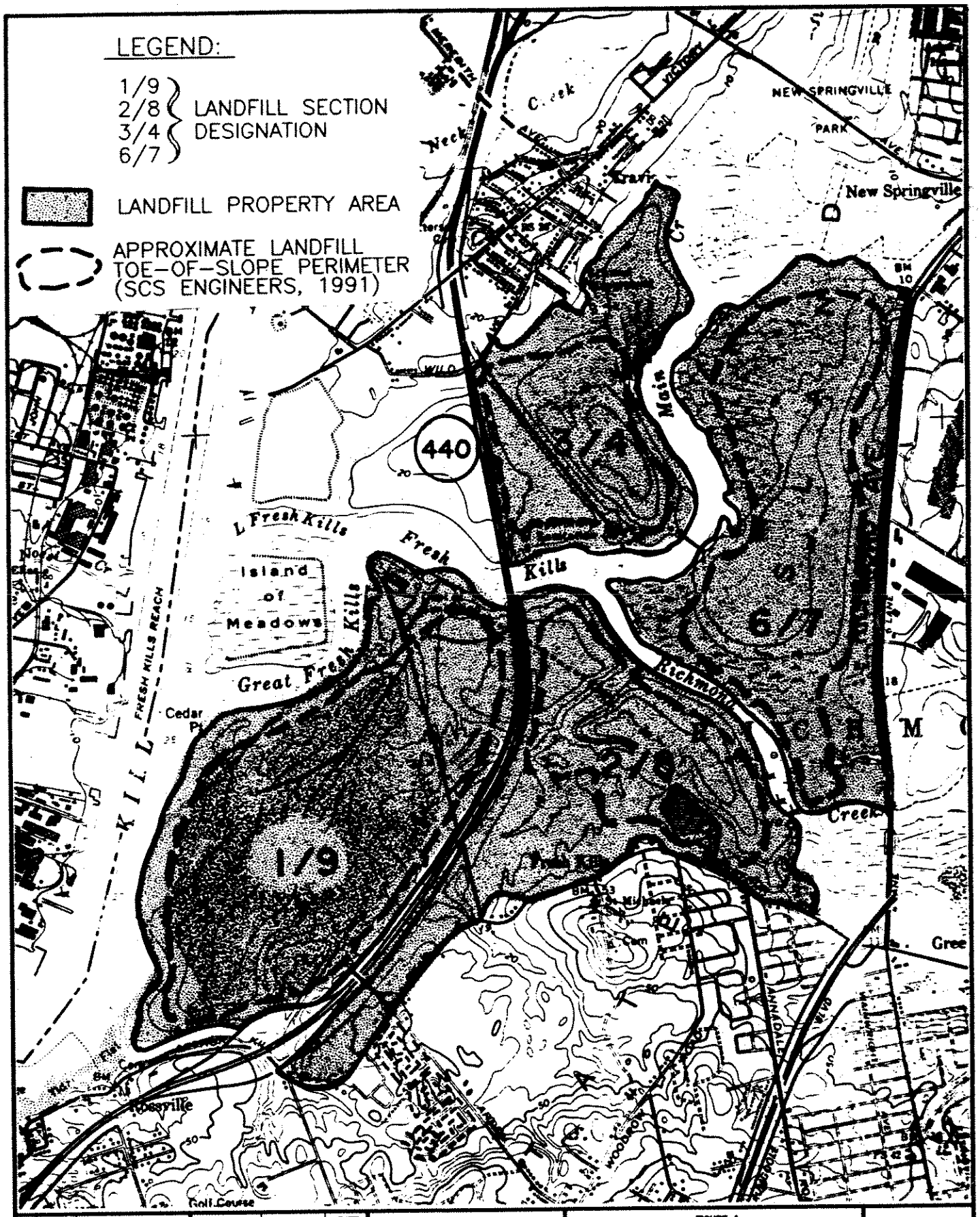
The Fresh Kills Landfill is currently the only municipal solid waste (MSW) landfill serving the five boroughs of the City of New York. The 2,400 acre landfill, located on the western shore of Staten Island (Figure 1), is owned and operated by the City of New York Department of Sanitation and has received household waste since 1948. In addition to the distinction of being the world's largest operating MSW landfill, the Fresh Kills Landfill is an integral part of New York City's solid waste management plan, and will remain so throughout the next decade.

The Landfill is divided into four sections that are named in accordance with historical City property tract designations, as follows: 1/9, 2/8, 3/4, and 6/7. Sections 1/9 and 6/7 are the largest landfills, and lie to the west and east of the full landfill property area; Sections 3/4 and 2/8 are approximately half the size of Sections 1/9 and 6/7, and lie to the north and south of the full landfill area. Until recently, Landfill Sections 1/9 and 6/7 operated primarily as barge fed landfills, while Sections 2/8 and 3/4 operated as truck fed landfills.

With the advent of the Federal Resource Conservation and Recovery Act of 1976 and the Clean Water Act of 1977, and complementary New York State legislation, more stringent criteria for the siting, construction, and operation of landfills were promulgated. These regulations required that the Fresh Kills Landfill be upgraded to appropriate standards to effectively mitigate environmental damage.

During April of 1990, the New York State Department of Environmental Conservation (NYSDEC) and the City of New York Department of Sanitation (NYCDOS) executed the terms of the Fresh Kills Order on Consent (DEC Case Number D2-9001-89-03) as the instrument through which environmental investigation and engineering design would be performed to meet this objective.

The Consent Order specifies a range of administrative, operational, investigative, and engineering requirements necessary for continued, permitted operation of the Fresh Kills Landfill in accordance with Articles 27, 17, and 25 of the New York State Environmental Conservation Law, and Title 6 Part 360 of the Official Compilation of Codes, Rules, and Regulations of the State of New York.



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DESIGN BY:		
DRAWN BY:	J.R.D.	7/16/92
CHECKED BY:		7/17/92
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APPROVED BY:		7/17/92

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SCALE
1"=2000'

FIGURE 1

SITE LOCATION MAP

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NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

JOB No.	529363
DATE	7/20/92
SHEET	OF
DWG No.	FK-J02

Regulatory agency review of this document resulted in an acceptable determination dated February 4, 1991.

As specified in the Consent Order, field investigations associated with the SIP are comprised of several primary components, as follows: (1) site-specific and regional well survey and literature review reports; (2) test boring programs; (3) monitoring well installation program; (4) soil sampling and testing; (5) in-situ hydraulic conductivity testing; (6) water quality/chemistry sampling and analysis; and (7) water level monitoring. A summary of the execution of each of these components is provided below.

1.1 Survey Reports

Three survey reports were prepared during the initial stages of the hydrogeological investigation:

- Groundwater Monitoring Well and Piezometer Survey Report
- Supply Well Survey Report
- Hydrogeological Literature Review

All of these reports were prepared in accordance with the Consent Order Milestone Schedule, and have been accepted as complete by NYSDEC either in their original form, or through development of clarification responses or addendum report documentation.

The investigation associated with the Groundwater Monitoring Well and Piezometer Survey Report entailed field reconnaissance of the status of all wells and piezometers previously installed at the Fresh Kills Landfill. A total of 41 (of 143) installations were identified, with the majority of these wells and piezometers representing installations completed by NYCDOS in 1989. The remaining installations were either verified or presumed destroyed as a result of ongoing landfilling activity. Review of the report by NYSDEC resulted in the issuance of an acceptable determination, contingent upon the performance of additional field reconnaissance to locate wells and piezometers not verified destroyed. The results of the additional survey were documented in an addendum report. An additional 7 wells/piezometers were located, and were identified for abandonment or use for water level monitoring purposes; abandonment was completed during 1992.

Investigation associated with the Supply Well Survey Report entailed a survey of public and private potable supply wells within a one mile radius of the landfill property boundary. The purpose of this survey was to identify wells capable of providing representative sample that may be potential receptors of contamination emanating from the landfill. Following review of 356 well permits from Staten Island and New Jersey, only 12 wells were identified as potentially applicable for inclusion in the survey, due to construction and location within the one mile radius. Information obtained from direct contact with well owners resulted in the identification of only one industrial water supply well accessible for sampling purposes. No potable water supply wells were identified within Staten Island, as such wells have not been permitted within the borough for several decades. One interesting finding from the survey was the identification of an irrigation supply well located approximately one half mile south of the landfill (South Shore Golf Course) that had been abandoned due to progressive increases in chloride content over the years, indicative of seawater intrusion into the Cretaceous sand unit within which the well was screened. This finding correlates with the results of water quality analysis performed as part of this investigation in the Cretaceous sand unit underlying Landfill Section 1/9, and provides a plausible explanation for the presence of sea water mixing with fresh water in the project area.

The Hydrogeological Literature Review Report was prepared to provide a basis and framework for interpretation of site-specific geologic and hydrogeologic data collected in accordance with implementation of the SIP. Preparation of the report involved the compilation of all pertinent site-specific and regional literature regarding geology and hydrogeology, historical aerial photographs and maps, and boring logs associated with highway, road, bridge, sewerage, and marine facility construction within a one mile radius of the landfill boundary, as well as boring logs associated with building construction within a one-half mile radius of the landfill boundary. The report was accepted by NYSDEC with several clarification requests that were provided in an addendum report.

1.2 Test Boring Programs

An exploratory "center" boring program was performed within the landfill refuse mounds to provide geologic (lithologic) data beneath each of the four Fresh Kills landfill sections. The boring program followed a phased installation approach to allow for preliminary data analysis, and the incorporation of regulatory agency review into the design of the final installation plan

at each section. As a result of this process, the location of a number of borings was optimized to improve data recovery, and several borings were eliminated from the program as unnecessary due to laterally consistent lithology. In support of the phased installation plan, two interim reports were prepared to document the findings of the Phase I programs, and provide the technical rationale for Phase II program design, as follows: Phase I Milestone Report-Center Boring Program-Landfill Section 6/7 (May 1991), and Phase I Milestone Report-Center Boring Program-Landfill Sections 2/8 and 3/4 (September 1991). No formal milestone report was prepared for Landfill Section 1/9.

The center boring program was initiated during January 1991, and completed during September 1991. A total of 15 borings were completed at Section 1/9, 12 borings at Section 6/7, and 9 borings each at Sections 2/8 and 3/4. Borings were advanced with hollow stem auger equipment through the refuse; following the setting and sealing of a temporary steel or PVC casing beneath the refuse to preclude vertical leachate migration, drilling continued using mud and/or water rotary drilling techniques until bedrock was encountered. Approximately 15 ft of NX diameter (2 in.) core was obtained from bedrock at each location. Borings ranged in depth from 65 ft in Landfill Section 6/7 to over 290 ft at Section 1/9. Temporary piezometers were installed within the saturated refuse mound and deep confined water bearing units (sand and/or bedrock) at three boring locations within each of Landfill Sections 1/9 and 6/7, and one location within each of Sections 2/8 and 3/4 to allow for collection of water level data from the central landfill areas. All boreholes not converted to piezometers were abandoned in accordance with the specifications of the SIP.

A perimeter boring program, specified within Consent Order Appendix A-4 to support perimeter leachate containment facility design, was performed within the context of the more comprehensive Hydrogeological Investigation. This program entailed shallow borings at 200 ft intervals and deep borings at 1000 ft intervals around the perimeters of Landfill Sections 1/9 and 6/7, for the purpose of identifying the presence of low permeability confining unit strata. In lieu of conventional borings, NYCDOS proposed and implemented the investigation program using piezo electric cone penetration test (P-ECPT) equipment. This equipment provides a continuous record of soil characteristics through direct measurements of friction and resistance against the test probe; estimates of saturated lateral hydraulic conductivity were also obtained at selected testing increments. The P-ECPT testing program was initiated during July 1991, and continued in several stages through March 1992. A correlation report comparing the findings of the P-

ECPT analysis to the results of soil classification resulting from conventional perimeter well borings, as well as the final P-ECPT testing program report have been completed.

1.3 Well Installation Program

As specified in the SIP, the Fresh Kills Landfill monitoring well array was designed to consist of: (1) shallow (water table) well installations at 500 ft intervals around each landfill section, (2) confined water bearing unit (deep sand/bedrock) well installations at 750 ft around the hydraulically down gradient and cross gradient perimeter of each landfill section, and (3) confined water bearing unit (deep sand/bedrock) well installations at 1500 ft around the hydraulically up gradient perimeter of each landfill section. The objective of this installation program was to provide for the characterization and long term monitoring of water quality laterally across and vertically beneath the Fresh Kills landfill complex, as well as the collection of lithologic data to supplement that obtained from the center boring program in support of sectional and site-wide stratigraphic correlation.

As with the center boring program, the well installation program was designed to proceed in a phased manner, allowing for an initial assessment of water chemistry and hydrogeology in support of regulatory agency data review, and final installation program design. The Phase I installation program consisted of the installation of cluster wells (shallow [water table], and confined water bearing unit wells) at approximate 1500 ft intervals around the perimeter of each landfill section. This work was initiated during February 1991 and completed during October 1991. A total of 99 wells and 1 piezometer were installed over this period, as follows:

Section 1/9:	11 shallow (water table) wells, 16 intermediate depth (confined water bearing unit) wells, 12 deep (bedrock) wells, and 1 deep (bedrock) piezometer;
Section 2/8:	4 shallow (water table) wells, 6 intermediate depth (confined water bearing unit) wells, and 8 deep (bedrock) wells;
Section 3/4:	7 shallow (water table) wells, 4 intermediate depth (confined water bearing unit) wells, and 7 deep (bedrock) wells; and

Section 6/7: 6 shallow (water table) wells, 5 intermediate depth (confined water bearing unit) wells, and 13 deep (bedrock) wells.

Following analysis of data recovered through performance of the continuous water level monitoring program, flow gradients in the confined sand and bedrock water bearing units were identified, and the Phase II well installation program was designed. This program consisted primarily of the installation of intermediate depth and deep (bedrock) monitoring wells midway between those installed during the Phase I program along crossgradient and downgradient landfill perimeter boundaries, as well as the placement of shallow monitoring wells between existing Phase I installations to establish a 500 ft spacing array for this monitoring zone. In addition, a series of test wells and piezometers were installed in the refuse, glacial till, and bedrock to obtain additional hydraulic data in these units, as recommended in the Interim Hydrogeological Report. The Phase II Well Installation Program was initiated in March 1992, and completed in October 1992. A total of 118 wells and 26 test wells/piezometers were installed over this period, as follows:

Section 1/9: 21 shallow (water table) wells, 11 intermediate depth (confined water bearing unit) wells, 6 deep (bedrock) wells, 4 shallow refuse piezometers, 1 deep refuse test well, 1 glacial till piezometer, and 1 bedrock test well.

Section 2/8: 14 shallow (water table) wells, 5 intermediate depth (confined water bearing unit) wells, 3 deep (bedrock) wells, 3 shallow refuse piezometers, 1 glacial till piezometer, and 1 bedrock test well.

Section 3/4: 19 shallow (water table) wells, 1 intermediate depth (confined water bearing unit) well, 4 deep (bedrock) wells, 3 shallow refuse piezometers, and 1 bedrock test well.

Section 6/7: 22 shallow (water table) wells, 4 intermediate depth (confined water bearing unit) wells, 8 deep (bedrock) wells, 4 shallow piezometers, 2 shallow refuse piezometers, 2 deep refuse test wells, 1 glacial till piezometer, and 1 bedrock test well.

Shallow (water table) wells were typically completed using 4 in. diameter Schedule 80 PVC riser pipe and 10-15 ft of screen. Intermediate depth (confined water bearing unit) wells were typically completed using 2 in. Schedule 40 or 80 PVC riser pipe (depending on depth) and 10 ft of screen. Intermediate depth wells were constructed in two or three stages, with the PVC riser placed within 12 in. and/or 8 in. exterior steel casing grouted in overlying low permeability strata to minimize the potential for vertical migration of shallow groundwater. Bedrock wells were typically completed as 15 ft of open borehole. As with the intermediate depth wells, bedrock well construction consisted of two or three stages, with 4 in. steel casing (grouted into the surface of bedrock) placed within 12 in. and/or 8 in. exterior steel casing. Well development was performed at all installations subsequent to completion to minimize the suspended sediment load in formation water. In many cases, redevelopment or well rehabilitation was required due to the low yield or material composition (e.g., refuse) of the monitoring zones.

A significant finding of the test well installation program performed during Phase II is that leachate mound elevations measured by shallow piezometers likely represent perched conditions, with actual saturated refuse thicknesses 30-60 feet lower than those calculated from the shallow head data. This finding has implications relative to the rate of vertical groundwater flow discharging from the refuse mound to underlying soils, and was evaluated through numerical flow analysis as part of the groundwater modeling component of the hydrogeological investigation.

1.4 Soil Sampling and Testing

Soil sample was recovered from all test borings associated with the center boring program, and all well borings associated with Phase I and Phase II well installation programs. Approximately 3,500 samples were obtained from drilling activities related to the test boring and Phase I well boring installations. Between 5-15 ft of rock core was obtained from all center borings and deep (bedrock) well borings. All soil samples and core are maintained within a sample archive facility at the Fresh Kills Landfill site.

In accordance with the specifications of the SIP, a subset of soil samples were processed for geotechnical index parameter analysis. Approximately 380 coarse grained samples (disturbed split spoon samples) were typically analyzed for grain size distribution, moisture content, Atterberg limits, specific gravity, and organic content. Approximately 160 fine grained samples

(undisturbed shelby tube samples) were typically analyzed for horizontal and vertical permeability (hydraulic conductivity), as well as several of the index parameters.

In addition to the geotechnical analyses, approximately 180 samples were selected for microfossil (palynological) analysis, to allow for age dating in support of lateral stratigraphic correlation of unconsolidated sediments.

Downhole geophysical logging was performed in a total of 62 selected test borings and Phase I well borings to support and enhance lithologic characterization and soil unit contact interpretation. Logs typically recovered included natural gamma, spontaneous potential, single-point resistance, and electromagnetic induction.

1.5 In-Situ Hydraulic Conductivity Testing

Instantaneous discharge (slug) tests were performed at all installed Phase I wells to obtain estimates of horizontal hydraulic conductivity within the shallow (water table) and confined water bearing unit monitoring zones. Slug withdrawal tests were typically performed in shallow (water table) wells where the well screen is only partially saturated. Slug injection tests were typically performed in confined aquifer wells with fully saturated well screens. Long term recovery tests were required in a number of wells exhibiting extremely low yield. In excess of 300 tests and quality control retests were performed in Phase I and II wells, test wells and piezometers, and NYCDOS 1989 wells and piezometers. In addition, discrete zone packer pump testing was performed for a series of vertical horizons within deep bedrock test well boreholes in Landfill Sections 1/9, 3/4, and 6/7 as part of the Phase II well installation program.

1.6 Water Quality/Chemistry Sampling and Analysis

Two quarterly monitoring programs were specified in the SIP for characterization of water quality at the Fresh Kills Landfill, as follows: (1) Sampling and analysis of NYCDOS wells installed in 1989, wells identified through performance of the Groundwater Monitoring Well and Piezometer Survey Report from which representative sample can be obtained, and newly installed (Consent Order specified) wells for 6 NYCRR Part 360 Expanded Parameters (general water chemistry,

metals and a full suite of organic compounds), and (2) sampling and analysis of NYCDOS piezometers installed in 1989 and off-site water supply wells identified through performance of the Supply Well Survey Report from which representative sample can be obtained for 6 NYCRR Part 360 Baseline Parameters (general water chemistry, metals and volatile organic compounds).

Sampling and analysis of NYCDOS 1989 wells was initiated on December 31, 1991 for the January 1991 sampling quarter. Ongoing analytical program development between NYCDOS and NYSDEC resulted in postponement of the April 1991 sampling quarter until July 1991; a total of 84 wells and 2 leachate collection pumping stations (at Section 1/9) were sampled during this quarter for Expanded Parameter analysis, as well as 4 piezometers and 1 industrial supply well for Baseline Parameters.

Following independent validation of analytical data obtained from the July 1991 sampling quarter, review of parameter data and test method performance by NYSDEC and NYCDOS resulted in additional analytical program refinement through December 1991. These activities resulted in the deferment of the October 1991 sampling quarter to January 1992. During both the January and April 1992 sampling quarters, a total of 121 wells and 2 leachate collection pumping stations (at Section 1/9) were sampled for Expanded Parameter analysis, as well as 4 piezometers and 1 industrial supply well for Baseline Parameters. During the July and October 1992 sampling quarters, the quantity of well samples progressively increased to over 200, commensurate with progress in the Phase II Well Installation Program.

During the January 1992 sampling quarter, a program of dedicated bladder pump installation was initiated in deep monitoring wells to improve consistency in sample recovery. This program was continued throughout 1992 until all wells within the monitoring array were outfitted with dedicated pumps.

Data from the January and July 1991, January, April, July, October 1992, and January 1993 sampling quarters are incorporated within this report. Independent data validation and data usability analysis has been completed for all sampling quarters. In addition, a data comparability assessment, to evaluate consistency in analytical results across sampling events, has been completed for all data through the January 1993 sampling quarter.

As a supplement to the sampling programs stipulated under the Consent Order and 6 NYCRR Part 360, a limited geochemical testing program was performed during the July 1991, January 1992 and July 1992 sampling quarters. This program entailed the collection and analysis of filtered sample for a suite of indicator parameters, metals, and environmental isotopes at a subset of up- and down gradient well clusters at each landfill section.

1.7 Water Level Monitoring

Throughout 1991 and 1992, pressure transducers and digital data recorders (data loggers) were installed in all Phase I monitoring wells and center boring piezometers. This equipment allows for the continuous monitoring of water level changes in the wells, the evaluation of which is necessary for the determination of ground water flow gradients in the tidally influenced Fresh Kills estuarine environment. Time averaged water level (head) data were supplemented on a periodic basis by synchronous manual water level measurements in Phase II wells and wells and piezometers previously installed at the landfill. A one month "window" within June and July 1992 was selected as a control period for the establishment of time-averaged head data and the development of maps depicting the surface of the water table and the piezometric surface of confined water bearing zones, from which ground water flow gradients were inferred. Due to the presence of saline intrusion within confined aquifer units along the western and southern portions of the landfill, density corrections (based on laboratory specific gravity analysis) were applied to water level data in these areas. Laboratory specific gravity analysis of groundwater in these areas was performed to improve the accuracy of the density corrections.

2.0 Characterization of Site Geology

Characterization of site geology represents the fundamental component of the Hydrogeological Investigation, as all subsequent analysis must consider the physical distribution of geologic materials as the reference point from which data evaluation proceeds. Literature review relative to the geology of Staten Island indicated a limited availability of current and pertinent information compared to neighboring areas of New Jersey and Long Island. Consequently, in the development of the investigation and analysis program for this project, maximum use of the

limited local data base was made, supplemented by prior site-specific subsurface investigations, and regional studies that included general reference to conditions within Staten Island.

The Fresh Kills Landfill occurs within two physiographic provinces: The Triassic Lowland portion of the Piedmont Province comprises the northern portion of the project area, and the Coastal Plain Province comprises the southern area. A relatively thin mantle of soil materials overlying bedrock and hilly terrain is characteristic of the Piedmont Province, while the Coastal Plan is characterized by relatively level terrain and thick layers of soil materials overlying bedrock. The division between the two physiographic provinces is termed the "Fall Line", which has been mapped beneath the project site. The presence of this regional boundary within the area of investigation complicates the geologic analysis and stratigraphic. Adding to this complexity are the effects of Pleistocene glaciation in the region, which modified the prior topography and deposited a sequence of highly variable soil materials. Due to its location near the terminal glacial advance, the geology of the Fresh Kills area is especially diverse in this regard, reflecting a range of subglacial, glaciofluvial, glaciolacustrine and ice contact depositional environments.

Recognizing these complexities, conventional geological (lithostratigraphic) analysis was supplemented by a series of additional investigative techniques to assist in data analysis. These included downhole geophysical logging (to assist in the definition of geologic contacts and the evaluation of soil characteristics), microfossil analysis (to establish the age of sediments in support of lateral correlation), and piezo electric cone penetration testing (to allow for a higher level of definition of lithologic structure in shallow sediments). The results of these analyses led to the development of a stratigraphic column for the project area, detailed on Figures 2A and 2B.

The stratigraphic column outlined above is very similar to that identified in previous investigations, although detailed knowledge of the vertical and lateral distribution of the deposits has been achieved only through performance of the Hydrogeological Investigation. Figures 3 and 4 illustrate in schematic cross-section the distribution of geologic materials underlying the Fresh Kills Landfill along a north-south profile and a west-east profile, respectively. Volumetrically, the majority of geologic deposits underlying the project area consist of fine grained silt and clay materials. Within this fine grained matrix, coarse grained strata of varying thickness and lateral extent occur. These latter are of importance because of their potential to act as migration pathways for landfill leachate. The characteristics and distribution of all identified

PERIOD OR EPOCH	FORMATION	GENERALIZED TEXTURAL DESCRIPTION OF THE FORMATION
RECENT	FILL (REFUSE) FILL (CLEAN)	REFUSE (HOUSEHOLD & CONSTRUCTION DEBRIS) STRUCTURAL FILL – RANGING FROM SILTY CLAY TO C–F SAND, LITTLE SILT
	NON-CONFORMITY	
RECENT	PEAT	BLACK PEAT, TRACE TO LITTLE SILT AND CLAY, TRACE FINE SAND
	RECENT SILT & CLAY	LIGHT GRAY TO BLACK CLAY AND SILT, TRACE FINE SAND TO DARK GRAY ORGANIC SILT, TRACE FINE SAND
	RECENT SANDS	LIGHT GRAY TO BLACK SAND, TRACE TO LITTLE SILT AND CLAY
	NON-CONFORMITY	
PLEISTOCENE	GLACIOLACUSTRINE CLAY & SILT	MODERATE RED BROWN SILT AND CLAY, TRACE TO LITTLE SAND, TRACE TO LITTLE FINE GRAVEL
	GLACIAL SANDS	MODERATE RED BROWN SAND, TRACE TO LITTLE SILT AND CLAY, TRACE TO AND GRAVEL
	GLACIAL TILL	MODERATE RED BROWN SILT AND CLAY, LITTLE TO AND SAND, LITTLE TO AND GRAVEL
	NON-CONFORMITY	
PLEISTOCENE OR TERTIARY	COLUMBIA GROUP	YELLOW TO ORANGE BROWN SAND, LITTLE TO AND SILT AND CLAY YELLOW SILT AND CLAY, LITTLE TO SOME SAND

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DESIGN BY:	TP	3/93
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ENGINEER:		
APPROVED BY:	SP	3/93

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Weiss Envirotech
Weiss–New York, Inc.

FIGURE 2A
GENERALIZED GEOLOGIC SECTION AND TEXTURAL DESCRIPTION OF THE SEDIMENTS AND BEDROCK AT THE FRESH KILLS LANDFILL SITE

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NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

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SHEET	1 OF 2
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PERIOD OR EPOCH	FORMATION	GENERALIZED TEXTURAL DESCRIPTION OF THE FORMATION
CRETACEOUS	CRETACEOUS CLAY	LIGHT GRAY TO BLACK OR MODERATE RED BROWN AND LIGHT GRAY CLAY AND SILT, TRACE FINE SAND
	CRETACEOUS SAND	LIGHT GRAY TO DARK GRAY SAND, TRACE TO LITTLE SILT AND CLAY
POST TRIASSIC	RESIDUAL CLAY LOCKATONG FORMATION	LIGHT GRAY TO MODERATE GRAY, OR BLUE, OR GREEN CLAY AND SILT, TRACE FINE SAND, TRACE GRAVEL
	RESIDUAL CLAY STOCKTON FORMATION	RED BROWN TO RED PURPLE CLAY AND SILT, TRACE FINE SAND, TRACE GRAVEL
POST ORDOVICIAN	RESIDUAL CLAY SERPENTINITE	DARK GREEN AND YELLOW GREEN CLAY AND SILT, TRACE FINE SAND, TRACE GRAVEL
TRIASSIC	WEATHERED BEDROCK LOCKATONG FORMATION	LIGHT GRAY TO BLACK, WEATHERED AND FRACTURED SHALE, FRIABLE WITH FREQUENTLY LESS WEATHERED ZONES
	WEATHERED BEDROCK STOCKTON FORMATION	RED-BROWN, FRACTURED WEATHERED SHALE, FRIABLE WITH FREQUENTLY LESS WEATHERED ZONES
ORDOVICIAN	WEATHERED BEDROCK SERPENTINITE	DARK GREEN TO YELLOW GREEN FRACTURED AND WEATHERED SERPENTINITE, OFTEN PORPHORITIC, OFTEN WEATHERS TO A SAND TEXTURE
JURASSIC, TRIASSIC, OR ORDOVICIAN	COMPETENT BEDROCK	PALISADE DIABASE--INTRUSIVE SILL GRAY, WHITE, BLACK, FINE GRAINED, DENSE, DIABASE, PREDOMINANTLY PLAGIOCLASE FELDSPAR AND AUGITE, MINOR AMOUNTS QUARTZ LOCKATONG FORMATION - LIGHT GRAY TO BLACK SHALE, FISSILE, FREQUENTLY BEDDED STOCKTON FORMATION - MODERATE RED-BROWN OR RED-PURPLE SHALES, SILTSTONE AND ARKOSIC SANDSTONE STATEN ISLAND SERPENTINITE--GREENISH CRYSTAILINE SERPENTINITE, ULTRABASIC

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APPROVED BY:	SP	3/93

INTERNATIONAL TECHNOLOGY CORPORATION

Weharen Environmental

FIGURE 28
GENERALIZED GEOLOGIC SECTION AND TEXTURAL DESCRIPTION OF THE SEDIMENTS AND BEDROCK AT THE FRESH KILLS LANDFILL SITE

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NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

JOB No.	529363
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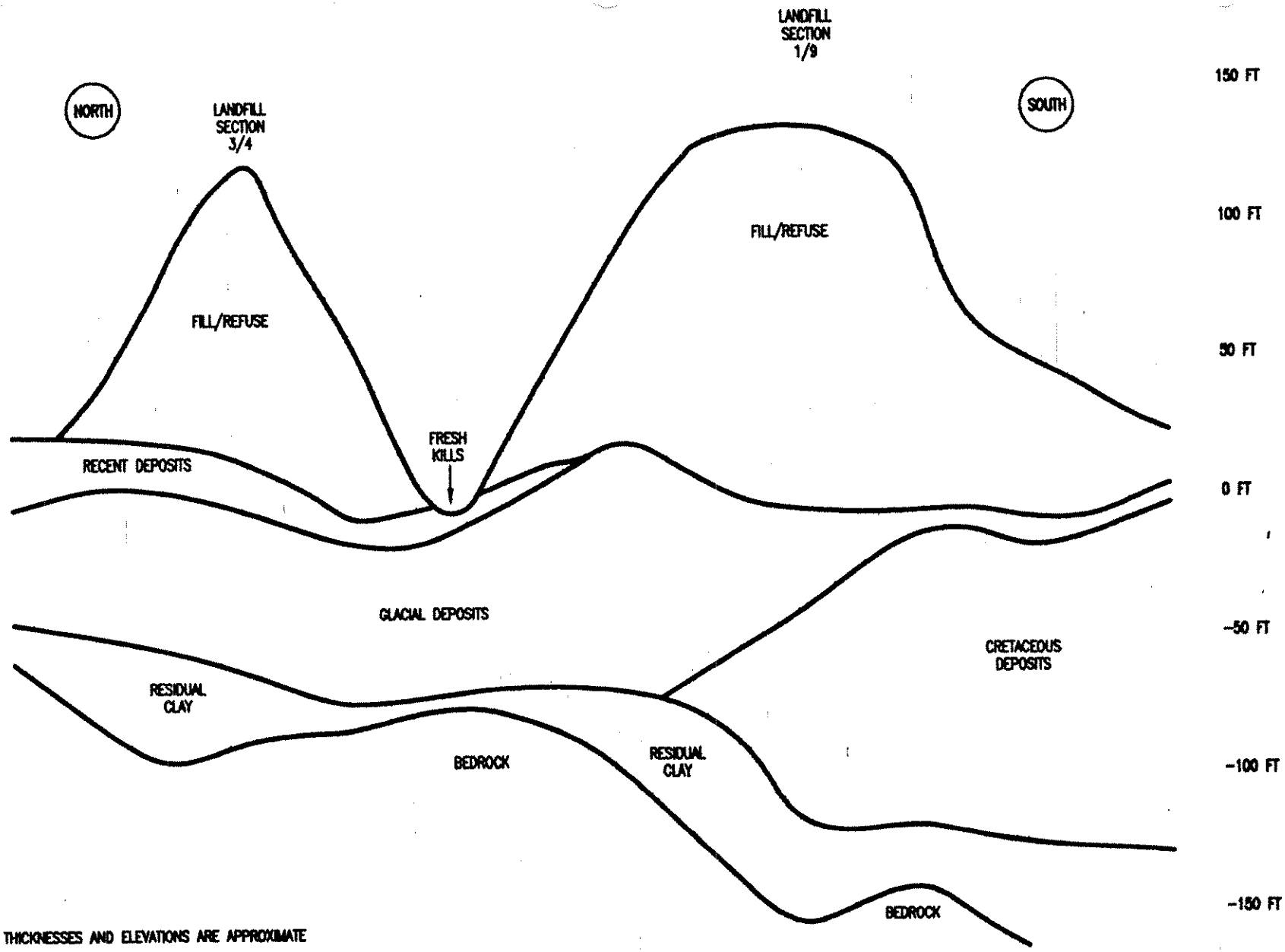

NOTE: THICKNESSES AND ELEVATIONS ARE APPROXIMATE

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APPROVED BY:	SP	3/93

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FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

FIGURE 3
NORTH-SOUTH SCHEMATIC PROFILE OF FRESH KILLS LANDFILL SUBSURFACE DEPOSITS

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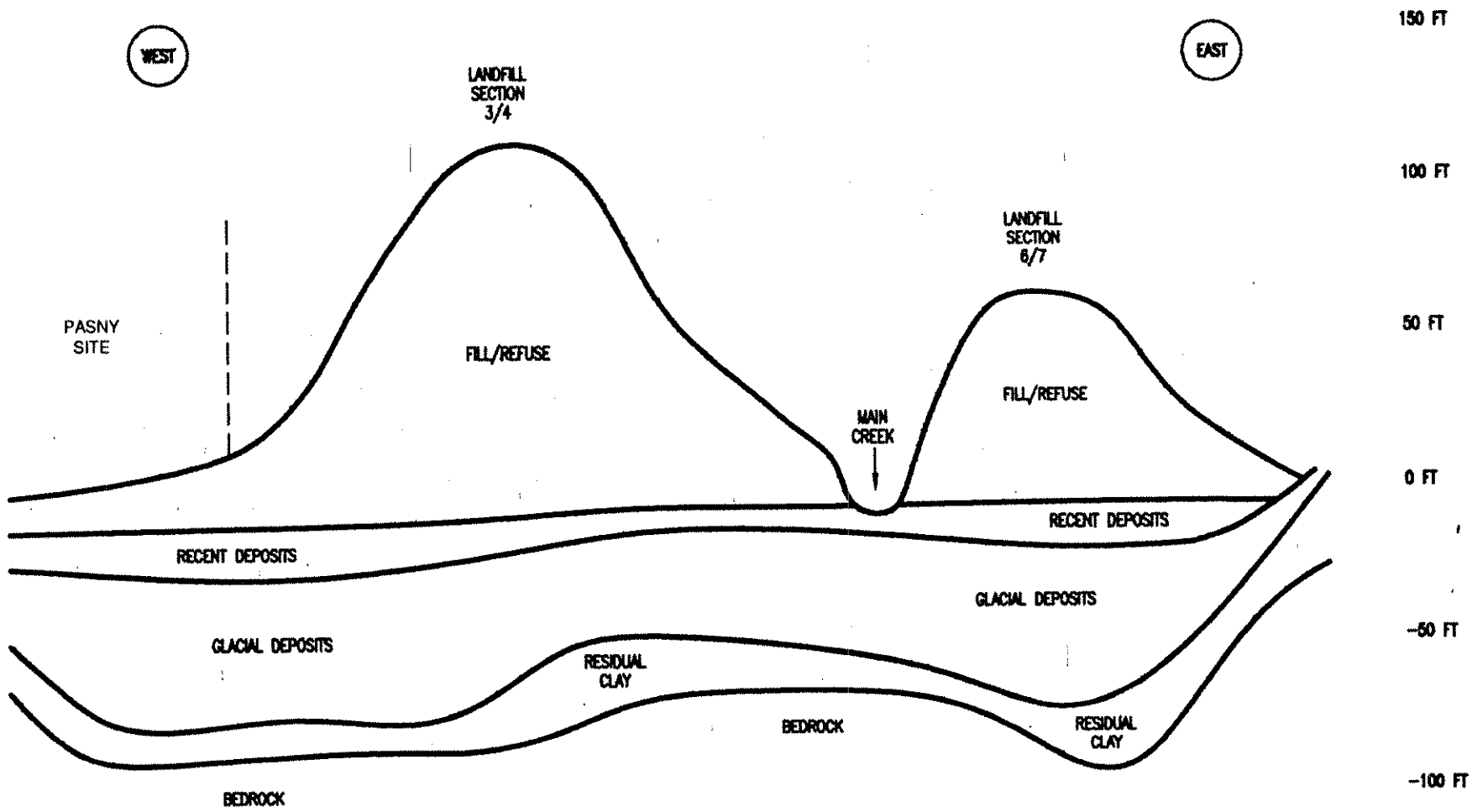

NOTE: THICKNESSES AND ELEVATIONS ARE APPROXIMATE

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ENGINEER:		
APPROVED BY:	SP	3/83

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NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

FIGURE 4
WEST-EAST SCHEMATIC PROFILE OF FRESH KILLS LANDFILL SUBSURFACE DEPOSITS

JOB No.	528383
DATE	3/83
SHEET	1 OF 1
DRAWING No.	FK-6-07.DWG

lithostratigraphic units are summarized below, with additional detail provided relative to the distribution of the coarse grained (sand) units.

2.1 Recent Deposits

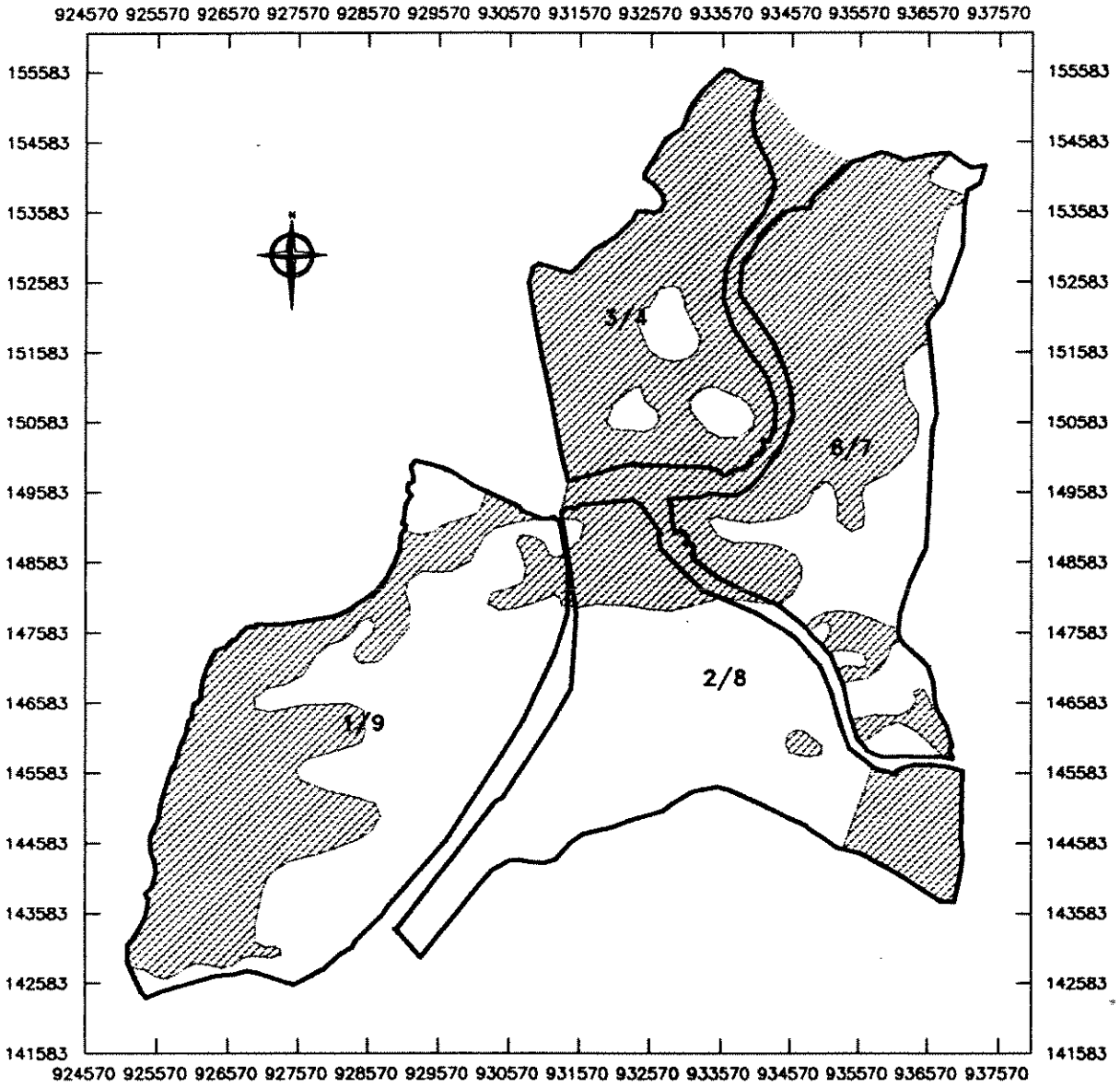
The uppermost deposits present across most of the landfill area consist of refuse and fill materials that overlie the natural geologic strata. Extensive thicknesses of these materials (currently ranging from less than ten to over 150 ft, and planned to several hundred feet) cover most of the landfill area.

Recent materials of natural origin occur across much of the project site within areas historically represented by tidal marsh environments prior to landfilling. The deposits are absent from historic upland areas, generally located to the east of Sections 1/9 and 6/7, the northwest of Section 3/4, and the south of Section 2/8. Recent deposits usually overlie Pleistocene (glacial) strata.

Peat consists of fibrous plant material or "meadow mat", and is located below refuse/fill and above or interbedded with other Recent deposits. The unit is generally on the order of several feet thick, and while lateral correlation is possible in several areas, it generally appears to be sporadically distributed horizontally and vertically.

Recent silt and clay occurs across most of the project site within the former tidal marsh areas. Where it occurs, it generally represents the unit located directly below refuse/fill. The thickness of the Recent silt and clay ranges from several feet to as much as 15 ft; the thickness distribution of the unit is not laterally consistent due to interbedding with peat and Recent sand deposits.

Recent sand is also limited to the former tidal marsh areas. It occurs as channel and sheet-like deposits of varying lateral extent. The unit is found at the ground surface, below refuse/fill, or below or interbedded with other Recent deposits. Recent sand appears to exist as a fairly correlative sheet-like deposit north of the Fresh Kills in Landfill Section 3/4. This deposit extends in the northwestern Landfill Section 6/7 northern Landfill Section 2/8 and northern and western Landfill Section 1/9. Thickness commonly ranges from several ft to 20 ft (Figures 5). Adjacent to the Arthur Kill, thicknesses in the range of 10 to 46 ft are observed.



LEGEND:

RECENT SAND

No.	DATE	REVISION/DESCRIPTION

	NAME	DATE
DESIGN BY:	T.P.	9/10/93
DRAWN BY:	d.m.b.	10/7/93
CHECKED BY:	E.W.	10/7/93
ENGINEER:		
APPROVED BY:	S.P.	10/7/93

INTERNATIONAL TECHNOLOGY CORPORATION

0 2500

SCALE IN FEET

FIGURE 5

DISTRIBUTION OF CORRELATIVE RECENT SAND UNITS

Prepared For:

NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

JOB No.	529363
DATE	11/22/93
SHEET	OF
DWG No.	529363-A845

529363A45 12/01/93 2:06pm D.M.B.

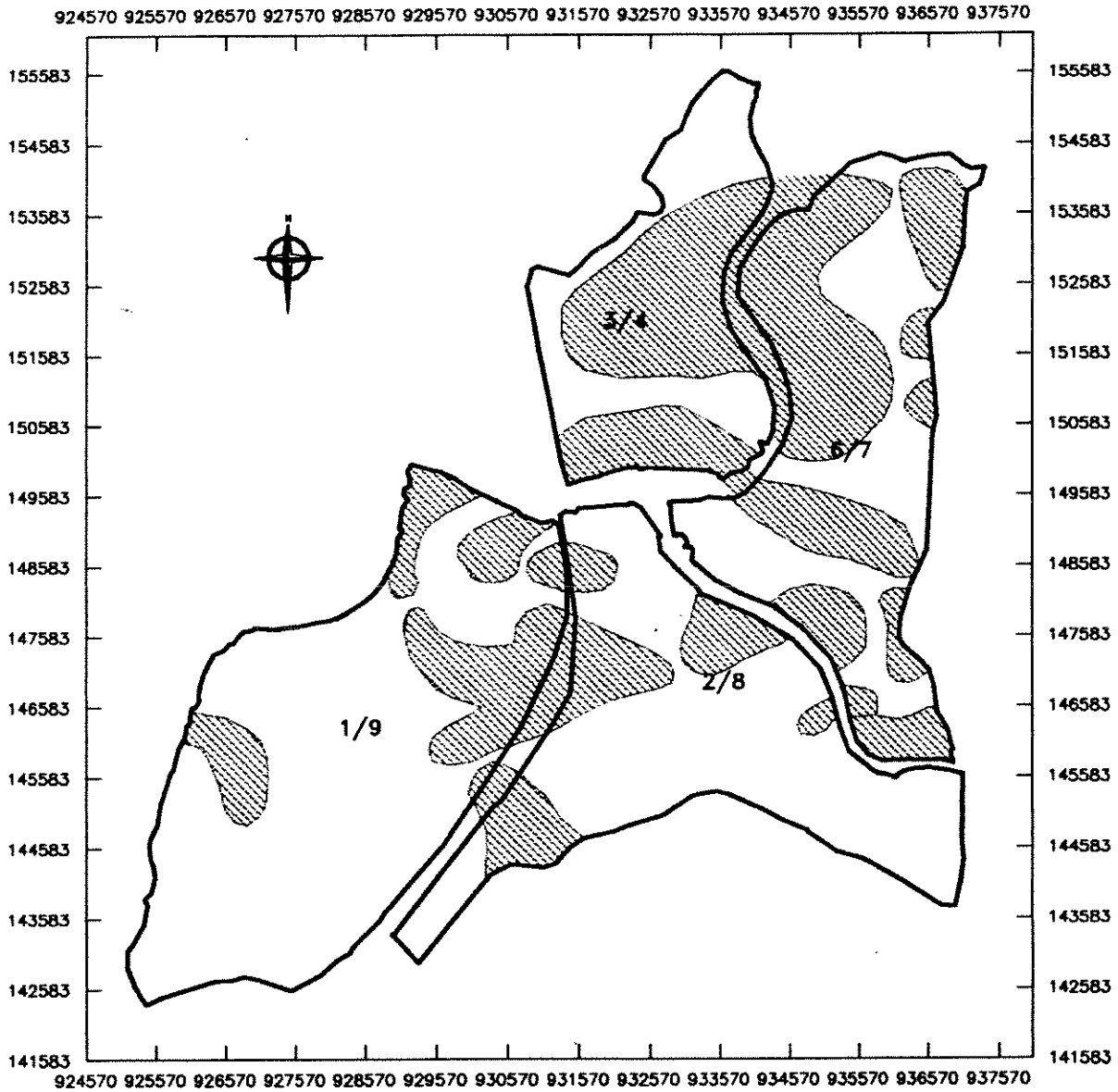
2.2 Pleistocene Deposits

Pleistocene (glacial) deposits underlie refuse/fill or Recent sediments, and overlie Cretaceous deposits or bedrock/weathered bedrock materials (including residual clay). In total, the Pleistocene deposits represent a thick, continuous site-wide feature. The processes associated with their deposition significantly altered the surface features and characteristics of underlying deposits, and established the topographic surface that controlled the mechanisms of Recent sediment deposition.

Glaciolacustrine silt and clay (fine grained sediment deposited in glacial lakes) occurs over most of the project area. The primary areas where it is absent is in the extreme eastern portion of Landfill Section 6/7, southern portion of Section 2/8, and western, southern, east central and northwest portions of Section 1/9. The unit ranges from a few feet to several tens of feet in thickness, the thickest sequence being in the western portion of Landfill Section 6/7 (> 30 ft). The thickness distribution of the glaciolacustrine silt and clay is not laterally continuous due to frequent interbedding with glacial till and glacial sand.

Glacial sand is present throughout the glacial sequence. It is most commonly associated with glacial kame (terrace) features located in Landfill Sections 1/9 and 3/4 (Figure 6). The glacial sand within the kame is often with interbedded with non-lodgement till/diamict and occasionally glaciolacustrine silt and clay. These sands correlate across Main Creek between Landfill Sections 3/4 and 6/7 and between Landfill Sections 1/9 and 2/8, and possibly across Richmond Creek between Landfill Sections 2/8 and 6/7.

Glacial till/diamict (unsorted, unstratified mixtures of boulders, gravel, sand, silt and clay) extends across the entire site except for the southern portion of Landfill Section 2/8, several portions of Landfill Section 1/9, and isolated areas of Landfill Sections 3/4 and 6/7. It occurs mostly as lodgement till, a dense, mostly fine grained, unsorted, unstratified unit at the base of the Glacial sequence. Non-lodgement till/diamict is encountered within the glacial sequence as melt-out till/flow till, water-laid till and turbidites. Including sand interbeds, the glacial till is observed to range in thickness from 5 to 65 ft across the project area.



LEGEND:

GLACIAL SAND

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DRAWN BY:	d.m.b	10/7/93
CHECKED BY:	E.W.	10/7/93
ENGINEER:		
APPROVED BY:	S.P.	10/7/93

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SCALE IN FEET

FIGURE 6

DISTRIBUTION OF CORRELATIVE GLACIAL SAND UNITS

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NEW YORK CITY DEPARTMENT OF SANITATION

FRESH KILLS LANDFILL

STATEN ISLAND, RICHMOND COUNTY, NEW YORK

JOB No. 529363

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S363A846 12/01/93 2:10pm D.M.B.

Columbia Group sediments have been identified in the southern portions of Landfill Sections 1/9 and 2/8. These deposits, either Tertiary or Pleistocene in age, consist of sandy or silt/clay units that were deposited prior to the existing glacial sediments.

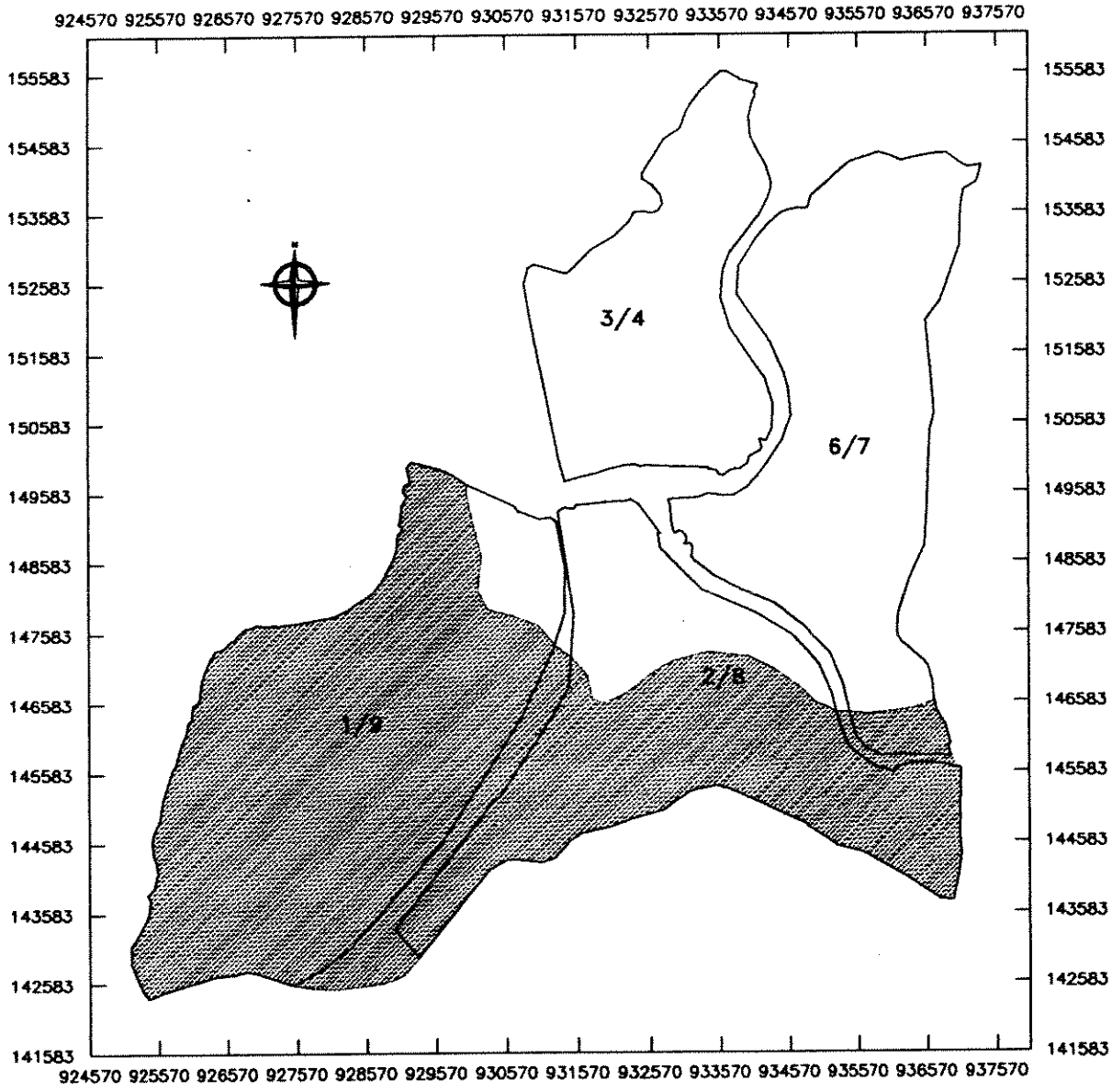
2.3 Cretaceous Deposits

The Cretaceous sediments were deposited in a relatively flat, broad (deltaic) environment, very close to sea level, with distributary streams extending across the deltaic plain, resulting in complexly stratified deposits. These Coastal Plain sediments occur over most of the project area south of the "Fall Line" (represented roughly by Fresh Kills/Richmond Creek), primarily within Landfill Sections 1/9 and 2/8. Cretaceous deposits are mostly overlain by glacial or Recent sediments, and underlain by bedrock or weathered bedrock/residual clay.

Cretaceous silt and clay occurs beneath most of Landfill Sections 1/9 and 2/8 as well as the extreme southern area of Landfill Section 6/7. These units dominate the upper portion of the Cretaceous sequence, although sand interbeds are common. It is laterally correlative throughout most of the area of occurrence extending from Landfill Section 1/9 eastward through Landfill Section 2/8 and into the southern portion of Landfill Section 6/7. The unit tends to thicken to the south, and thicknesses of tens of feet are common.

Cretaceous sand also occurs beneath most of Landfill Sections 1/9 and 2/8, as well as the extreme southern portion of Landfill Section 6/7 (Figure 7). It extends as a correlative unit at the base of the Cretaceous sequence. It is thickest in Landfill Section 1/9 (a composite thickness of over 80 ft) and thins to the east into Landfill Sections 2/8 (roughly 20 ft) and Section 6/7. Above the basal unit, the sand is complexly interbedded with the Cretaceous clay and silt. Interbedded sand strata above the basal unit are more difficult to correlate, although correlations have been made between upper units within Landfill Sections 1/9 and 2/8. A sand unit exceeding 40 ft in thickness occurs in the east central portion of Landfill Section 1/9, which may represent stacked or aggradational channel deposits.

Analysis of microfossil data from Cretaceous sediments recovered from the Fresh Kills project area suggests the potential for correlation of at least a portion of the Cretaceous sediments beneath the landfill to the Cretaceous sediments in adjacent areas. Sea water degradation of



LEGEND:

CRETACEOUS SAND

No.	DATE	REVISION/DESCRIPTION

	NAME	DATE
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DRAWN BY:	D.M.B.	10/7/93
CHECKED BY:	E.W.	10/7/93
ENGINEER:		
APPROVED BY:	S.P.	10/7/93

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0 2500

SCALE IN FEET

FIGURE 7

DISTRIBUTION OF CORRELATIVE CRETACEOUS SAND UNITS

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FRESH KILLS LANDFILL

STATEN ISLAND, RICHMOND COUNTY, NEW YORK

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Cretaceous sands underlying a large portion of Landfill Section 1/9 mitigates against the potential effects of a dilute leachate influence in this unit on possibly correlative strata to the west and south.

2.4 Bedrock/Weathered Bedrock

Within the project area, bedrock consists of the Triassic Stockton Formation (shale, siltstone and sandstone) and Lockatong Formation (shale), the Staten Island serpentinite (highly mineralized metamorphic rock), and schist. The trend of the contact between bedrock units is northeast/southwest across the project area. The Lockatong Formation underlies the northern half of Landfill Section 3/4. The Stockton Formation underlies the northern half of Landfill Section 6/7, the southern half of Section 3/4, the northern and western half of Section 2/8, and all of Section 1/9. The serpentinite underlies the southern portions of Sections 6/7 and 2/8. The schist has been identified within the extreme southern area of Section 6/7 and the southeastern area of Section 2/8. Altered bedrock is occasionally observed near the Stockton Formation/serpentine contact that includes formation of quartzite, vugs (voids), quartz and calcite veins, and color changes.

Weathered bedrock is a common component at the top of the bedrock surface. Residual clay usually occurs above bedrock in the shales and siltstones, and less commonly above the serpentinite and schist. Thicknesses of tens of feet have been encountered.

3.0 Characterization of Site Hydrogeology

Once knowledge of the lateral and vertical distribution of geologic units has been achieved, evaluation of the groundwater flow regime is feasible through the integration of information regarding the hydraulic characteristics of the geologic materials and the distribution of hydraulic head (water levels) in a conceptual model of groundwater flow. Within the context of hydrogeological analysis, data limitations regarding the relative continuity or extent of geologic units generally do not represent serious impediments, because many of these units exhibit similar hydraulic properties that allow for grouping into broader hydrogeologic categories. The ability to group geologic units into broader hydrostratigraphic categories in many cases reduces the

required level of detail in geologic mapping, and enables a better description of the processes that move groundwater within and beneath the specified project area.

In addition to the development of hydrostratigraphic units, definition of a series of basic elements are required to evaluate area hydrogeology and to aid in the development of the conceptual model. These include: (1) unit hydraulic conductivity distribution and thickness, (2) hydraulic boundary conditions, (3) hydraulic head distribution, (4) temporal hydraulic head variation, and (5) groundwater flux analysis.

3.1 Definition of Hydrogeologic Parameters

Based on the results of detailed geologic mapping, hydraulically transmissive and restrictive units were defined across the project area, resulting in the development of a series of laterally continuous hydrostratigraphic units. At the regional scale, these are represented by the refuse/fill, unconsolidated overburden, and bedrock units. The unconsolidated overburden consists of the Recent, Pleistocene (glacial), and Cretaceous soils and sediments that lie between the refuse/fill at ground surface and the bedrock "basement". On a more local, landfill section scale, segregation of the unconsolidated overburden unit into sub-units of transmissive and restrictive strata has been performed in support of further, more detailed hydrologic evaluation.

The hydraulic conductivity (water transmitting capacity) of geologic deposits, which forms the basis for hydrostratigraphic unit and sub-unit development, has been defined through the performance of in situ and laboratory testing of soil materials. Table 1 provides a regional summary of the results of this testing.

Boundary conditions relate to hydraulic features or processes that are external to the physical groundwater flow system, and prescribe the means by which water is routed either into or out of the study area. Broadly defined, boundary conditions include infiltration from precipitation, surface water/sea level elevation, the base of the bedrock flow system, landfill alterations (grading), and local or regional hydraulic gradients. Figure 8 provides a schematic illustration of the regional hydrogeologic setting of the Fresh Kills Landfill within Staten Island. This diagram indicates the generalized groundwater flow system within the unconsolidated overburden and bedrock hydrostratigraphic units at both the area-wide and local scale. Recharge to the

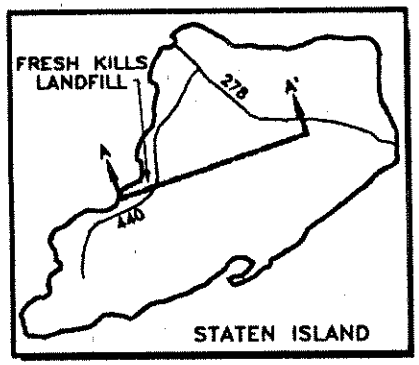
TABLE 1
SUMMARY OF HYDRAULIC CONDUCTIVITY (Kh / Kv) DATA
FRESH KILLS LANDFILL LEACHATE MITIGITATION SYSTEM PROJECT

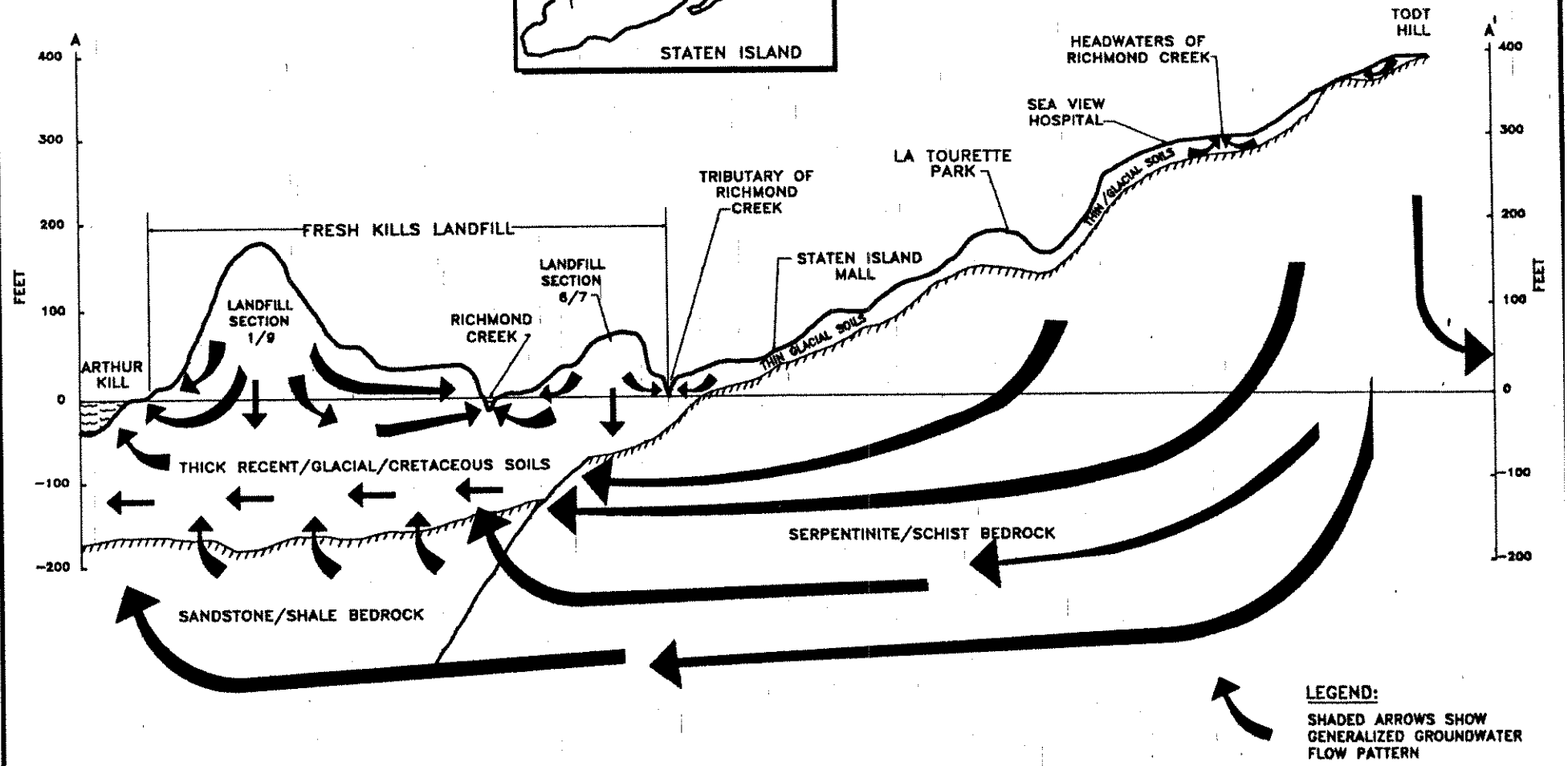
		REGIONAL DATA BASE		
		Number	Geometric Mean	
Lithologic Unit	Type of Test	of Tests	cm/sec	ft/day
Refuse/Fill	In-Situ	170	3.2E-03	9.1E+00
Recent Silt and Clay	Lab Kv	20	1.3E-07	3.7E-04
	Lab Kh	17	5.2E-08	1.5E-04
Recent Sand	Hazen [c]	56	1.3E-03	3.7E+00
	In-Situ	24	3.3E-04	9.3E-01
Glacial Clay	Lab Kv	102	1.7E-07	4.9E-04
	Lab Kh	82	1.7E-07	4.7E-04
Glacial Sand	Hazen [c]	31	1.1E-03	3.1E+00
	In-Situ	9	6.3E-04	1.8E+00
Glacial Till (Undifferentiated)	Hazen [c]	62	1.5E-05	4.2E-02
	Lab Kv	12	1.3E-07	3.7E-04
	In-Situ	16	1.4E-05	4.0E-02
Cretaceous Clay	Lab Kv	32	8.4E-08	2.4E-04
	Lab Kh	27	5.7E-08	1.6E-04
Cretaceous Sand	Hazen [c]	107	2.4E-04	6.7E-01
	In-Situ	29	9.4E-04	2.7E+00
Residual Clay	Lab Kv	9	1.4E-07	4.0E-04
	Lab Kh	7	9.4E-08	2.7E-04
Weathered Bedrock	In-Situ	40	9.8E-06	2.8E-02
Stockton	In-Situ	30	5.3E-06	1.5E-02
Lockatong	In-Situ	2	3.6E-04	1.0E+00
Serpentinite	In-Situ	4	2.3E-05	6.5E-02
Schist	In-Situ	4	6.9E-05	2.0E-01
Bedrock	In-Situ	24	4.4E-05	1.2E-01
Stockton	In-Situ	11	1.8E-05	5.0E-02
Lockatong	In-Situ	6	3.6E-04	1.0E+00
Serpentinite	In-Situ	5	7.4E-06	2.1E-02
Schist	In-Situ	1	6.9E-05	2.0E-01
Diabase	In-Situ	1	6.6E-08	1.9E-04
WB/B [a]	In-Situ	10	9.1E-05	2.6E-01
Stockton	In-Situ	5	1.3E-05	3.7E-02
Lockatong	In-Situ	--	--	--
Serpentinite	In-Situ	5	6.2E-04	1.8E+00
Schist	In-Situ	--	--	--
Composite Bedrock [b]	In-Situ	74	2.0E-05	5.6E-02

[a] Open borehole in hydraulic communication with both Weathered Bedrock (WB) and Bedrock (B)

[b] Composite of all data from Weathered Bedrock, Bedrock, and WB/B unit classifications

[c] Hazen (1911) approximation of hydraulic conductivity derived from soil grain size distribution





LEGEND:

SHADED ARROWS SHOW GENERALIZED GROUNDWATER FLOW PATTERN

No.	DATE	REVISION/DESCRIPTION	INIT.
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	NAME	DATE
DESIGN BY:	S.P.	2/27/93
DRAWN BY:	JRD/MSM	3/12/93
CHECKED BY:	J.G.	3/12/93
ENGINEER:		
APPROVED BY:	S.P.	3/12/93

INTERNATIONAL TECHNOLOGY CORPORATION

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NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

SHEET TITLE:

FIGURE 8
SIMPLIFIED GEOLOGIC CROSS SECTION OF STATEN ISLAND SHOWING GROUNDWATER FLOW PATTERNS IN RELATIONSHIP TO FRESH KILLS

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DATE	3/12/93
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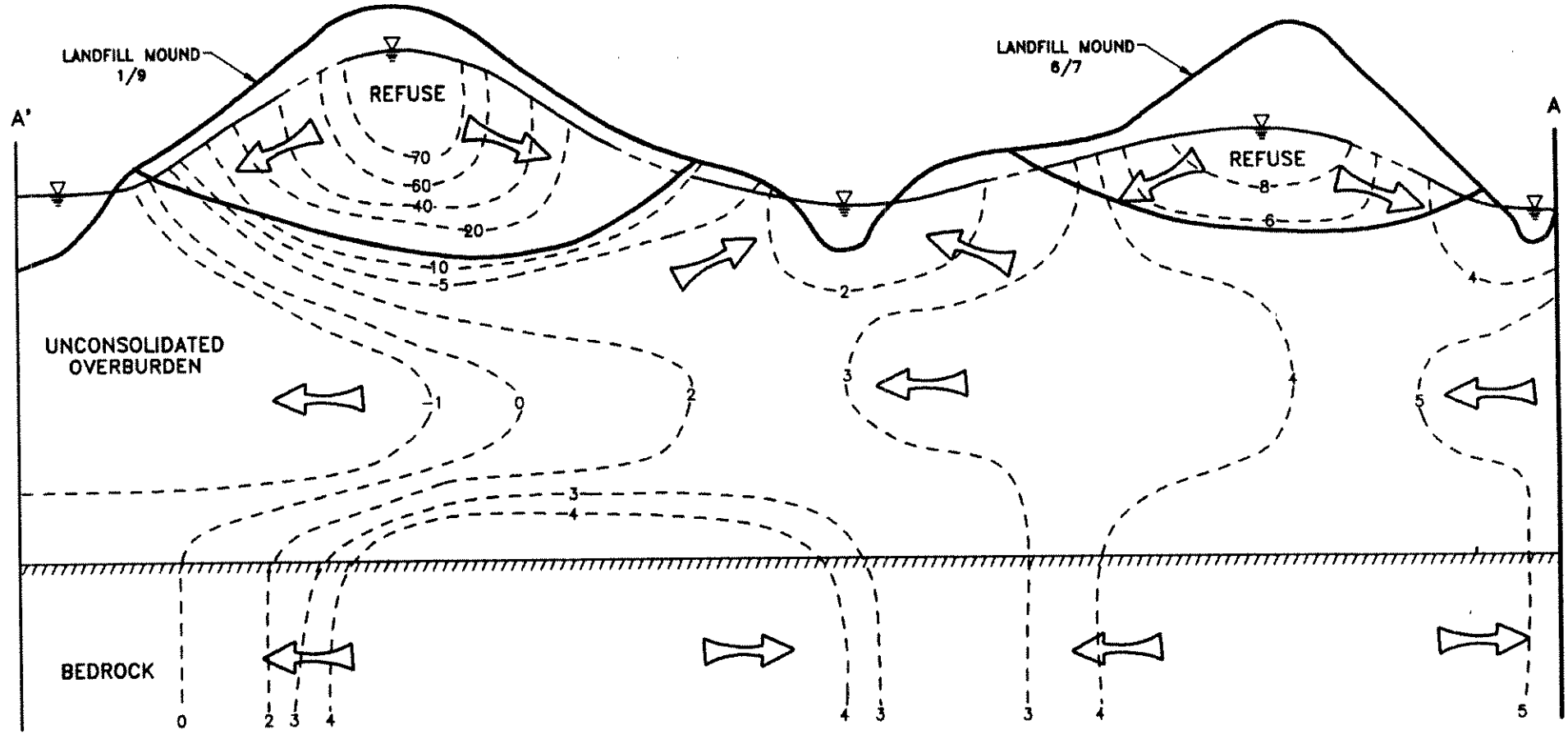
regional flow system is derived from the upland areas to the east, with discharge from the bedrock unit to overlying overburden units in the vicinity of the landfill and the Fresh Kills estuarine system. Groundwater flow in the overburden materials is derived primarily from the east/northeast and is either discharged locally into stream channels, or continues as a regional flow component to the south/southwest.

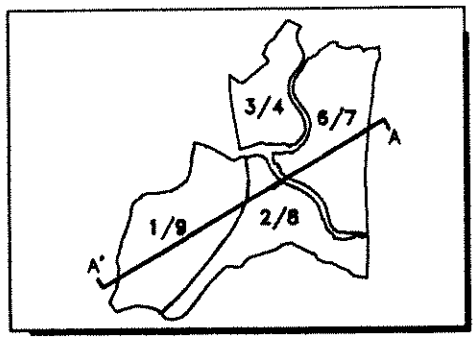
The lateral and vertical hydraulic head (water level elevation) distribution defines the driving force for the ground water flow system. The existing data base generally allows for an adequate definition of the lateral distribution of hydraulic head in the transmissive hydrostratigraphic units or sub-units identified in the project area. These data indicate a radial flow pattern within the refuse, a south/southeast flow component in the basal Cretaceous sand unit, and a southern regional flow component in the bedrock with upgradient areas to the north and east.

Based on available data obtained from test borings and shallow/deep cluster piezometers installed in the refuse, the elevations of the leachate mounds within the refuse units are not believed to be representative of full saturation. The presence of unsaturated zones within the refuse mounds suggests that fully saturated conditions exist at elevations 30 - 60 ft below leachate levels observed in shallow refuse piezometers. Field data are sufficient to allow for numerical evaluation of the effects of such perched conditions on horizontal and vertical groundwater flux.

The presence of a saline water influence, primarily in portions of the Cretaceous sand unit within Landfill Section 1/9, has necessitated correction of field measured salt water heads to equivalent fresh water heads to achieve lateral correlation with data obtained at other monitoring locations. Laboratory specific gravity analysis of groundwater within this unit and bedrock was used for density related corrections to the water level elevation database.

The vertical head distribution is well established at monitoring well (cluster well) locations; while these point relationships generally cannot be extrapolated spatially with a high degree of precision, they do allow for a qualitative site-wide assessment. Based on the available data, the following relationships are observed, as illustrated schematically in cross-section on Figure 9: Flow from within the refuse mounds to adjacent surface water discharge areas, and vertically downward to overburden materials; upward gradients from the bedrock unit into overburden materials; lateral discharge from overburden units into adjacent surface waters, or out of the





LEGEND:

- EQUIPOTENTIAL CONTOUR
- WATER-TABLE
- GENERALIZED GROUNDWATER FLOW DIRECTION

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DESIGN BY:	PW	6/92
DRAWN BY:	DMB	7/92
CHECKED BY:	SP	7/93
ENGINEER:		
APPROVED BY:	SP	7/93

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WehranEnviroTech

NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

FIGURE 9
SCHEMATIC CONCEPTUAL GROUNDWATER FLOW IN PROFILE

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project area along the regional hydraulic gradient. These site-specific relationships are consistent with the regional conceptual model illustrated previously on Figure 8.

Available data from within the bedrock units underlying the central portions of the landfills suggest areas of mounding in the bedrock piezometric (water level) surface. Such mounding is believed to primarily represent a transient pressure effect caused by depression/compaction of overburden strata due to the weight of overlying refuse materials, rather than a downward flow of groundwater to the bedrock. This assessment is based on the thickness distribution of hydraulically restrictive materials underlying the refuse, as well as the observed vertical (upward) hydraulic gradient distribution.

Temporal hydraulic head relationships (resulting primarily from tidal effects within the Fresh Kills estuarine system) have been recorded at cluster well installations and within surface waters through the use of continuous water level recorders. Water levels within shallow/refuse wells screened in the unconfined (water table) water bearing zone are generally not tidally influenced. The influence of tidal fluctuation on water levels in wells screened in intermediate depth confined or semi-confined sand strata is mixed, dependent on the spatial location and continuity of the transmissive unit. Water levels in the bedrock wells generally exhibit tidal fluctuation, consistent with pressure induced effects. While only short term variations have been examined as of this time, it appears that the steady-state analyses of groundwater flow considered to date are consistent under transient conditions.

Barometric pressure effects observed in shallow refuse wells suggests that groundwater within the refuse potentially flows under semi-confined conditions. The presence of positive gas pressure in the overlying unsaturated refuse is hypothesized as the cause of the semi-confining pressure.

3.2 Results of Conceptual Groundwater Flow Models

Conceptual groundwater flow models were developed for the regional and landfill section specific flow systems. The purpose of these models was to obtain a qualitative, and where data were sufficient, an analytical quantitative assessment of groundwater flow and the potential for leachate migration. Two dimensional cross-sectional numerical models were developed for Landfill

Section 1/9, Section 6/7, and Sections 2/8 and 3/4 combined. These models were used to refine the conceptual model analysis and evaluate the effects of variations in hydraulic input parameters on groundwater flow and solute transport, and allow for optimal development of a comprehensive, three dimensional groundwater flow model of the project area.

Results of the conceptual model analyses indicate that, consistent with the relationships illustrated on Figure 9, the majority of leachate leaves the flow system as horizontal flow to the major river or tributary stream channels along the periphery of the landfill sections. Very little leachate (ranging from 1 to 14 percent) has the potential to move vertically downward to the underlying unconsolidated overburden or bedrock hydrostratigraphic units.

Findings of the conceptual and cross-sectional numerical performed for each of the landfill sections are summarized below:

3.2.1 Landfill Section 6/7

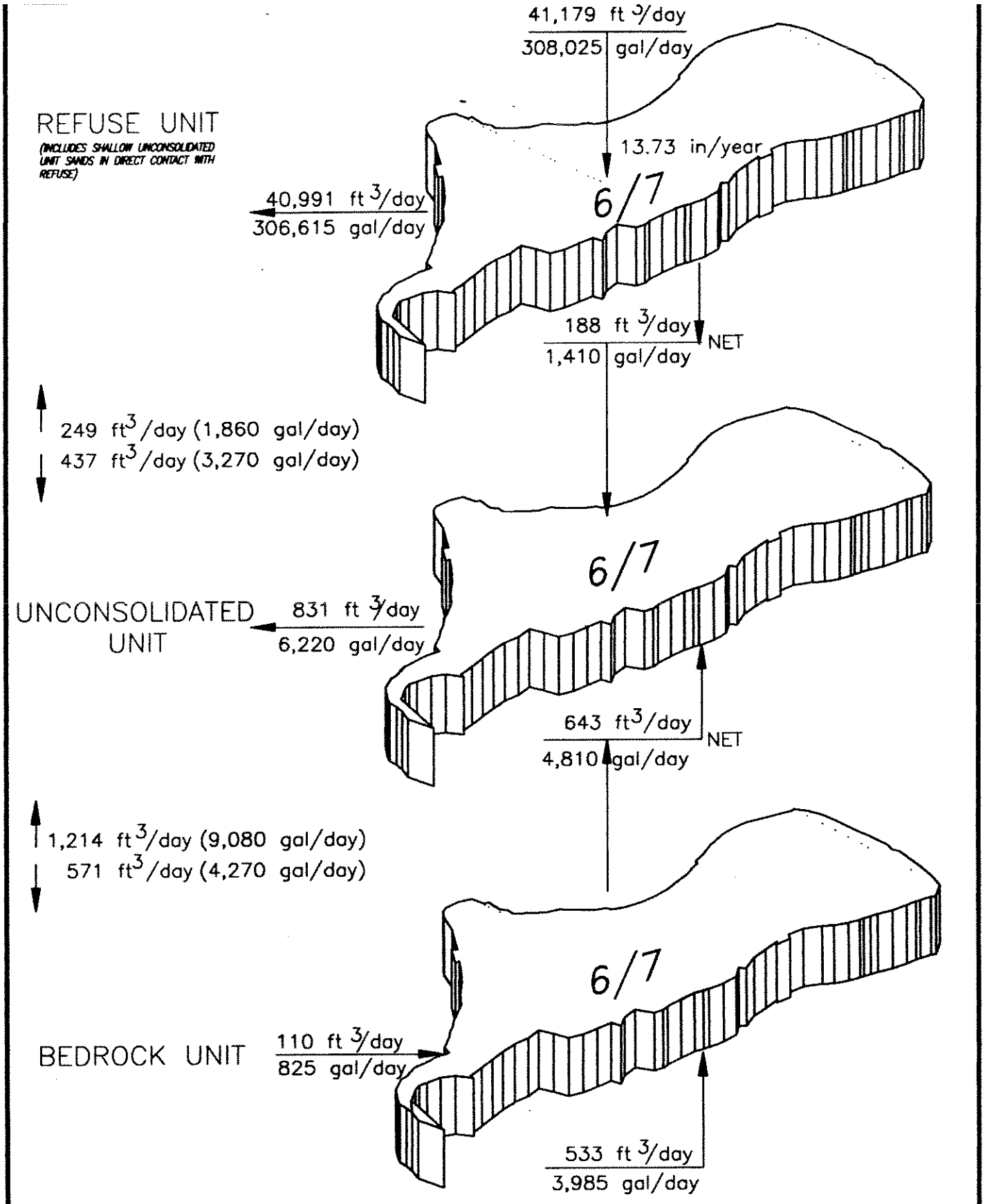
(1) Analytical flux analysis results (Figure 10) suggest that about one percent of the total recharge that enters the landfill can leave the refuse unit (and shallow, hydraulically interconnected sands) as vertical flux to deeper unconsolidated overburden units.

(2) Recharge to the landfill was estimated through net flux analysis as 13.73 inches per year.

(3) Sensitivity analyses performed on the cross-sectional model indicate that the presence of laterally continuous high permeability sand lenses beneath the refuse (1) do not significantly alter the refuse head distributions or mass flux exiting/entering the landfill, (2) can affect the distribution of contaminant (solute) migration, with more direct solute discharge to the surface water and less to the underlying units. In addition, increases in the hydraulic conductivity of the till unit increase the potential for solute to migrate into the bedrock unit on the eastern model boundary, where unconsolidated deposits thin and the bedrock surface rises.

3.2.2 Landfill Section 1/9

(1) Analytical flux analysis results (Figure 11) suggest that approximately 14 percent of the total recharge that enters the landfill can leave the refuse unit (and shallow, hydraulically interconnected sands) as vertical flux to deeper unconsolidated overburden units.



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DRAWN BY:	KAS	2/93
CHECKED BY:	LC	2/93
ENGINEER:		
APPROVED BY:	RM	2/93

INTERNATIONAL TECHNOLOGY CORPORATION

Wehran Envirotech
Wehran-New York, Inc.

FIGURE 10
SCHEMATIC SUMMARY OF THE NET FLUX OF GROUNDWATER CALCULATED THROUGH ANALYTICAL ANALYSIS LANDFILL SECTION 6/7

Prepared For:
NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

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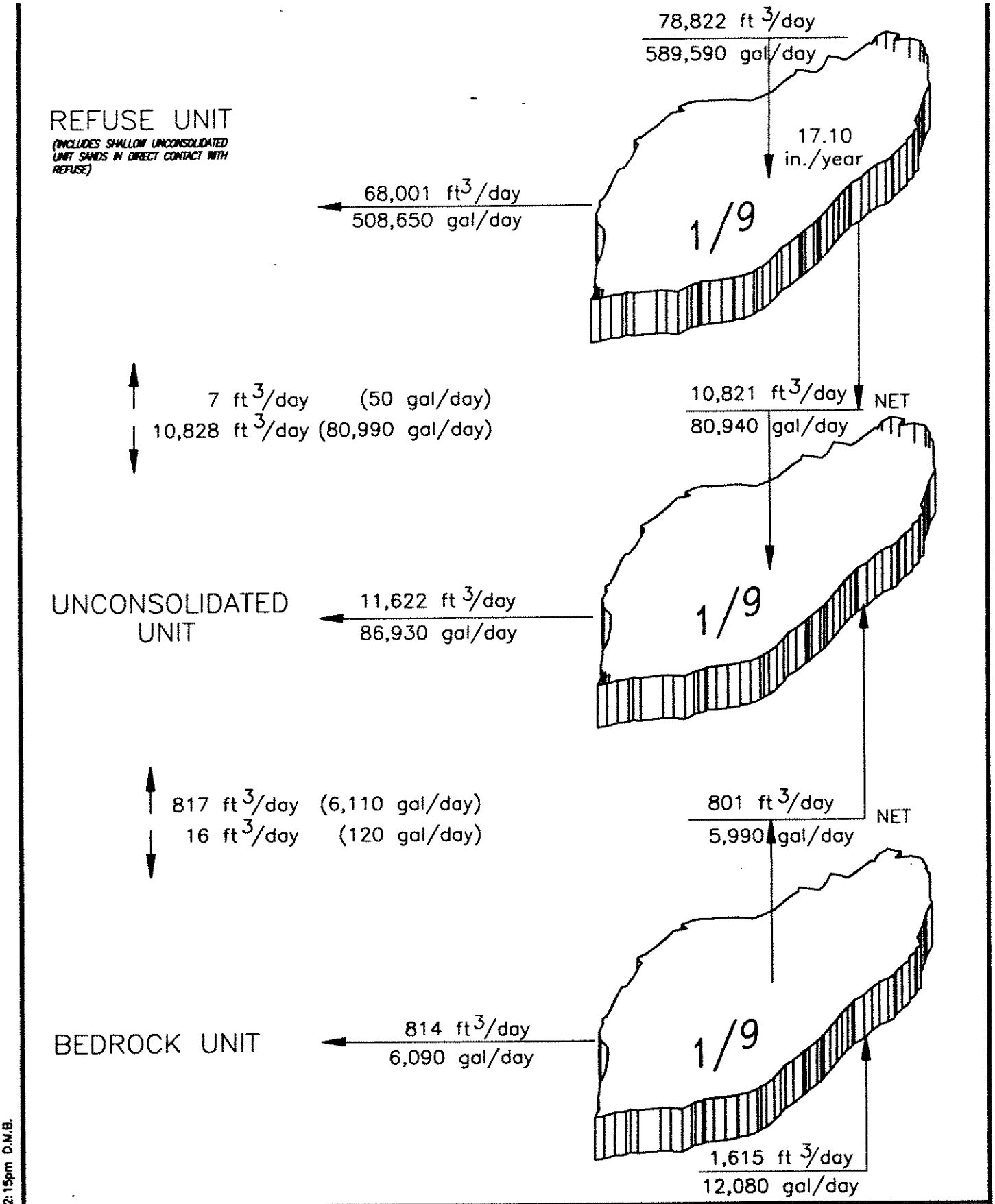

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	NAME	DATE
DESIGN BY:	RM	1/93
DRAWN BY:	KAS	2/93
CHECKED BY:	LC	2/93
ENGINEER:		
APPROVED BY:	RM	2/93

INTERNATIONAL TECHNOLOGY CORPORATION

Weston EnviroTech
Weston—New York, Inc.

FIGURE 11
SCHEMATIC SUMMARY OF THE NET FLUX OF GROUNDWATER CALCULATED THROUGH ANALYTICAL ANALYSIS LANDFILL SECTION 1/9
Prepared For:
NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

JOB No.	529363
DATE	2/26/93
SHEET	1 OF 1
DWG No.	529363-A848

5363A848 12/01/93 2:15pm D.M.B.

(2) Recharge to the landfill was estimated through net flux analysis as 17.10 inches per year.

(3) Analysis of two-dimensional model simulations indicated that a seven layer model would be required for regional three dimensional (areal) model simulation, consisting of refuse, transmissive (high permeability) Recent/glacial sand units, restrictive (low permeability) strata above the Cretaceous sand unit, the Cretaceous sand unit, low permeability strata below the Cretaceous sand unit, and bedrock.

(4) Numerical model sensitivity analysis results suggested that low permeability dry zones within the refuse unit could significantly reduce the water level elevations at the base of the refuse unit and decrease the potential for vertical leakage of leachate.

3.2.3 Landfill Sections 2/8 and 3/4

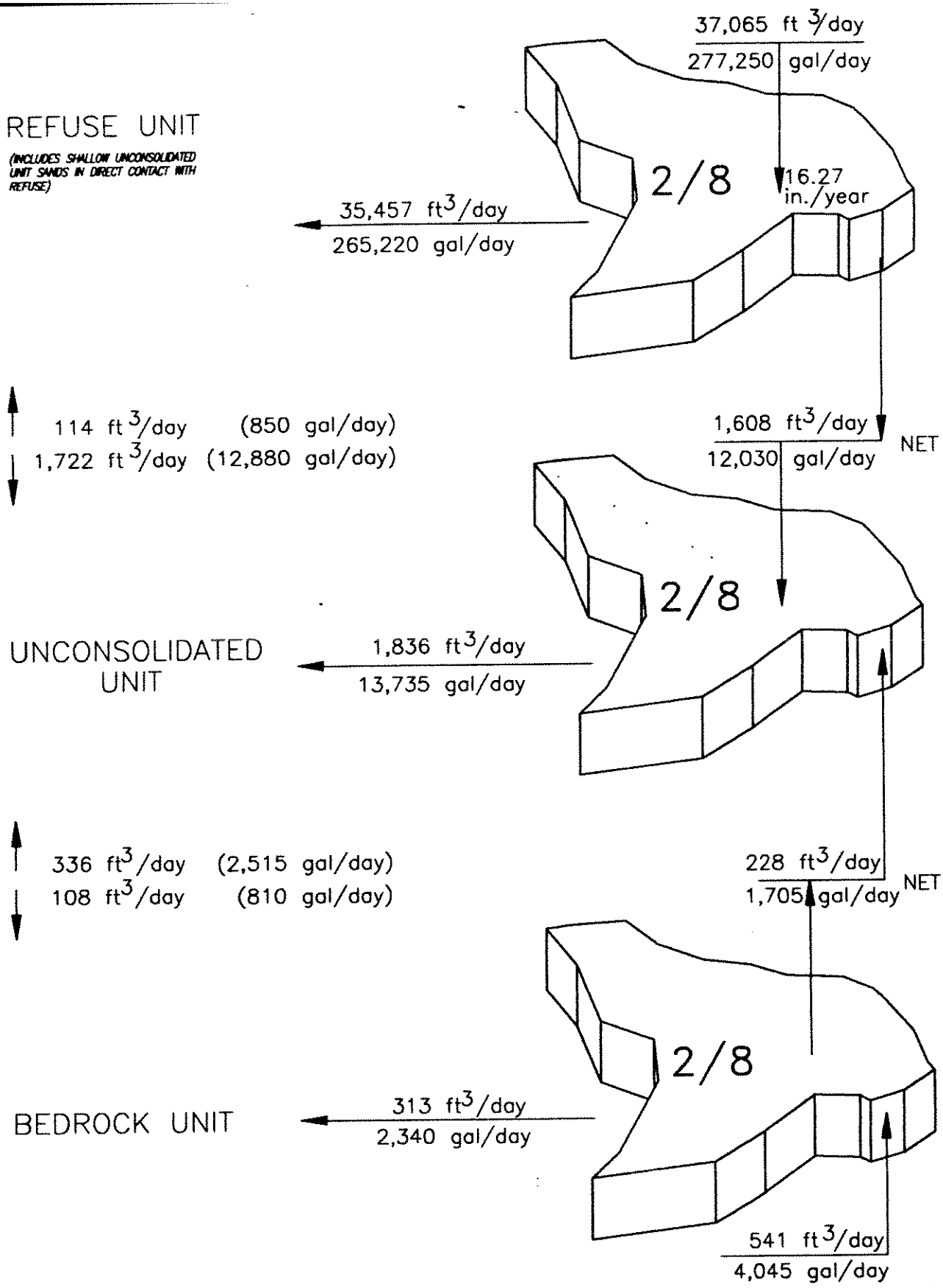
(1) Analytical flux analysis results for Landfill Section 2/8 (Figure 12) indicate that approximately five percent of the total recharge that enters the landfill can leave the refuse unit (and shallow, hydraulically interconnected sands) as vertical flux to deeper unconsolidated overburden units. Recharge was estimated through analytical flux analysis as 16.27 inches per year to the refuse unit.

(2) Analytical flux analysis results for Landfill Section 3/4 (Figure 13) indicate that approximately 11 percent of the total recharge that enters the landfill can leave the refuse unit (and shallow, hydraulically interconnected sands) as vertical flux to deeper unconsolidated overburden units. Recharge was estimated through flux analysis as 18.25 inches per year to the refuse unit.

(3) Numerical cross-sectional model results indicate that the majority of groundwater flow within Landfill Section 3/4 takes place within the refuse and upper Recent sand units.

3.3 Regional Three-Dimensional Numerical Model

The regional three-dimensional numerical model was designed to consist of seven layers, representing the refuse unit (two layers), an upper Recent/glacial sand unit, a lower Recent/glacial sand unit, an upper Cretaceous sand unit, a lower Cretaceous sand unit, and the bedrock. All model layers were designed to accurately reflect the distribution of high and low permeability units defined in the stratigraphic analysis. High permeability "windows" were simulated between model layers to allow for vertical communication, where such interconnection was suggested in the stratigraphic model.



No.	DATE	REVISION/DESCRIPTION
1	11/93	rev. flux

	NAME	DATE
DESIGN BY:	RM	1/93
DRAWN BY:	KAS	2/93
CHECKED BY:	LC	2/93
ENGINEER:		
APPROVED BY:	RM	2/93

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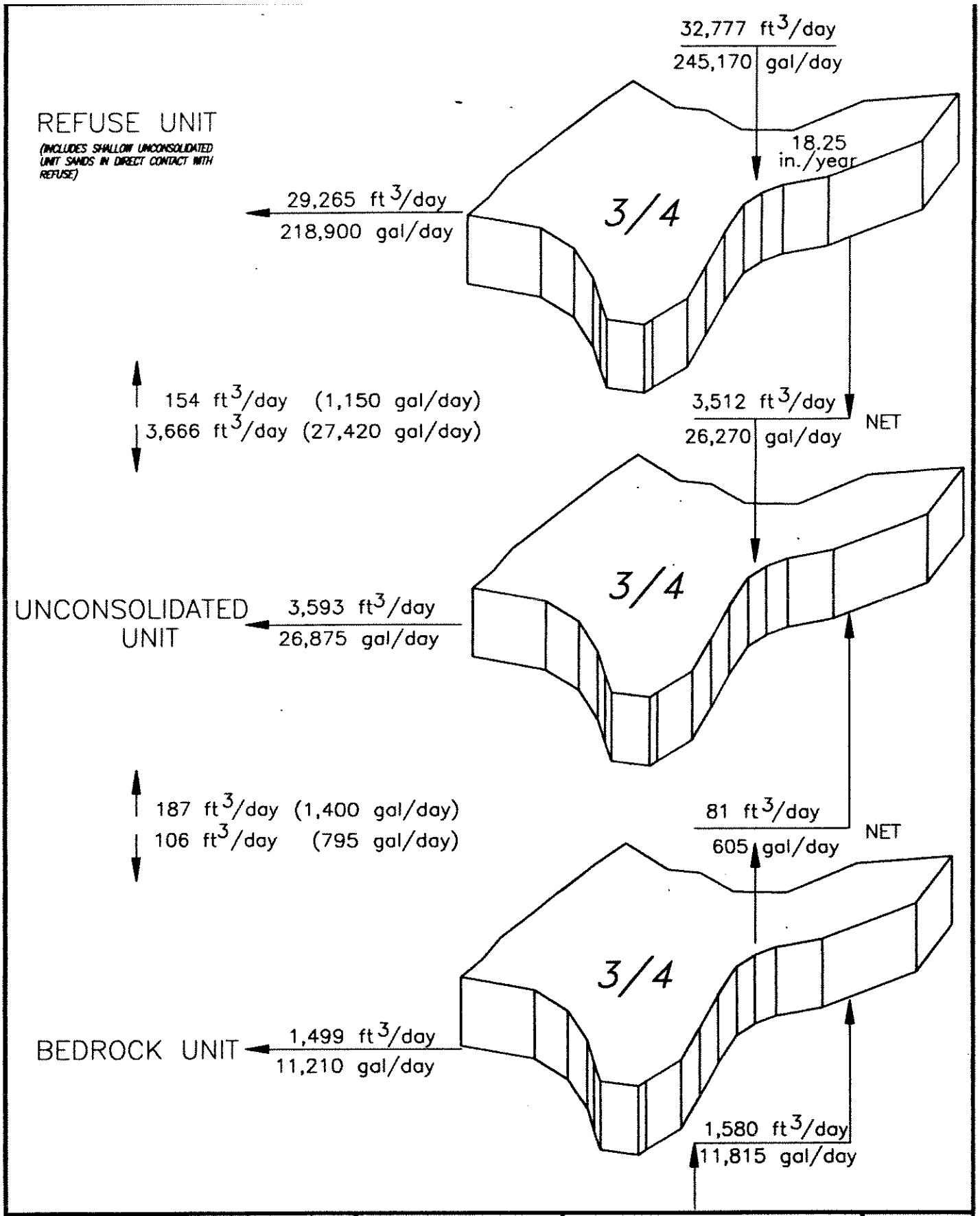
Weston Envirotech
Weston—New York, Inc.

FIGURE 12
SCHEMATIC SUMMARY OF THE NET FLUX OF GROUNDWATER CALCULATED THROUGH ANALYTICAL ANALYSIS LANDFILL SECTION 2/8
Prepared For:
NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

JOB No.	529363
DATE	2/26/93
SHEET	1 OF 1
DWG No.	529363-A849

5363A849 12/01/93 2:17pm D.M.B.



No.	DATE	REVISION/DESCRIPTION
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	NAME	DATE
DESIGN BY:	RM	1/93
DRAWN BY:	KAS	2/93
CHECKED BY:	LC	2/93
ENGINEER:		
APPROVED BY:	RM	2/93

INTERNATIONAL TECHNOLOGY CORPORATION

Weharen Environtech
Wehran—New York, Inc.

FIGURE 13
SCHEMATIC SUMMARY OF THE NET FLUX OF GROUNDWATER CALCULATED THROUGH ANALYTICAL ANALYSIS LANDFILL SECTION 3/4

Prepared For:
NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

JOB No.	529363
DATE	2/26/93
SHEET	1 OF 1
DWG No.	529363-A851

5363A851 12/01/93 2:22pm D.M.B.

Model computed results agree well with head data observed in the field, and flux estimates calculated with analytical methods. Model output indicates that the presence of low permeability dry zones within the refuse unit may be creating a perched water level elevation within central portions of the refuse mounds, and that the water level elevation at the base of the refuse is probably less than currently mapped. Model results indicate vertical flux to shallow Recent/glacial sand units in all landfill sections, and to the Cretaceous sands underlying portions of Landfill Sections 1/9 and 2/8. Model results also indicate little potential for flux of groundwater to the bedrock unit, and that observed mounding in the bedrock is probably due primarily to the added weight of the saturated refuse increasing pressures within the bedrock.

4.0 Characterization of Site Water Quality/Chemistry

Two groundwater sampling programs have been initiated at the Fresh Kills Landfill. These include a primary, comprehensive quarterly water quality sampling program for 6 NYCRR Part 360 specified Expanded Parameters (indicator parameters, metals, and organic compounds), and a limited geochemical sampling program (filtered indicator parameters, metals, and environmental isotopes). Data from the January and July 1991, and January, April, July, and October 1992, and January 1993 sampling quarters are summarized and described within this report.

Table 2, and the series of figures referenced in the following discussion, summarize the results of water quality analysis by monitoring zone across the entire project area. While variation is noted in constituent concentrations between landfill sections, the relationships identified within and between monitoring zones are generally consistent across the entire project site. Three primary monitoring zones are defined for the landfill area:

(1) Shallow/refuse zone consisting primarily of fill, and occasionally shallow Recent or glacial deposits. This zone, generally in direct hydraulic communication with the refuse mounds, exhibits leachate contamination across the entire project area (Figure 14).

(2) Intermediate depth monitoring zone consisting of confined or semi-confined sand units. The intermediate depth zone consists of an upper horizon comprised of Recent and glacial sands, and a lower horizon of Cretaceous sands. Leachate contamination is evidenced in several areas within the upper horizon (Figure 15), and within portions of the lower horizon at Section 1/9 (Figure 16). Fresh water in these horizons is influenced by mixing with sea water, which complicates the interpretation of water chemistry relative to the presence of dilute leachate influences. Figures 15 and 16 also indicate the results of a conservative (advection only) solute transport simulation performed with the regional three-dimensional numerical flow model. With the exception of the Cretaceous sand unit in Section 2/8, the model computed results closely simulate areas of observed leachate migration. The discrepancy at Section 2/8 may represent potential future areas of leachate migration, the results of excessive leachate mound head applied over the simulation period, or model boundary condition effects (resulting from a thinning of model layers) in that area.

TABLE 2

SUMMARY STATISTICS OF LEACHATE INDICATOR PARAMETER ANALYTICAL DATA (ug/l)

FRESH KILLS LANDFILL LEACHATE MITIGATION SYSTEM PROJECT

LANDFILL SECTION 1/9

Indicator Parameter	Shallow/Refuse Monitoring Zone				Intermediate Monitoring Zone (Recent/Glacial)				Intermediate Monitoring Zone (Cretaceous)				Deep (Bedrock) Monitoring Zone			
	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median
Alkalinity	160	70,000	12,300,000	3,505,000	34	26,000	1,120,000	665,000	85	10,000	740,000	126,000	69	1,000	1,540,000	50,000
Ammonia	156	20	4,960,000	530,000	35	20	26,800	3,360	84	20	40,200	613	67	20	1,550,000	199
BOD	143	2,000	1,200,000	51,000	35	2,000	90,000	2,000	87	2,000	13,800	2,000	68	2,000	75,000	2,000
TOC	156	13,500	2,650,000	398,500	34	1,600	201,000	26,900	87	1,000	55,300	10,200	69	1,000	52,800	4,430
COD	159	20,000	7,110,000	1,000,000	33	7,600	426,000	37,900	81	5,000	384,000	28,800	70	5,000	235,000	16,150
TKN	157	486	17,200,000	714,000	35	200	70,400	12,000	87	200	85,200	2,110	69	200	2,580	516
TDS	160	760,000	23,300,000	4,510,000	35	116,000	36,300,000	12,600,000	90	131,000	35,200,000	4,700,000	69	116,000	16,000,000	940,000

LANDFILL SECTION 6/7

Indicator Parameter	Shallow/Refuse Monitoring Zone				Intermediate Monitoring Zone (Recent/Glacial)				Intermediate Monitoring Zone (Cretaceous)				Deep (Bedrock) Monitoring Zone			
	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median
Alkalinity	167	204,000	4,480,000	1,740,000	33	54,000	1,030,000	190,000	9	1,000	146,000	22,000	100	32,000	712,000	121,000
Ammonia	166	326	1,060,000	204,500	30	20	2,320	174	9	20	271	114	94	20	817	68
BOD	152	2,000	420,000	17,900	33	2,000	183,000	2,000	9	2,000	3,300	2,000	96	200	5,340	2,000
TOC	167	189	761,000	172,000	31	1,000	217,000	9,570	9	1,000	33,200	4,740	100	1,000	26,400	4,495
COD	166	20,800	3,140,000	251,500	30	5,000	229,000	11,000	8	5,000	44,100	13,695	100	5,000	45,600	8,605
TKN	163	1,060	1,860,000	310,000	32	200	17,700	593	9	200	636	297	95	200	1,540	289
TDS	167	340,000	10,400,000	2,140,000	36	106,000	21,500,000	6,495,000	9	620,000	3,360,000	1,340,000	100	24,000	8,240,000	336,000

LANDFILL SECTION 2/8

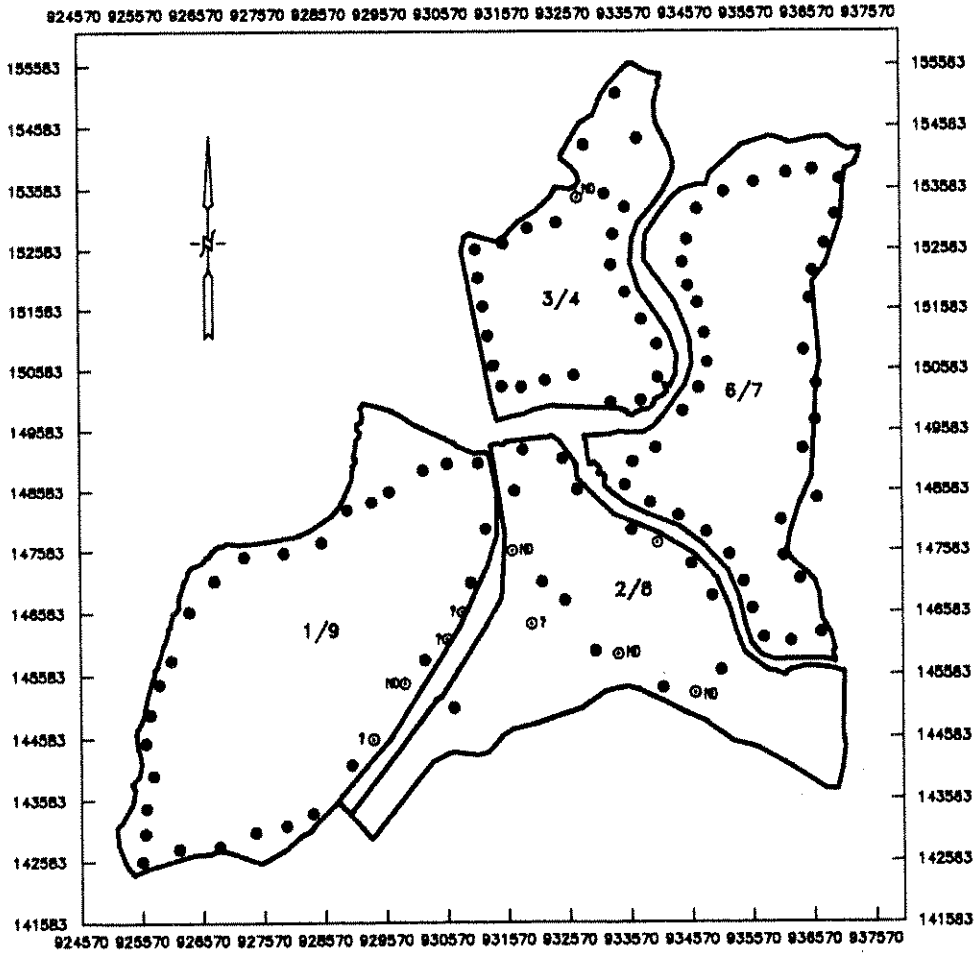
Indicator Parameter	Shallow/Refuse Monitoring Zone				Intermediate Monitoring Zone (Recent/Glacial)				Intermediate Monitoring Zone (Cretaceous)				Deep (Bedrock) Monitoring Zone			
	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median
Alkalinity	44	98,000	7,400,000	1,280,000	14	101,000	1,050,000	840,000	31	78,000	310,000	120,000	48	42,000	1,160,000	109,000
Ammonia	45	20	3,130,000	87,600	12	20	9,860	431	28	20	187	20	44	20	1,250,000	20
BOD	45	2,000	99,000	17,000	14	2,000	101,000	2,000	31	2,000	2,000	2,000	47	2,000	24,000	2,000
TOC	45	10,800	556,000	150,000	14	30,300	207,000	77,250	31	2,240	30,300	7,060	47	1,000	28,700	7,010
COD	42	5,000	874,000	221,500	14	53,600	312,000	120,050	31	5,000	36,000	5,460	46	4,120	171,000	7,860
TKN	43	221	4,260,000	193,000	13	200	13,300	5,300	31	200	440	200	47	200	3,520	200
TDS	44	230,000	3,800,000	1,910,000	14	440,000	2,760,000	1,920,000	30	72,000	800,000	202,000	48	86,000	4,900,000	330,000

LANDFILL SECTION 3/4

Indicator Parameter	Shallow/Refuse Monitoring Zone				Intermediate Monitoring Zone (Recent/Glacial)				Intermediate Monitoring Zone (Cretaceous)				Deep (Bedrock) Monitoring Zone			
	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median	N	Minimum	Maximum	Median
Alkalinity	73	196,000	7,680,000	2,660,000	36	58,000	2,880,000	590,000	--	--	--	--	43	6,000	226,000	82,000
Ammonia	72	28,500	2,980,000	312,500	35	20	397,000	1,400	--	--	--	--	41	20	421	102
BOD	70	2,000	288,000	20,550	36	2,000	384,000	7,450	--	--	--	--	46	2,000	52,000	2,000
TOC	74	28,000	1,100,000	267,000	35	1,000	347,000	29,400	--	--	--	--	45	1,000	33,500	3,370
COD	74	58,500	2,850,000	531,000	36	7,670	644,000	150,000	--	--	--	--	45	5,000	188,000	6,400
TKN	71	52,000	7,400,000	412,000	35	200	768,000	4,220	--	--	--	--	44	200	1,070	270.5
TDS	74	780,000	7,980,000	2,940,000	36	10,600	21,500,000	6,495,000	--	--	--	--	46	40,000	6,520,000	360,000

Summary statistics derived from all monitoring wells samples obtained from January 1991 - January 1993 sampling quarters.

--: No Cretaceous sediments occur within Section 3/4



LEGEND:

- ⊙ MONITORING WELL LOCATION (NO LEACHATE INFLUENCE)
- ● MONITORING WELL EXHIBITING LEACHATE INFLUENCE
- ? POSSIBLE LEACHATE INFLUENCE
- ND NO ANALYTICAL DATA AVAILABLE

No.	DATE	REVISION/DESCRIPTION	INIT.
1	–	–	–

	NAME	DATE
DESIGN BY:	J.D.	3/93
DRAWN BY:	D.M.B.	3/93
CHECKED BY:	S.P.	3/93
ENGINEER:		
APPROVED BY:	S.P.	3/93

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NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

FIGURE 14
LEACHATE INFLUENCED GROUNDWATER
SHALLOW / REFUSE
MONITORING ZONE

JOB No.	529363
DATE	12/4/93
SHEET	1 OF 1
DRAWING No.	529363-A853

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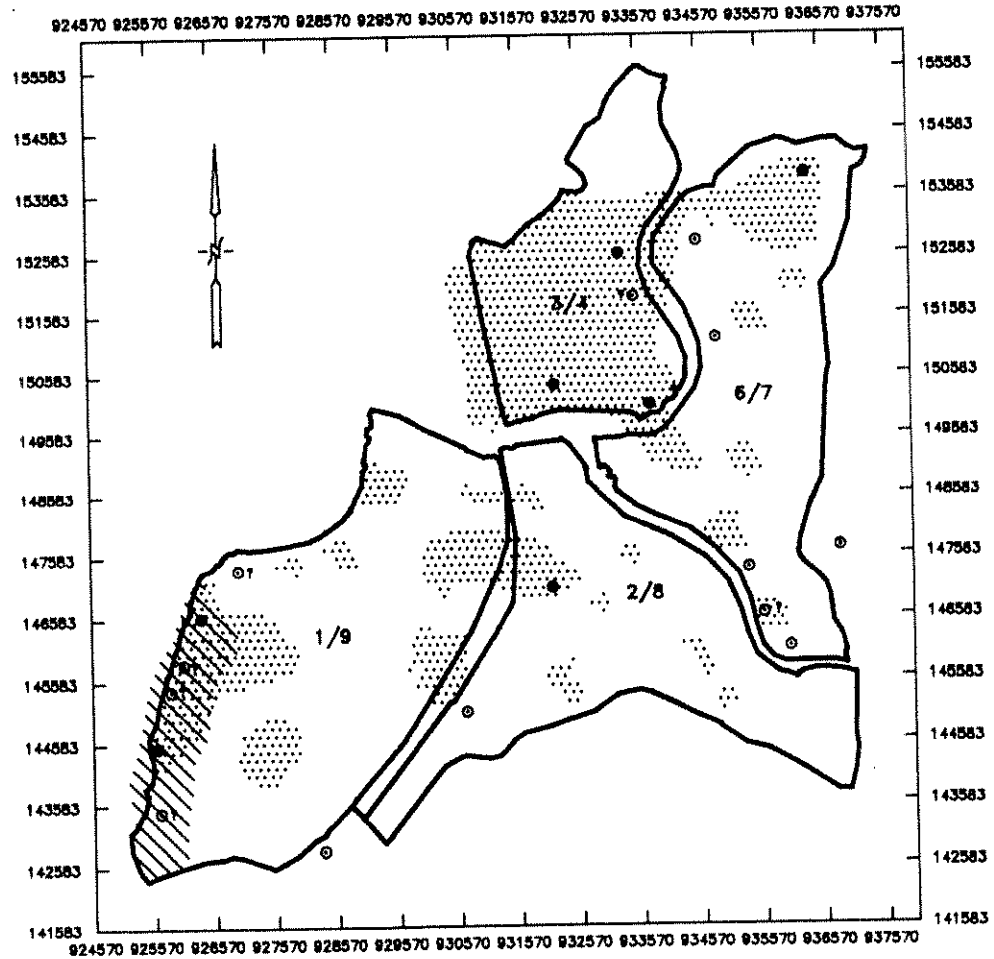

LEGEND:

- MONITORING WELL LOCATION (NO LEACHATE INFLUENCE)
- MONITORING WELL EXHIBITING LEACHATE INFLUENCE
- POSSIBLE LEACHATE INFLUENCE
- SEA WATER INFLUENCE
- OBSERVED SOLUTE TRANSPORT (ADVECTIVE FLOW ONLY)

No.	DATE	REVISION/DESCRIPTION	INIT.
1	--	--	--

	NAME	DATE
DESIGN BY:	J.D.	3/93
DRAWN BY:	D.M.B.	3/93
CHECKED BY:	S.P.	3/93
ENGINEER:		
APPROVED BY:	S.P.	3/93

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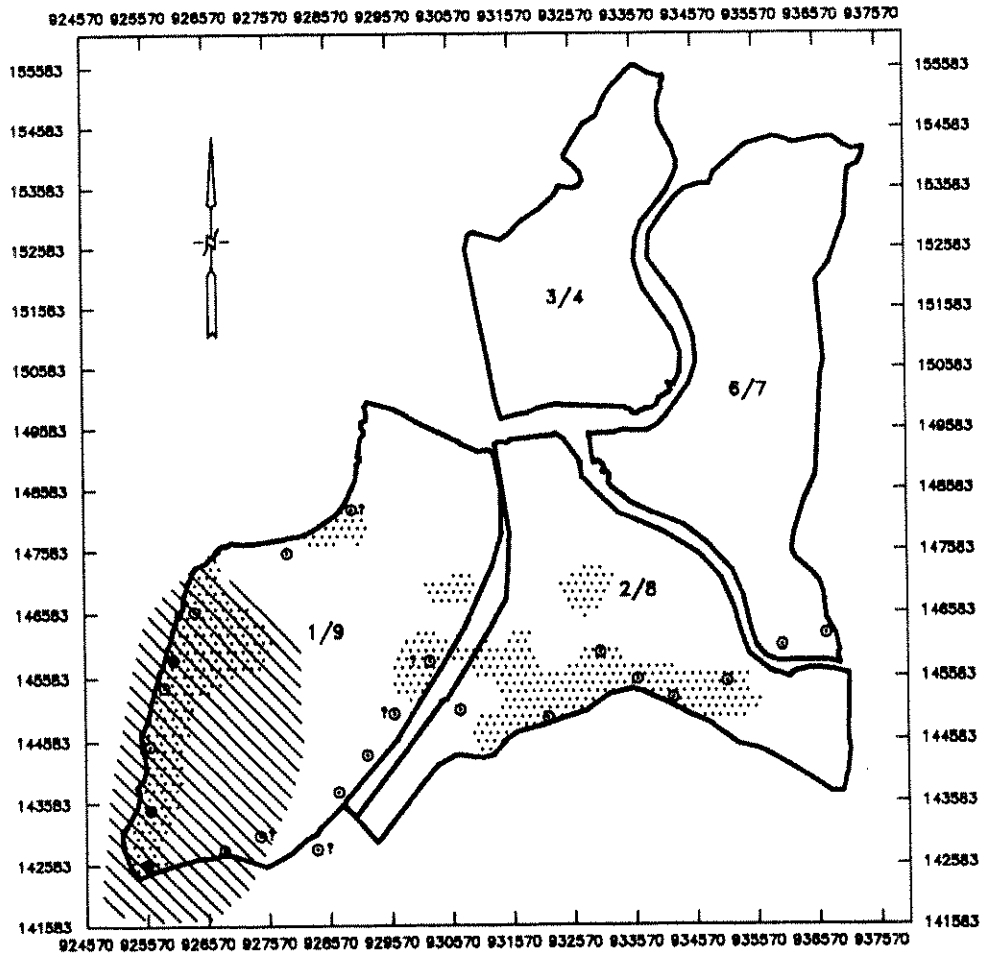
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

FIGURE 15
LEACHATE / SEA WATER INFLUENCED GROUNDWATER INTERMEDIATE DEPTH (RECENT/GLACIAL SAND) MONITORING ZONE

JOB No.	529383
DATE	12/4/93
SHEET	1 OF 1
DRAWING No.	529383-A856

5363A856 12/04/93 6:47pm T. M.



LEGEND:

- ⊙ MONITORING WELL LOCATION (NO LEACHATE INFLUENCE)
- ● MONITORING WELL EXHIBITING LEACHATE INFLUENCE
- ? POSSIBLE LEACHATE INFLUENCE
- SEA WATER INFLUENCE
- OBSERVED SOLUTE TRANSPORT (ADVECTIVE[4] FLOW ONLY)

No.	DATE	REVISION/DESCRIPTION	INIT.
1	–	–	–

	NAME	DATE
DESIGN BY:	J.D.	3/93
DRAWN BY:	D.N.B.	3/93
CHECKED BY:	S.P.	3/93
ENGINEER:		
APPROVED BY:	S.P.	3/93

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STATEN ISLAND, RICHMOND COUNTY, NEW YORK

FIGURE 16
LEACHATE / SEA WATER INFLUENCED GROUNDWATER INTERMEDIATE DEPTH (CRETACEOUS SAND) MONITORING ZONE

JOB No.	529383
DATE	12/4/93
SHEET	1 OF 1
DRAWING No.	529383-A856

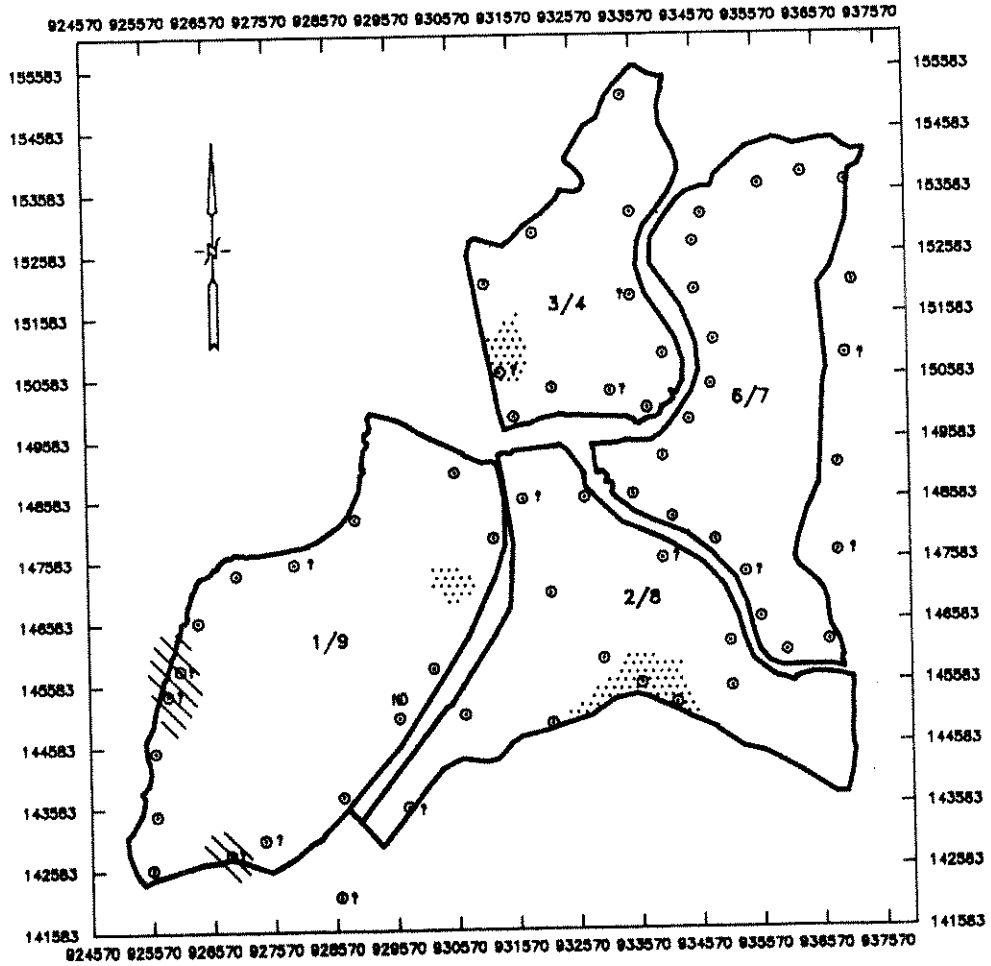
5363A855 12/04/93 703pm T. M.

(3) Deep monitoring zone, consisting of weathered bedrock and bedrock. Anomalous water chemistry is noted at several locations within the bedrock (Figure 17), although leachate influence in this monitoring zone is generally not supported by the groundwater hydraulic regime, which typically indicates upward vertical flow from the bedrock to overlying sand units. Figure 17 also indicates the results of the advective solute transport simulation, indicating several small regions of potential leachate migration. With the exception of Section 2/8, such migration is simulated within areas where Cretaceous sediments are not present between Recent/glacial deposits and bedrock. No migration to bedrock was observed when dispersion and sorption were incorporated into the solute transport simulation.

4.1 Shallow/Refuse Monitoring Zone

Groundwater within the shallow/refuse water table monitoring zone at all landfill sections exhibits elevated concentrations of nitrogen and carbon series leachate indicator parameters (ammonia, total kjeldahl nitrogen [TKN], biochemical oxygen demand [BOD], chemical oxygen demand [COD], and total organic carbon [TOC]). Regulated general water chemistry constituents are generally well in excess of water quality standards. Metals, typically boron, iron, and magnesium are present in elevated concentrations. It should be noted that for all samples processed under the 6 NYCRR Part 360 monitoring program, analysis of unfiltered sample for metals constituents results in a high bias due the effects of turbidity and acid sample preservation on the dissolved solute concentration. This is observed in the comparison of filtered and unfiltered sample concentrations, and comparison of field data with literature and background water chemistry.

While detected, organic compounds exhibit a low concentration distribution and, with the exception of several constituents in the shallow/refuse and deep (bedrock) monitoring zones, their occurrence is sporadic. Virtually all of the detected organic compounds that occur over successive sampling quarters consist of volatile and semivolatile organic compounds (VOCs). The concentration distribution of detected pesticides and herbicides is extremely low, and PCB compounds are virtually undetected.



LEGEND:

- ⊙ MONITORING WELL LOCATION (NO LEACHATE INFLUENCE)
- ? POSSIBLE LEACHATE INFLUENCE
- ND NO ANALYTICAL DATA AVAILABLE
- SEA WATER INFLUENCE
- OBSERVED SOLUTE TRANSPORT (ADVECTIVE) FLOW ONLY)

No.	DATE	REVISION/DESCRIPTION	INIT.
1	-	-	-

	NAME	DATE
DESIGN BY:	J.D.	3/93
DRAWN BY:	D.M.B.	3/93
CHECKED BY:	S.P.	3/93
ENGINEER:		
APPROVED BY:	S.P.	3/93

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NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

FIGURE 17
LEACHATE / SEA WATER INFLUENCED GROUNDWATER DEEP (BEDROCK) MONITORING ZONE

JOB No.	529383
DATE	12/4/93
SHEET	1 OF 1
DRAWING No.	529383-A854

53638454 12/04/93 7:02pm T. M.

4.2 Intermediate Depth Monitoring Zone

In general, the concentration of leachate indicator parameters in the confined sand water bearing units is one to several orders of magnitude below concentrations observed in the shallow/refuse monitoring zone. In the deeper sand units, exceedence of water quality standards is limited primarily to a number of metals constituents; in most cases, elevated concentrations of these analytes is believed to represent the mineral content of the soil material, and the incidental, localized effects of turbidity and acid preservation on sample analysis. With very few exceptions, the presence of organic compounds is sporadic and not associated with leachate migration.

The majority of exceedences of water quality standards within the intermediate zone are represented by three areas where vertical leachate migration is believed to have occurred, or potentially occurred. These are: (1) within Recent sands at Landfill Section 3/4 and the western area of Section 1/9, (2) within a shallow glacial sand unit along the western portion of Landfill Section 2/8, (correlated with a larger glacial kame deposit within Landfill Section 1/9) and (3) within portions of the Cretaceous sand unit underlying the western and southern margin of Landfill Section 1/9. Within intermediate depth wells along the western and southern areas of Section 1/9, water chemistry exhibits a pronounced seawater influence, which makes positive identification of a dilute leachate influence in the deeper Cretaceous sands difficult. Limited mixing of leachate in this horizon is observed in two and three dimensional numerical analysis of groundwater flow and solute transport. Deep well pumpage, with induced recharge of saline water from local river channels, is also supported by numerical analysis as a rationale for observed seawater mixing in the Landfill Section 1/9 Recent and Cretaceous sand units.

4.3 Deep (Bedrock) Monitoring Zone

The concentration of leachate indicator parameters in the confined bedrock water bearing units is consistently one to several orders of magnitude below concentrations observed in the shallow/refuse monitoring zone. Periodic exceedence of water quality standards is limited primarily to several metals constituents; elevated concentrations of these analytes is believed to represent the mineral content of the rock matrix, and the incidental, localized effects of turbidity and acid preservation on sample analysis.

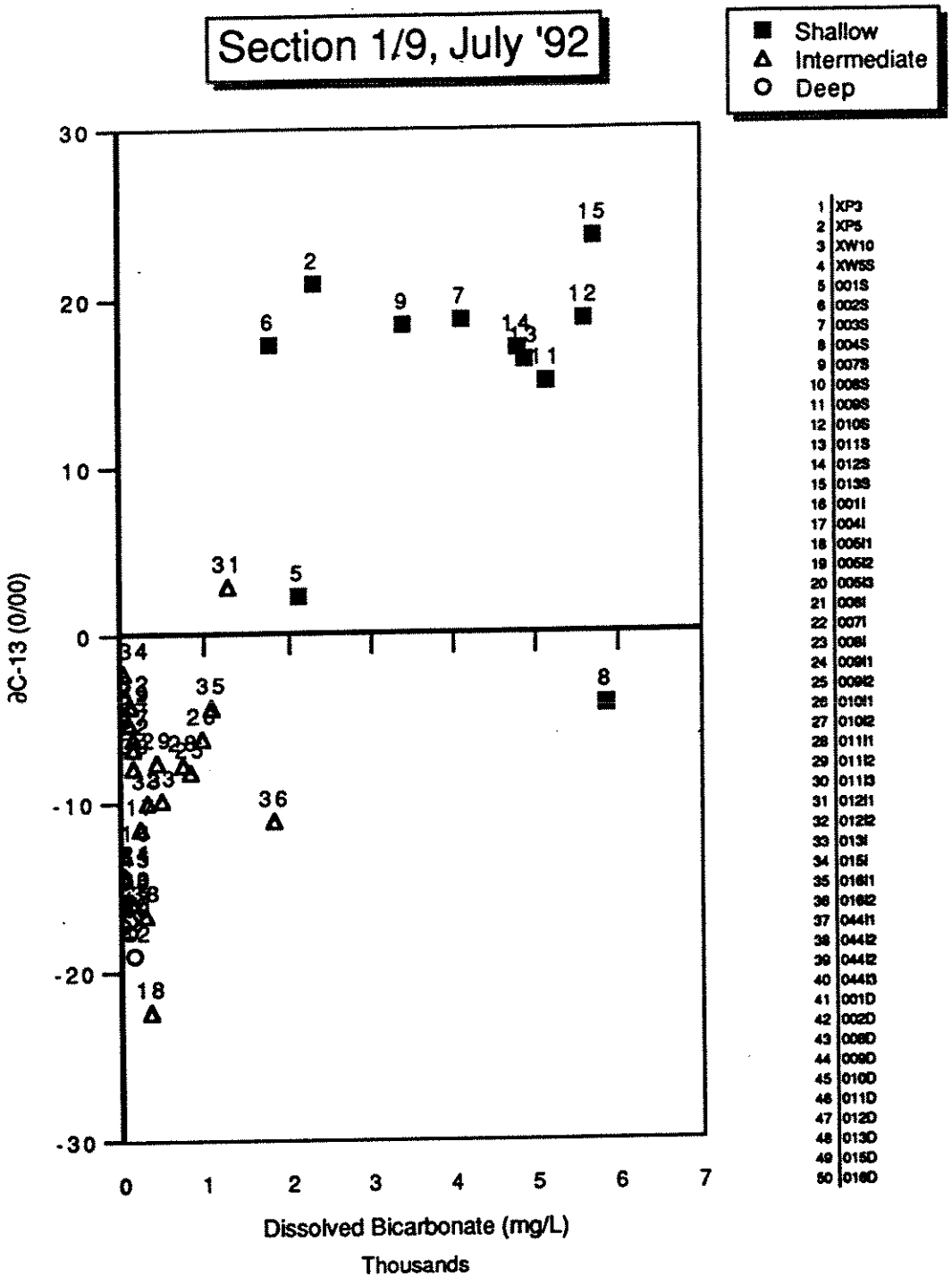
With one exception, the occurrence of organic compounds in the deep monitoring zone is extremely limited and sporadic in nature. The exception relates to the presence of two volatile organic compounds that appear to form a pattern of occurrence in a number of bedrock wells across the project area. Based on a series of factors, including the absence of these compounds in the overlying intermediate and/or shallow/refuse monitoring zones, the observed hydraulic head distribution, and the results of numerical flow and solute transport analysis, the presence of these compounds is not believed to be associated with vertical leachate migration. Field testing has indicated that, at least in some areas, the observed concentrations may be spurious. NYCDOS is currently investigating the potential for an upgradient, off-site source for these compounds.

4.4 Geochemical Sampling and Analysis

Filtered sample was collected from a subset of the monitoring well locations at all landfill sections to allow for the geochemical analysis of groundwater. Filtered sample is used within this context to allow for quantification of the ionic forms of dissolved solutes, resulting in the identification of formation water characteristics that are distinctive between leachate affected, sea water affected, and natural groundwaters. Sample was also collected for the stable and radiogenic forms of the environmental isotopes of carbon, sulfur, hydrogen, lead and strontium to supplement the conventional geochemical analysis.

The results of this investigation provide a clear distinction between the inherent characteristics of the leachate affected shallow/refuse water bearing zone, and the deeper intermediate and bedrock zones. Figure 18 illustrates an example of the clear differentiation between leachate influenced and natural groundwater observed through application of geochemical analysis; in this case a plot of the carbon isotope ratio ($^{13}C/^{12}C$ or $\delta^{13}C$) of dissolved inorganic carbon versus bicarbonate for wells installed at Landfill Section 1/9. As indicated, the "heavier" isotopic content of water in shallow/refuse wells (resulting from fractionation of the ^{12}C isotope during methane production in the landfill), is distinguished from the "lighter" isotopic content of intermediate and deep groundwaters. Geochemical analysis was also useful in clearly identifying sea water influences in groundwater, as illustrated on Figure 19. This figure illustrates a series of "Stiff diagrams" for a number of the intermediate depth wells installed Landfill Section 1/9. Stiff diagrams visually summarize the concentrations (expressed as electrochemical equivalent

Section 1/9, July '92



1	XP3
2	XP5
3	XW10
4	XW5S
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8	004S
9	007S
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11	009S
12	010S
13	011S
14	012S
15	013S
16	001I
17	004I
18	005I1
19	005I2
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21	006I
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24	009I1
25	009I2
26	010I1
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45	010D
46	011D
47	012D
48	013D
49	015D
50	016D

SOURCE: STEARNS & WHEELER/SYRACUSE UNIVERSITY GEOLOGY DEPARTMENT, 1993

No.	DATE	REVISION/DESCRIPTION
-	-	

	NAME	DATE
DESIGN BY:	S.P.	3/15/93
DRAWN BY:	T.M.	3/15/93
CHECKED BY:	J.G.	3/15/93
ENGINEER:		
APPROVED BY:	S.P.	3/15/93

INTERNATIONAL TECHNOLOGY CORPORATION

NOT TO SCALE

FIGURE 18
DELTA-13 C vs. BICARBONATE
LANDFILL SECTION 1/9

Prepared For:
NEW YORK CITY DEPARTMENT OF SANITATION
FRESH KILLS LANDFILL
STATEN ISLAND, RICHMOND COUNTY, NEW YORK

JOB No.	529363
DATE	3/15/93
SHEET	OF
DWG No.	529363-A66

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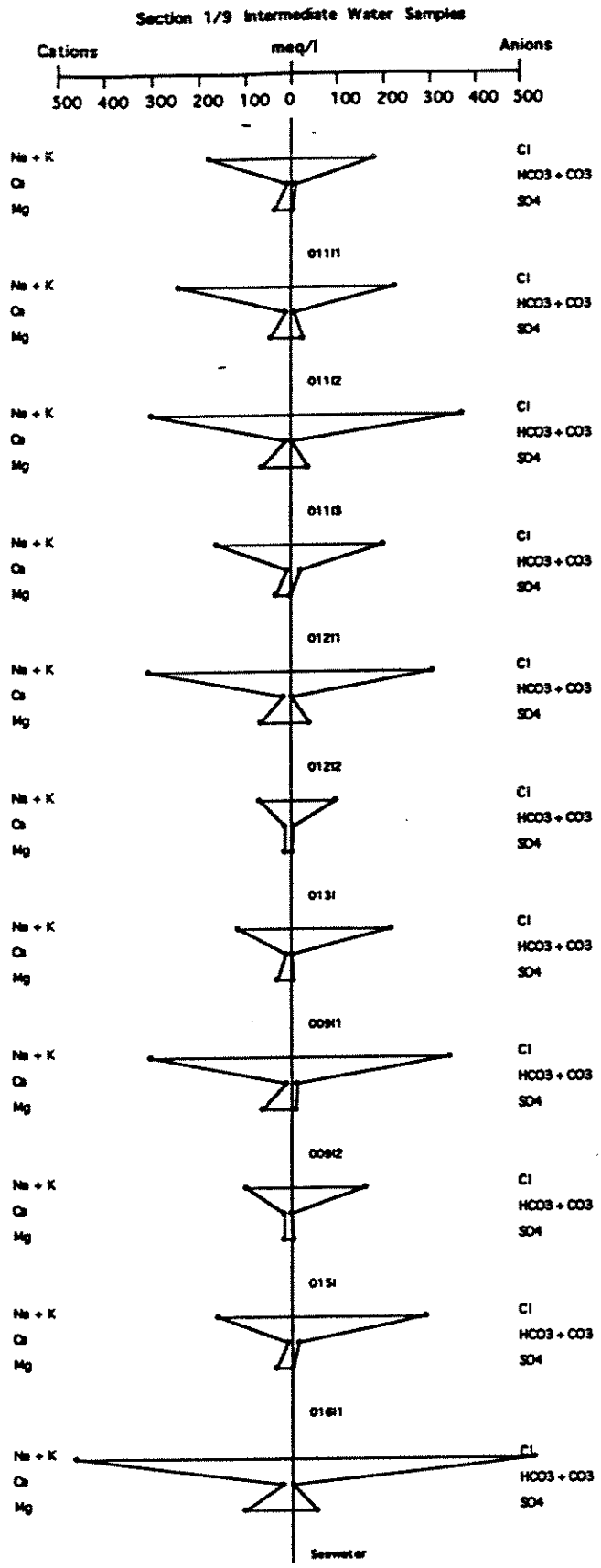

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INTERNATIONAL TECHNOLOGY CORPORATION

NOT TO SCALE

FIGURE 19
STIFF DIAGRAMS INTERMEDIATE DEPTH GROUNDWATER LANDFILL SECTION 1/9
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JOB No.	529383
DATE	3/15/93
SHEET	OF
DWG No.	529383-A678

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concentrations) for the major inorganic solutes in water. The characteristic shape of the sea water diagram (high in sodium and chloride) is provided at the bottom of Figure 19 for reference.

Consistent with the assessment of indicator parameter data derived from the 6 NYCRR Part 360 sampling program, clear evidence of leachate mixing at depth is not apparent, with the exception of Recent sands at Landfill Sections 1/9 and 3/4, glacial sands at Section 2/8 and a limited area of Cretaceous sands at Section 1/9. These data additionally support the contention that exceedences of water quality criteria for metals parameters in intermediate depth and deep (bedrock) monitoring wells are related to the incidental effects of turbidity on sample analysis, or the natural mineral content of the soil and rock material, rather than reflecting a leachate influence.

4.5 Long Term Monitoring Program

Under the terms of the Consent Order, NYCDOS is required to develop a long term groundwater monitoring program that is capable of distinguishing landfill derived contamination from "existing" water quality at the site, and which identifies trigger mechanisms to initiate contingency monitoring, as appropriate. The contingency monitoring program has already been triggered at Fresh Kills based on currently observed water quality at the site, and development of corrective actions is ongoing in accordance with the specifications of Consent Order Appendix A-3 (closure and capping of Landfill Sections 2/8 and 3/4) and Appendix A-4 (leachate capture and treatment at Landfill Section 1/9 and 6/7).

Long term monitoring program development (Environmental Monitoring Plan and Site Analytical Plan) included definition of the site critical stratigraphic section, analytical data quality objectives project critical parameters, groundwater protection standards, sample location and frequency, and sample collection and analytical protocols. These components of program design were developed through review of the existing water quality database, and considerations regarding the physical spacing of the existing well array within each monitoring zone across the critical stratigraphic section, as well as the potential sensitivity of each monitoring zone to leachate impact.

The critical stratigraphic section was defined to include the shallow/refuse, intermediate depth (confined sand), and deep (bedrock) groundwater monitoring zones underlying the landfill. Data

quality objectives were defined for all Part 360 expanded parameters through review of NYSDEC water quality standards, criteria, and guidance values, and analytical test method practical quantitation limits (PQLs). Critical parameters were defined as all analytes detected through the quarterly monitoring program. A distinction was made between rountely detected and sporadically detected organic compounds. Primary leachate indicator parameters (including a suite of geochemical analytes) were also identified. The proposed sampling program consists of a rotating schedule for 6 NYCRR Part 360 expanded and baseline parameter and geochemical analysis. An increased frequency of analysis was identified for the intermediate depth (confined sand) and deep (bedrock) monitoring zones. Supplemental hydraulic head monitoring of bedrock and selected Cretaceous sand wells was also incorporated into the monitoring program. Sampling and analytical protocols were specified as those in existing Quality Assurance Program and Project Plans (QAPP, QAPjP).

5.0 Summary of Findings

From a broad perspective, geologic materials within the project site are represented by three distinct layers or units: Refuse/fill, unconsolidated overburden, and bedrock. Refuse/fill consists of man-made deposits (i.e., the landfills) deposited on top of natural soil materials; these deposits currently range in thickness from several feet to over 150 ft. The unconsolidated overburden consists of natural soil materials lying between the refuse/fill and the bedrock. Volumetrically, these materials are predominantly fine grained, and are laterally extensive across the site. The thickness of the overburden materials range from several tens of feet to over 200 ft.

At a more localized scale, significant variation is evident within the overburden, with included deposits of hydraulically transmissive sand lenses, layers or channel deposits. With several major exceptions, these deposits tend to be areally limited (discontinuous), and located within the upper portions of the overburden. These exceptions include laterally extensive: (1) Recent sand deposits underlying the western area of Landfill Section 1/9, Landfill Section 3/4 and portions of the northern area of Section 6/7, (2) glacial sand/till kame deposits primarily underlying portions of Landfill Sections 1/9, 2/8, and 3/4, and (3) Cretaceous sand deposits underlying much of Landfill Section 1/9 and the southern portion of Landfill Section 2/8.

The results of analytical calculations of groundwater flow, numerical cross-sectional analyses of flow and solute transport, and three dimensional (areal) analysis of flow indicate that the majority of leachate discharge from the refuse mounds is horizontal through the refuse and shallow sand units to adjacent surface waters. Migration of leachate to Recent and glacial sand units is observed in numerical simulations at Landfill Sections 1/9, 2/8, and 3/4, and to a lesser degree, the Cretaceous sand unit at Section 1/9. Very limited evidence for migration to the bedrock is indicated in the conservative (advective) three-dimensional flow simulation; no such migration is observed in simulations that incorporate dispersion and sorption. Two-dimensional simulations suggest leachate migration to the bedrock only at Section 6/7, where the elevation of the bedrock surface rises to a shallow depth in the east.

The results of water quality and geochemical analysis strongly support the geologic model, relative to the extensive distribution of fine grained, hydraulically restrictive materials, as well as the findings of numerical flow and solute transport analysis. The shallow/refuse water bearing unit clearly reflects the influence of leachate. Within the unconsolidated overburden unit, leachate mixing with natural groundwater has been observed in shallow sand deposits within all landfill sections. Dilute mixing of leachate in the Cretaceous sand unit is indicated in the analytical data and the results of numerical groundwater flow analysis in a portion of the southern area of Section 1/9; a concentrated sea water influence in this unit makes positive contaminant identification difficult elsewhere within the landfill section. Little or no evidence of leachate contamination is indicated within the bedrock.

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1.0 INTRODUCTION

This document, the Final Hydrogeological Report, has been prepared to satisfy, in part, the requirements set forth in the New York State Department of Environmental Conservation (NYSDEC) Order on Consent (Case Number D2-9001-89-03) with the City of New York Department of Sanitation (NYCDOS), relative to Environmental Conservation Law Articles 27, 17 and 25 and Title 6 Part 360 of the Official Compilation of Codes, Rules and Regulations of the State of New York. In particular, this report addresses the Final Report documentation component and milestone schedule of Appendix A-6 (Hydrogeological Investigation) to the Consent Order.

The full text of the Consent Order specifies a range of administrative, operational, investigative and engineering design requirements for continued permitted operation of the Fresh Kills Landfill. The majority of these requirements are specified in a series of technical appendices to the Consent Order that identify performance tasks and corresponding milestone implementation schedules (Figure 1.1). The Hydrogeological Investigation (Appendix A-6) represents one component of a larger group of investigations designed to characterize and ultimately control leachate generation and migration into ground and surface waters. As indicated on Figure 1.1, this group of investigations represents the Fresh Kills Landfill Leachate Mitigation System Project, and includes the surface water and sediment investigations associated with Consent Order Appendix A-7, and the landfill leachate mitigation investigations associated with Appendix A-4.

Stipulated reporting requirements of the Final Hydrogeological Report include:

> "an evaluation and interpretation of all hydrogeological data and information generated during the Hydrogeological Investigation, the Interim Hydrogeological Report, and the Literature Review. The report shall also include recommendations for the Long-Term Environmental Monitoring Plan for Fresh Kills Landfill including design of the appropriate monitor well array and sampling plan."

Hydrogeological reporting requirements of 6 NYCRR Part 360 include: (1) description of Site Investigation Plan (SIP) implementation [prepared in accordance with 6 NYCRR Part 360-2.11(a)], (2) description of regional and site-specific geology and hydrogeology [6 NYCRR Part 360-2.11(b)], and (3) description of site environmental monitoring plan [6 NYCRR Part 360-2.11(c)]. Supplementing these generic requirements, the Consent Order stipulates a series of technical reporting requirements relative to unique site conditions, including:

- glacial depositional model,
- conceptual three-dimensional model of Cretaceous silt/clay and sand deposits, and their hydraulic interrelationship
- assessment of the configuration and distribution of Triassic and Ordovician bedrock, and their hydraulic relationship with overlying unconsolidated deposits,
- conceptual model of estuarine diurnal effects on confined aquifer hydraulic head,
- evaluation of the effects of landfill size and age on the chemodynamics and hydrodynamics of leachate generation,
- quantitative assessment of lateral and vertical groundwater flow based on field observations of hydraulic head,
- quantitative assessment of lateral and vertical groundwater flow based on the results of chemical analysis of ground and surface water, and
- detailed assessment of local and regional hydrogeologic systems (including New Jersey), and the relationship between these systems and those present beneath the project site.

The Final Report incorporates the results of all field investigations performed between January 1991 and April 1993 in support of the stipulated requirements of Consent Order Appendix A-6. These investigations included: (1) the Phase I (1991) and Phase II (1992) well installation programs, (2) the exploratory center landfill boring program, (3) the perimeter boring program (specified under Consent Order Appendix A-4, but included in the hydrogeologic investigation to supplement stratigraphic analysis), (4) the groundwater monitoring program (January, July 1991; January, April, July, October 1992; and January 1993 sampling quarters), and (5) a series of corollary activities consisting of sampling, archiving, and geotechnical testing of soil samples, well development, and provision of survey control for all borings and well installations.

The Final Hydrogeological Report provides a detailed discussion of the findings associated with review and analysis of the extensive field data obtained during the period 1991-1993, and compiled in the Interim and Draft Final Reports. This document provides further evaluation and analysis of a series of technical issues, includes a number of expanded data presentations, and incorporates the results of supplemental subsurface investigation performed during the spring of 1993.

1.1 Report Structure

The structure of the Final Hydrogeological Report follows the framework established in the Draft Final Report and is designed to address all pertinent 6 NYCRR Part 360-2.11(b),(c) and Consent Order reporting requirements. This document compiles all data submitted previously in support of the Interim and Draft Final Hydrogeological Reports (IT Corporation, Wehran Environtech, and O'Brien & Gere, 1992a, 1993a), as well as the Site Investigation Plan (IT Corporation, 1990a) and a series of initial survey reports performed in accordance with the requirements of Consent Order Appendix A-6.

The Final Report document consists of 43 designated (46 physical) volumes. The core of the report is represented by this volume (I:Text), which is linked closely with Volume IIA (Report Tables), Volumes IIB and IIC (Report Figures), and Volumes IIIA and IIIB (Map Sheets). Volumes IV through XVIII contain supporting appendices, and Volumes XIX through XLIII contain supporting attachments.

Structurally, the Final Hydrogeological Report consists of five major components, as follows:

(1) Introduction (Sections 1.0 through 3.0 of the report): Background information regarding the context and scope of the Fresh Kills Consent Order, Landfill Leachate Mitigation System Project, and Final Hydrogeological Report; overview of regional and site-specific literature and subsurface investigations; and summary of the content of the project Hydrogeological Site Investigation Plan (SIP),

(2) Field Investigation/Data Recovery (Section 4.0): Description of all field data collection activity stipulated in the Consent Order and SIP, including survey report preparation, phased center boring installation, perimeter boring installation (piezo electric cone penetration testing), phased perimeter well installation, soil testing and geotechnical laboratory analysis, in-situ hydraulic testing, downhole geophysical logging, water quality sampling and analysis, and ground and surface water level collection.

Report text in these sections describe the objectives, scope, and schedule of data collection activity, indicates any variances from established protocols, and summarizes collected data where appropriate. Summary tables of recovered data are presented for those data that are not described in detail independently in latter (analytical) sections of the report. For example, laboratory hydraulic conductivity data are integrated with other available permeability data into the development of hydrostratigraphic units under the conceptual groundwater modeling phase of the project (Section 6.0), but otherwise are not presented in a format that would allow

for easy comparison between the full suite of measured geotechnical test indices. Consequently, a summary table of all recovered geotechnical test data is included within the Section 4.0 presentation. Conversely, the analytical results of groundwater quality sampling are discussed in depth in Section 7.0 of the report; consequently, Section 4.0 provides a summary tabulation of the location and quantity of samples recovered during each sampling quarter, rather than tabulating the results of sample analysis.

(3) Data Analysis (Sections 5.0 through 7.0): Technical interpretation and evaluation of recovered data in accordance with the data analysis requirements of the Consent Order and 6 NYCRR Part 360 relative to local and regional geology, local and regional hydrogeology, geochemical analysis, and water quality analysis. These analyses include stratigraphic interpretation, geologic depositional model development, conceptual and numerical groundwater flow model development, and water quality/geochemical characterization.

(4) Conclusions (Sections 8.0 and 9.0): Long term monitoring plan development based on the results of water chemistry, stratigraphic, and groundwater flow modeling analyses. Summary of findings regarding the geologic, hydrogeologic, and water chemistry regime identified at the project site and its relationship to the region.

(5) Supporting Data (Glossary, References, Appendices, Attachments): Glossary of technical terms, list of references (bibliography) to technical and administrative documents cited in the report text, reference to appendices (by letter designation), and attachments (by number designation). Appendices contain compilations of supporting data in final format (e.g. final boring logs corrected for regional stratigraphic interpretations, final piezo electric cone penetration test reports, etc.). Attachments generally contain compilations of supporting data in field collected, or initially processed format (e.g., original field boring logs, water level measurements, instantaneous discharge (slug) test data, etc.).

1.2 Site Location and History

The Fresh Kills Landfill is located on the western shore of Staten Island, one of the five boroughs comprising the City of New York (Figure 1.2). Based initially on property tract designations, and subsequently on the operational character of the disposal areas, the landfill has been subdivided into four areas, designated Sections 1/9, 2/8, 3/4 and 6/7.

Section 1/9 is bordered on the north by the Fresh Kills, on the east and south by State Highway 440 (West Shore Expressway), and on the west by the Arthur Kill and Great Fresh Kills. Section 2/8 is bordered on the north by the Fresh Kills, on the east by Richmond Creek, on the south by

Arthur Kill Road, and on the west by State Highway 440. Section 3/4 is bordered on the north by the Travis residential community, on the east by Main Creek, on the south by the Fresh Kills, and on the west by State Highway 440 and Wild Avenue. Section 6/7 is bordered on the north by Main Creek, on the east by Richmond Avenue, on the south by Richmond Creek, and on the west by Main and Richmond Creeks. Land uses surrounding the landfill vary from residential, light commercial, and heavy industrial development to undeveloped marsh land.

The total area of the Fresh Kills landfill and associated properties is approximately 2,400 acres. Data for the individual landfill sections, including a series of internal and external boundary areas of relevance to ongoing landfill engineering design, are contained in Table 1.1 (with referenced boundaries indicated on Figure 1.3).

The Fresh Kills Landfill is owned and operated by the City of New York and has been collecting household waste since 1948. Based on data compiled by NYCDOS over the period 1990 - 1992, the landfill receives on average between 14,000 and 16,000 tons per day of refuse. In addition to the distinction of being the world's largest operational municipal solid waste landfill, the Fresh Kills Landfill is an integral part of New York City's solid waste management plan, and will remain so through the next decade.

Refuse is brought to the site via two modes of transportation: truck and barge. In accordance with the 1985 Operations Plan, the Landfill is being developed into four distinct mounds that roughly correspond to the areas designated as Sections 1/9, 2/8, 3/4 and 6/7. Historically, Sections 1/9 and 6/7 operated primarily as barge-fed landfills and Sections 2/8 and 3/4 operated exclusively as truck-fed landfills. With the imminent closure of Landfill Sections 2/8 (1993) and 3/4 (1994), these distinctions are no longer fully apparent. Landfill Sections 1/9 and 6/7 are currently proposed to receive refuse from both sources for the remainder of their operational life.

The development of Fresh Kills Landfill was similar to many landfills that historically reclaimed marshlands -- once considered nuisance wastelands -- for such productive uses as recreational parkland and commercial development. At the time of its original development, there was little recognition or consideration of the long-term impacts the facility would have on the environment: specifically, the groundwater, marine wetlands, and tidal streams that encompass the site.

With the advent of the Federal Resource Conservation and Recovery Act of 1976 and Clean Water Act of 1977, and New York State's complementary legislation under the State

Environmental Conservation Law, and Title 6 of the Official Compilation of Codes, Rules, and Regulations of the State of New York (6 NYCRR), more stringent criteria for the siting, construction and operation of landfills were promulgated. These regulations required that the Fresh Kills Landfill be upgraded to appropriate standards to effectively mitigate environmental damage. The negotiated Consent Order between the State of New York Department of Environmental Conservation (NYSDEC) and the New York City Department of Sanitation (NYCDOS) represents the mechanism through which environmental investigation and engineering design will be performed to achieve this objective. This document, the Hydrogeological Report, provides the framework from which much of the engineering design, and ultimately procurement of necessary operating permits, will be based.

2.0 OVERVIEW OF PERTINENT LITERATURE

This section provides a summary of background information describing the regional geologic setting within which the Fresh Kills Landfill project area is located, and identifies the scope and findings of previous subsurface investigations performed at the landfill site. This information represents the database from which planning for project implementation was initiated (i.e., development of the Hydrogeological Site Investigation Plan), and provides a framework within which the subsequent, detailed analyses of site geology and hydrogeology are considered.

2.1 Regional Geological Setting

As previously referenced, Figure 1.2 identifies the location of the Fresh Kills Landfill relative to surrounding areas of Staten Island and New Jersey. This area (mapped at a more appropriate level of scale and detail for this investigation on Sheet 5.1) generally represents the primary area of interest in this report. The Hydrogeological Literature Review (IT Corporation and Wehran EnviroTech, 1991a) contains a review of the regional geology of a much larger area, including much of central New Jersey and the New York metropolitan area including Long Island. The reader is referred to that document (Attachment 44) for an overview of the geologic setting at that scale.

A significant finding of the literature review was the scarcity of geologic and hydrogeologic literature specific to Staten Island. A surprisingly small amount of literature exists that is current and pertinent to this investigation; primary references are often from investigations performed in New Jersey and/or Long Island. The result is a very limited selection of references available for a detailed discussion of the geology of the area of Staten Island surrounding the Fresh Kills Landfill. Information is especially sparse regarding the Recent, Pleistocene, Cretaceous, and residual clay deposits. Therefore, maximum use is made in the ensuing discussion of current and pertinent Staten Island studies that have been obtained, with support from regional studies that include Staten Island. A much larger and more detailed body of literature exists regarding the portion of New Jersey that is included in the regional area identified previously.

Following an initial discussion on the physiography of the project area, the region is described in terms of the occurrence of the major geologic deposits: Holocene (Recent), Pleistocene

(glacial), Cretaceous, residual clay, and bedrock. Several simplified figures based on the regional data base are presented herein to aid in this review. The map sheets and map figures associated with Section 5.0 provide a much higher level of detail and resolution relative to geologic unit definition.

2.1.1 Physiography

The Fresh Kills Landfill site occurs within two physiographic provinces, the Piedmont and the Coastal Plan. Figure 2.1 is a diagram of the major physiographic divisions and provinces of the United States in relation to the Fresh Kills site. Figure 2.2 is a map of the physiographic provinces of the New Jersey-New York City area showing the Piedmont-Coastal Plain boundary in Staten Island and respective subdivisions. The landfill site occurs within the Triassic Lowlands and Manhattan Prong (subdivisions of the Piedmont), and the Inner Plain subdivision of the Coastal Plain.

In northern New Jersey and Staten Island, the Triassic Lowland portion of the Piedmont province is underlain almost entirely by Triassic strata and associated volcanic and intrusive igneous rocks. These rocks consist primarily of red shale and sandstone, black and brown argillite, varied-colored conglomerate, and interbedded volcanic flows and intrusive sills. In general, these "units" have been tilted 10 to 15 degrees northwestward. In some areas they have been warped into gentle folds and have undergone some faulting. The general trend of the folds and the strike of the tilted strata is northeast-southwest (Kummel, 1940).

The Coastal Plain sediments are deposited on a Mesozoic basement complex consisting of greiss, schist, granite, and other crystalline rocks. In central New Jersey (and a portion of Staten Island), the Coastal Plain sediments overlap the sedimentary rocks of the Triassic Lowland (Olsson and others, 1988). The terrain is quite flat. The southeast to east dip of the sediments decrease upward from more than 60 feet per mile near the base of the section to about 10 feet per mile at the top. These sediments range in age from Cretaceous to Recent and consist of clay, silt, sand, and gravel of both marine and non-marine origin, deposited as the ancient shoreline fluctuated across the continental margin (Richards et al., 1983). The emerged or land portion is the northwestern thinner edge of a wedge-shaped pile of unconsolidated sediments which extend

southeastward to the ocean. The submerged or continental shelf portion of the Coastal Plain is covered by the ocean to a maximum depth of 600 feet (Widmer, 1964).

The Fall Line occurs at the juncture between the Piedmont and the Coastal Plain. The Fall Line is expressed as an east-facing slope that is relatively minor in terms of its physiographic expression. It is not really a line but a zone of appreciable width which sometimes leads to the designation of "Fall Zone". However, quite obvious differences in rock structure, geology, physiography, soil, and vegetation occur on opposite sides of the boundary. Theories regarding the origin of the Fall Line include differential erosion of the Piedmont's more resistant strata and the Coastal Plains' less resistant sediments, monoclinal flexing/faulting, or the intersection of two older peneplains (Renner, 1927a, 1927b). At the Fresh Kills Landfill site, the physiographic expression of the Fall Line (zone) is obscured by the mantle of glacial sediments that were deposited over the Piedmont/Coastal Plain boundary.

- ***Topography***

The topography of Staten Island is illustrated on Figure 2.3. The most obvious feature is the highland in the northeastern portion of the Island. This hilly region is due primarily to the underlying resistant serpentinite bedrock providing relief of up to 405 feet above sea level (Soren, 1988). In general, this hilly area trends in a northeast-southwest direction. The somewhat hummocky terrain of the Harbor hill terminal moraine wraps around the southeast flank of the serpentinite hill and continues in a southwesterly direction to the southern tip of the Island. The morainal terrain shows less relief than the serpentinite hill, rarely exceeding 100 feet in elevation. An area of very low relief extends along the ocean southeast of the moraine from Great Kills Harbor to the Verazzano-Narrows Bridge. Another area of low relief also exists along the western side of the Island to an area just south of the Fresh Kills Landfill.

- ***Drainage***

In the northern portion of Staten Island, the surface drainage generally runs radially away from the hilly area in the northeast. Most drainage channels are small streams, the largest being the Richmond Creek-Main Creek-Fresh Kills drainage in the area of the Landfill site. The southern

portion of the Island is drained primarily by small streams flowing off the moraine. As expected, residential, commercial and industrial development that has occurred on the Island has modified portions of the surface drainage system.

By observing sustained flow in some streams during dry periods, Soren (1988) has surmised that segments of the streams on the Island receive groundwater discharge (influent streams). He also notes that the various ponds on the Island, some of which may now be artificially controlled, reflect the surface of the water table.

The surface water discharge eventually flows to the large bodies of water that surround the Island. The Atlantic Ocean borders the south and east portions of the Island. Newark Bay and Kill Van Kull border the northern portion of the Island. The Arthur Kill borders the western boundary of the Island and also forms the western boundary of the Fresh Kills Landfill site. Most of the surface drainage in the regional area of Staten Island is part of the Fresh Kills/Main Creek/Richmond Creek drainage. Some of the remaining tidal marsh areas north and upland areas south of the landfill on the western portion of the island drain directly to the Arthur Kill. South of the peak of the Harbor Hill moraine, surface drainage is to the south.

2.1.2 Recent Deposits

Five types of Recent (Holocene) deposits have been identified on Staten Island. They are:

- Beach/Shore Deposits
- Tidal Marsh Deposits
- Upland Marsh Deposits
- Alluvial Deposits
- Artificial Fill

Beach sand occurs along the shoreline of Staten Island. The source areas for these sands are rocks of the New York City Group, the Staten Island Serpentinite, Palisades Diabase, Cretaceous sediments, glacial deposits, and outcrops of other rock formations further up the Hudson Estuary. River tidal currents carry the sediment in the Arthur Kill, while the prevailing southwest flowing longshore current deposits sediments along the beachface of the eastern portion of Staten Island

(Okulewicz, 1990). In many locations on Staten Island, the shore deposits of sand have been covered by artificial fill (Soren, 1988).

The Post-Pleistocene rise in sea level inundated large low-lying areas of western Staten Island (Roberts-Dolgin, 1989). The sediments that were deposited in these areas consist mostly of organic silts, clays, peat, and sand. However, most of these areas have also been filled in with artificial fill (Soren, 1988; Roberts-Dolgin, 1989). The previous extent of the tidal marsh deposits in this region can be obtained from historical topographic maps obtained as part of the Hydrogeologic Literature Review (IT Corporation and Wehran EnviroTech, 1991a: Figures 3-1, 3-2 and Sheets 1 through 6), and Figure 5.18 in this report.

Upland swamp/marsh deposits exist in many areas where drainage is poor due to shallow bedrock or impermeable layers in the unconsolidated deposits (Roberts-Dolgin, 1989). These deposits have also been artificially filled in many cases (Soren, 1988, Roberts-Dolgin, 1989).

Soren (1988) believes that the above-mentioned Holocene (Recent) deposits are relatively thin with thicknesses not significantly thicker than ten feet. Perlmutter and Arnow (1953) agree but report no thickness range.

Thin deposits of alluvial clay, silt, sand, and gravel occur in the channels of fresh water streams in this region. The same type of deposits occur in tidal channels but are, in general, thicker. Maximum thickness is at least 100 feet, but should average much less (Perlmutter and Arnow, 1953). This category would include the Arthur Kill, Fresh Kills, Main Creek, and Richmond Creek.

As mentioned above, artificial fill has been placed over much of the Holocene deposits in this region (Soren, 1988; Roberts-Dolgin, 1989). Included is most of the Fresh Kills Landfill site. Soren (1988) and Cadwell (1989) provide maps showing in small scale the areas of artificial fill. Included in the regional area for this study is the Fresh Kills Landfill site and other former tidal marsh areas to the north.

No information on beach or upland swamp deposits has been identified for the portion of New Jersey delineated as part of the regional area. Regardless, they likely occur.

Examination of the 1890 Historic Topographic obtained as part of the Hydrogeologic Literature Review (Figure 5.18) shows large tidal marsh areas extending from Carteret, westward past the present location of the New Jersey Turnpike, then northward to the area of the present Goethals Bridge. Current topographic maps (U.S. Geological Survey, 1981) show only a small area of these tidal marshes remaining. It is assumed that these areas were filled with artificial fill. Waskman et al., (1943) report that most of the peats of the Rahway drainage region are of "salt marsh variety" that contain considerable mineral sediment with some reed and sedge material. Average depths are 8 to 10 ft, with maximum depths at 11 to 16 ft.

Barksdale, et al. (1943) report that alluvial deposits of sand, gravel, silt, clay, and organic materials is deposited in tidal flats and along stretches of streams in Middlesex County where gradients are low. They map alluvial deposits (possibly including beach sands) along the Rahway River and Arthur Kill in the regional study area.

Regional borings indicate the presence of Recent silt and clay, Recent sand, and peat within the Fresh Kills Ash/Residue Landfill site, Brookfield Avenue Landfill, and the area between Carteret and the Arthur Kill.

2.1.3 Pleistocene Deposits

Most of the region surrounding the Fresh Kills Landfill is covered by glacial deposits, as is most of Staten Island (Kaarsburg, 1975) and the area of New Jersey indicated on the regional map. The glacial deposits form an unconformable contact with the underlying Cretaceous or bedrock units (Soren, 1988).

The glacier deposited a basal (lodgement) till layer during its advance, and likely other types of till (melt-out, flow) in some locations during its retreat. Cadwell (1989) and Stanford et al. (1990) maps were used to illustrate the glacial geology of the region as reflected in Figure 2.4. It is likely that glacial till is the basal unit underlying most of the other glacial sediments in this region. Stanford et al. (1990) give a possible range of till thickness of 20 to 200 ft in New Jersey. Soren reports that in Staten Island, the thickness of the till ranges from 0 to 150 ft. He also states that local bodies of stratified sand and gravel commonly occur within the till.

The Harbor Hill terminal moraine, which represents the maximum upland extent of the Wisconsin glacial advance, occurs in the southern portion of the regional study area (Soren, 1988; Cadwell, 1989). The terminal moraine occupies a belt that runs from the northeast corner of Staten Island at the Narrows and trends southwestward along the coast to Tottenville, Staten Island, except for the eastern-most portion of the Island between the Verrazano-Narrows Bridge and Great Kills Park, where glacial outwash occurs (Roberts-Dolgin, 1989). It then continues in New Jersey through the Perth Amboy-Fords region in a north-northwesterly direction, south and west of the regional study area (Stanford et al., 1990). It forms an irregular, hilly area one to two miles wide (Soren, 1988). The moraine is composed of till, sandy diamict and minor sand and gravel, which consists of mostly unsorted sand, gravel, cobbles, and boulders within a silty and clayey matrix (Soren, 1988; Stanford et al., 1990). The sediments appear to be largely derived from local rock units (Soren, 1988). Perlmutter and Arnow (1953) report thickness to 150 ft while Stanford et al. (1990) report thicknesses to 200 ft. (Regional borings RS-28, RT-27, and RV-25 are believed to be thorough and, therefore, representative of morainal stratigraphy.)

Glaciolacustrine sedimentation took place in much of the area of the Fresh Kills Landfill site and along the Arthur Kill across the river in New Jersey (Stanford et al., 1990). Glaciolacustrine sedimentation probably took place at the Fresh Kills Landfill site during Lake Woodbridge and/or Lake Bayonne time (Standford and Harper, 1991). These areas appear to very strongly correlate with former or existing tidal marsh areas. The former or existing tidal marsh areas along the Arthur Kill in Staten Island are probably also underlain by these sediments. These sediments consist of silts, clays, and fine sands that can, in some cases, be up to 250 ft thick (Stanford and others, 1990). In addition to the eastern portion of Staten Island mentioned above, outwash deposits also occur in the northwestern corner of Staten Island.

North of the landfill site, regional borings generally show glaciolacustrine silt and clay over till, or till alone with glacial sand above, below, and within the units as observed at the Fresh Kills site. East of the site, the borings indicate a relatively thin, sandy till over bedrock. South of the site, regional test borings indicate a southerly thickening glacial till, into the area of the terminal moraine. Sandy units are common within the morainal/till sediments. Scattered occurrences of glaciolacustrine sediments southeast of the site were probably deposited in tributary streams to Richmond Creek, that glacial lake waters backed up into during deglaciation. The glacial

deposits in New Jersey are very similar to those north of the site. (Scattered regional borings (NJ-16, NY-27) indicate no glacial sediments.)

2.1.4 Cretaceous Deposits

The separation of the North American and European Plates initiated in the Triassic – Jurassic period, resulted in the formation of fault block basins and continued through the Cretaceous (Olsson, 1980). During the Mesozoic and Cenozoic Eras, the block faulting of the basement created highs and lows in the basement surface along the Atlantic Continental Margin (Zapecza, 1989).

In the uplifted area, the velocity of the streams increased, while the relatively flat and coastward area became a zone of accumulation for the sediments that were deposited by the rejuvenated rivers (Kummel, 1940). The result is a seaward-dipping wedge of unconsolidated sediments mostly composed of clay, silt, sand and gravel, classified as continental, coastal, or marine-type sediments. These deposits generally strike northeast-southwest and dip gently to the southeast 10 to 60 ft/mile (Zapecza, 1989).

The Cretaceous deposits in this region occur in the area shown in (Figure 2.5). Published literature identifies two major Cretaceous units on Staten Island: the Raritan and the Magothy (Perlmutter and Arnow, 1953; Kureshy, 1975; Connors and Cousminer, 1979; Lyttle and Epstein, 1987; Soren, 1988; Cadwell, 1989; Roberts-Dolgin, 1989; Okulewicz, 1990). However, Connors and Cousminer (1979) did identify Cretaceous strata transitional between the Patapsco and Raritan formations from pollen analyzed from sediments obtained from southeastern Staten Island. The few regional borings south of the landfill that totally penetrate the Cretaceous strata indicate a thickening wedge of alternating Cretaceous silt/clay and sand layers, similar to what is seen beneath the landfill site. Cretaceous clay is the most abundant unit. Tens of feet of interlayed Cretaceous silt/clay and sand occur southeast of the Fresh Kills Landfill beneath the Brookfield Avenue Landfill. Cretaceous sediments do not occur in the regional borings north and east of the Fresh Kills Landfill.

The lowermost of the two units, the Raritan, is described as an Upper Cretaceous Formation consisting of rapidly alternating lenses of white or yellow sand and white, cream, red, or light

to dark gray clay/silt which show considerable variation in texture, composition and thickness (Kureshy, 1975; Roberts-Dogin, 1989). Lignite, mica and pyrite are common in certain units (Kureshy, 1975; Soren, 1988). The sandy beds are often cross-stratified (Kureshy, 1975; Roberts-Dogin, 1989; Okulewitcz, 1990).

The Magothy, also an Upper Cretaceous Formation is described as several interbedded members of gravel, light colored coarse quartz sands, fine to medium gray micaceous sand mixed with dark carbonaceous silt, and dull colored or dark micaceous pyritic, kaolinitic clayey silt. Lignite is also occasionally found. (Lyttle and Epstein, 1987; Okulewicz, 1990). Not all investigators recognize the existence of Magothy sediments on Staten Island.

For the Cretaceous sediments, in general, Perlmutter and Arnow (1953) stated that they occur in discontinuous lenses that may or may not be traceable from one borehole to another. Water-bearing zones (sand?) occurred at several depths, but data was not available to determine if there existed any extensive lateral continuity. In other areas, the Cretaceous sediments were predominantly clay and completely lacking water-bearing zones of sufficient thickness to be utilized as aquifers.

The Cretaceous sediments also extend into the area of New Jersey delineated on the regional map (Figure 2.5). Barksdale and others (1942) map the unit as Raritan Formation. This delineation provides an excellent match with the northern extent of Cretaceous sediments on the eastern side of the Arthur Kill as observed at the Fresh Kills Landfill. Zapecza (1989) shows the northern extent of the Cretaceous Potomac Group and Raritan Formation sediments further south than Barksdale and others (1943). It is interpreted that Zapecza (1989) is showing the outcrop area of the above formations and that the portion of the Cretaceous deposits that are covered by glacial sediments is not illustrated. Regional borehole data from New Jersey acquired for this study supports this scenario. Given Farlekas' (1979) delineation of the Farrington Sand, it could be surmised that the Cretaceous sediments occurring in New Jersey in the area shown on the regional map are the Raritan Fire Clay, or Lower Cretaceous sediments, though no data exists to suggest that Lower Cretaceous deposits occur there. It is also possible that Farlekas (1979) did not map the Cretaceous sediments that occur below the glacial deposits and that only the Farrington Sand and/or Raritan Fire Clay extend below the glacial sediments shown on the regional map.

The Raritan Fire Clay is described as a blue, brown, gray, or red clay. Typically, the basal portion of the clay has a brick-red color identical in shade to the Triassic red shale from which it was derived. Observed thicknesses range from 0 to 85 ft (Barkesdale and others, 1943).

2.1.5 Residual Clay

Barksdale et al. (1943) report that the rocks of the Newark Group weather to a relatively tight and impervious clayey soil, analogous to the residual clay identified through previous investigations at the Fresh Kills Landfill site. An interesting observation they make is that the average yield of wells were lower in areas where the Triassic rocks have a mantle of residual clay. They believe a possible cause of these lower yields, other than decreased infiltration, may be the filling of fractures by the fine materials derived from the decomposition of the rock to clay. Additional studies have been conducted in other locations on these types of units, many with potential relevance to this study due to their location or subject. A brief summary of these studies is given below. The term "saprolite" is somewhat synonymous with the term "residual clay".

Sevon (1975) studied saprolite formed from sandstone in eastern Pennsylvania, and Gardner and others (1981) studied the geochemistry and mineralogy of a diabase saprolite in South Carolina.

Costa (1974) studied the saprolite in the Piedmont Province in an effort to correlate saprolite thickness, stream valley morphology, and sediment deposition to climatic, eustatic, and tectonic factors.

Pavich and Obermeier (1977) studied weathering profiles in the Atlantic Coastal Plain near Washington, D.C. in an effort to determine the time of formation. They suggested that not all saprolite buried by Cretaceous sediment was pre-Cretaceous in age and, therefore, formed in more recent times.

Pavich (1974) analyzed the saprolite from the Atlantic Coastal Plain 25 miles southeast of the Fall Line in South Carolina. He claimed that the saprolite was formed prior to Cretaceous Tuscaloosa sedimentation, and had not been diagenetically altered in the subsurface.

Reinhardt and Cleaves (1978) studied the relationship between saprolite and Lower Cretaceous sediments along the Fall Line in Maryland. They claimed that 1) the crystalline bedrock had weathered to saprolite before sediment emplacement, 2) the sediment was deposited by a highly erosive agent, 3) the saprolite was water-saturated and deformed plasticaly during sedimentation, and 4) later reorientation of the sediment-suprolite deformation structures took place probably during sediment compaction.

Residual clay is identified in infrequent and scattered borings from the regional test boring data base. The relevant findings in regard to the residual clay and this investigation are similar to those stated in the Hydrogeologic Literature Review. They are:

1. An upper, highly weathered bedrock zone (residual clay) is found over a wide region in the Coastal Plain, Piedmont, and elsewhere in the eastern United States.
2. In some cases this zone is caused by subaerial weathering, but elsewhere is caused by subsurface geochemical processes.
3. The thickness of this zone may vary greatly over short distances, and in some cases can be related to the nature of overlying materials (thinner under clays and thicker under gravels), or bedrock fracture zones (thicker in such zones).
4. Bedrock aquifers below residual clay units may show decreased yield due to the factors relating to the formation or existence of the residual clay.
5. Although the literature considers the hydraulic or geotechnical properties of saprolites, their role in groundwater flow systems is apparently not documented.

2.1.6 Bedrock

Information on the consolidated bedrock type in certain areas surrounding the Fresh Kills Landfill is sparse. The thickness of the overlying sediments and the lack of detailed deep exploration, especially in the Coastal Plain, have led to a general lack of published data on the nature of the consolidated bedrock in these areas. Geologic maps of the area (Lewis et al., 1950; Fisher et al., 1970; Lyttle and Epstein, 1987) simply illustrate the Cretaceous sediments in these areas. Regardless, some data is available on the consolidated bedrock in the areas of the thick Cretaceous sediments.

The Piedmont section of New Jersey west of the Fresh Kills Landfill, and parts of Staten Island, are floored by the Triassic and Jurassic sediments of the Newark Group (Lyttle and Epstein,

1987). Work by Van Houten (1965, 1969) and Olsen (1980) show that the Triassic/Jurassic Newark Group bedrock also extends beneath the Cretaceous sediments in the area from Carteret to Perth Amboy. Soren (1988) illustrates the consolidated bedrock geology of Staten Island as the Trenton Group and Palisades Diabase in the western portion of the island. The serpentinite occurs in the northeastern portion of the island, and the Manhattan Schist in the southeastern portion of the island.

The Triassic Newark Group formations lie unconformably upon Precambrian and Paleozoic rocks in this area (Kummel, 1940; Van Houten, 1969). The Triassic sediments were deposited as a result of the breaking apart of the welded North American-African super-continent about 200 million years ago, resulting in a fault-bounded rift basin known as the Newark Basin (Isachsen, 1980). Non-marine sedimentary rocks of fluvial and lacustrine origin and associated intrusive and extrusive basic rocks were deposited in the basin (Van Houten, 1969; Isachsen, 1980). The strike generally parallels the trend of the basin and the dip is 5 to 25 degrees NW. Measured dips in New Jersey, north and northeast of the site, range from 8 to 12 degrees. The strata are locally warped into open anticlines and synclines broken by many small normal faults (Van Houten, 1969; Olsen, 1980).

The Stockton Formation is the oldest and most widespread unit, forming the basal beds of the Newark Group. It consists principally of light yellowish gray to pale reddish brown fairly well sorted arkose and poorly sorted conglomerate, archeozoic sandstone and red siltstone to mudstone. The predominant facies trend is upward fining. The greatest thickness is in Pennsylvania where the formation may be as much as 6,000 ft thick. Thicknesses in the region of the landfill are much less, being about 750 ft thick at Hoboken and Weehawken, New Jersey, and about 2,760 ft near Princeton, New Jersey. In the region of the Newark Basin occupied by the Landfill, the Stockton grades upward into the conformably overlying Lockatong Formation (Van Houten, 1969; Olsen, 1980).

The Lockatong Formation is a relatively large unit of lacustrine deposits (Van Houten, 1969; Olsen, 1980). It is a predominately laminated to thick bedded gray and black siltstone and shale. It is composed of alternating detrital and chemical lacustrine cycles interpreted to be the result of the expansion and waning of a lake (Van Houten, 1969; Lyttle and Epstein, 1987). This unit also has its greatest thickness (approximately 3,750 ft) in Pennsylvania (Van Houten, 1969). The formation thins in all directions away from the central area, passing into the Stockton and Passaic

Formations along the exposed edges of the Newark Basin (Olsen, 1980). Just west of Staten Island, the unit has been estimated at 500 to 750 ft thick. Metamorphism was also observed in the Lockatong in that area. Throughout most of its extent, it grades upward into the Passaic (Brunswick) Formation (Van Houten, 1969).

The Passaic Formation consists predominately of grayish red to reddish brown, evenly to irregularly bedded shale, siltstone, very fine to coarse grained sandstone, and red matrix conglomerate (Lyttle and Epstein, 1987). The Passaic is a recently named formation that is equivalent to the pre-basalt portion of Kummel's Brunswick Formation. In this region, the Passaic Formation rests conformably on the Lockatong Formation, or where the Lockatong is absent, on the Stockton Formation (Olsen, 1980). No Passaic Formation strata has been identified within the Fresh Kills area of Staten Island.

Large diabase and gabbro plutons and sills are emplaced through portions of the Newark Basin sequence (Olsen, 1980). The Palisades Diabase sill intrusion was emplaced in this region. It is a dark gray to black, very fine to coarse grained diabase composed largely of calcic plagioclase and augite (Lyttle and Epstein, 1987). The intrusion extends southwest from Haverstraw, New York, forms the Palisades Cliffs along the west side of the Hudson Estuary, then dips below Hoboken, New Jersey where it is cut by an unnamed fault in the Kill Van Kull. It passes through western Staten Island and disappears under the Arthur Kill, where it has been traced by borehole data into Carteret, New Jersey. The sill generally dips 10 to 15 degrees to the northwest. The thickness has been estimated at 900 ft in New Jersey. This rock was intruded upward between the surrounding Lockatong or Stockton rock as a liquid magma, possibly along an existing fault. The molten liquid cooked and baked the surrounding rocks and converted them into contact metamorphic rocks known as quartzite and hornfels (Okulewicz, 1990).

The Staten Island serpentinite is a northeast-southwest trending oval-shaped body located in the northeast portion of Staten Island. Its outcrop dimension is approximately 20 square miles (Ohan, 1975). Originally a harzburgite/dunite rock, the body has been metamorphosed under green schist facies into various amounts of serpentine group minerals. As a whole, it represents the remains of an ophiolite complex (Okulewitz and NUS Corporation, 1990). Its age is somewhat controversial, with estimates ranging from Precambrian to Ordovician (Soren, 1988). The unit is fault-bounded and exhibits northeast trending folds. It is unconformably overlain by Triassic bedrock on the west and Cretaceous sediments along the east and south borders. The

serpentinite unit shows the effects of glacial erosion with a roche moutonnee form, valley widening, and evidence of glacial plucking (Okulewicz and NUS Corporation, 1990).

In the area of Staten Island south of the Fresh Kills Landfill, the consolidated bedrock type and extent is less well defined. Along the Arthur Kill, Soren (1988) defines the consolidated bedrock as the Newark Supergroup, undivided. In the remaining portion of Staten Island, south of the serpentinite, the consolidated bedrock is defined as the Manhattan Schist. The Manhattan Schist is a mica schist of Precambrian to Cambrian age (Lyttle and Epstein, 1987; Okulewicz, 1990). Generally, the mica schists of this unit are jet black to silvery-white to rusty brown and are well foliated with muscovite or biotite mica in abundance. The unit was complexly folded, and faulted and eroded to a peneplain upon which younger formations were deposited (Soren, 1988), and shows a marked foliation (Perlmutter and Arnow, 1953).

Adding the regional test borings that encounter bedrock more clearly define that the Fresh Kills Landfill site is above a former bedrock "channel" or "valley" between the resistant diabase to the west and resistant serpentinite to the east. Regionally, the bedrock slopes gradually from north to south from the Piedmont to the Coastal Plain as the bedrock surface is traced from areas north of the site to areas south of the site.

2.2 Previous Site Investigations

An extensive review of prior subsurface investigations performed at or in the immediate vicinity of the Fresh Kills Landfill site has been provided within the context of the Hydrogeological Literature Review Report (IT Corporation and Wehran EnviroTech, 1991a; Attachment 44) prepared in accordance with Consent Order Appendix A-6, Task (8) [refer to Report Section 4.1]. Previous reports on subsurface investigations at or in the vicinity of Fresh Kills Landfill provide extensive (albeit incomplete) discussions of the geology and hydrogeology of the site. These reports include Parsons Brinckerhoff-Cosulich (1981, 1982), Wehran Engineering (1983a,1983b, 1984, 1988), Woodward Clyde Consultants (1990, 1991), and Wehran EnviroTech (1991). The purpose of reviewing available information was to establish a general hydrostratigraphic model of the site, in support of the development and execution of the Hydrogeological Site Investigation Plan. This section summarizes the previous site investigations and presents the chronological

development of the hydrostratigraphic model. A summary of the primary geologic and hydrogeologic findings of these investigations is presented in Table 2.1.

2.2.1 Parsons Brinckerhoff-Cosulich (1981-1982)

An early investigation was conducted by Parsons Brinckerhoff-Cosulich between February 21, 1979 and June 16, 1979. The first phase consisted of the installation of 24 soil borings across all Fresh Kills sections and within the Brookfield Avenue Landfill (east of Section 2/8; Figure 1.2). Twenty of these soil borings were converted to 1-1/4 in. piezometers (observation wells) and one was converted to a 4-in. monitoring well. Results of the Phase I investigation were detailed in the Preliminary Hydrogeologic Report submitted to the NYCDOS on December 1, 1981. Based on data obtained from the new and existing soil borings, published reports and available site data, subsurface materials were divided into four primary stratigraphic units including Recent, Pleistocene, Cretaceous, and bedrock deposits.

From November 1981 through march 1982, Phase II of the investigation was completed across all Fresh Kills sections and within the Brookfield Avenue Landfill. Phase II of the investigation consisted of drilling 135 soil borings. Of these borings, 134 were converted to groundwater monitoring points. Ten borings were converted to 4-in. Schedule 40 PVC monitoring wells with screened intervals ranging from 9 to 45 ft. One boring was converted to a 4-in. open borehole rock well, while the rest were completed at 1-1/4 in. piezometers with screens ranging from 2 to 32 ft. Results of this investigation were summarized in the Interim Hydrogeologic Report submitted to the NYCDOS in September 1982. This report identified three major aquifers at the site including:

- Unconsolidated sands and gravel of Pleistocene and Recent age,
- Unconsolidated sands of Cretaceous age; and
- Consolidated bedrock

In addition, a preliminary water balance was prepared by evaluating the major components of the hydrologic regime, including direct surface runoff, groundwater flow, evapotranspiration, precipitation and tidal flow. The estimated annual averages were 45 in. of precipitation, with 4

to 15 in. as direct surface runoff, 5 to 12 in. as groundwater flow, and 18 to 36 in. as evapotranspiration.

2.2.2 Wehran (1983)

The most comprehensive site-wide evaluation of hydrogeology at the Fresh Kills site was performed by Wehran in 1983 (Wehran Engineering, 1983a). The objective of this investigation was to define the nature of geologic materials beneath the site and the significance of existing aquifers and aquitards, as well as assisting in the development of preliminary engineering designs. The interpretation of hydrogeologic conditions existing at the site was primarily based upon Wehran's review of the soil boring, monitoring well, and piezometer installation program conducted previously under the supervision of Parsons Brinckerhoff-Cosulich. To supplement the earlier data, 29 additional borings were drilled during April, May and June of 1983. The Wehran Engineering Hydrogeologic investigations confirmed that the geologic conditions encountered within the area were consistent with what was previously reported for the site and the region. Further description of each major strata of the geologic formation was detailed, including the estimated range of grain size, permeability, and geological map and cross-section preparation. The report concluded that groundwater occurs within four identifiable water-bearing zones that include:

- The unconfined, upper water-bearing zone which consists in part of saturated refuse and/or fill, Recent sand and glacial sand, glacial till and undifferentiated Cretaceous sand.
- The confined, artesian, intermediate water-bearing zone of the upper Cretaceous sand.
- The confined, artesian water bearing zone within the lower Cretaceous sand.
- The confined artesian water bearing bedrock of the Triassic Stockton/Lockatong formation and fractures of the Staten Island Serpentinite.

The results of the analyses of groundwater sampling performed by Parsons-Brinckerhoff (1982) indicated leachate contamination in the unconfined upper water bearing zone underlying and adjacent to the four landfill sections. Data from the deeper confined aquifer units (Cretaceous sands and bedrock) were limited. Some evidence of leachate migration was indicated in the

upper Cretaceous sand aquifer at Section 1/9, although the magnitude of this influence was not reported to be significant (relative to water quality standards). In most cases, concentrations of leachate indicator parameters in the confined aquifer zones were an order of magnitude lower than in the unconfined upper water bearing zone, reflecting the presence of relatively impermeable strata between the two units.

Wehran Engineering also presented an Executive Summary to the Hydrogeologic Evaluation of the Old Muldoon Area of Fresh Kills Landfill (Wehran Engineering, 1988). The summary was based on the investigations previously reported by Wehran Engineering (1983a) on the hydrogeology of the Fresh Kills Landfill. The report included geological maps, hydrogeologic cross-sections, and permeability test results for each geologic strata. The emphasis of the summary was on the presence, thickness, lateral extent, and permeability of impeding strata within the formation that may act to assist in the protection of deeper groundwater resources.

2.2.3 Wehran (1984)

In the period between 1983 and 1984, Wehran completed investigations at the Brookfield Avenue Landfill and within Landfill Section 1/9; Wehran submitted the Brookfield Avenue Landfill Hydrogeologic Report and the Veterans Avenue West Leachate Control report in November 1983 and September 1984, respectively. The Brookfield Avenue Landfill Report (Wehran, 1983b) was a confirmatory investigation to define the nature of the materials beneath the site and various hydrogeologic characteristics, in addition to providing data for subsequent engineering design. The investigation identified the same major water bearing zones as the 1983 Fresh Kills Hydrogeologic Investigation. Unconfined groundwater flow was toward tidal streams and ditches. The vertical flow direction to the first confined water bearing unit was downward. The horizontal component of flow in that unit was estimated to be northward.

The hydrogeological investigation along Veterans Avenue West (Wehran Engineering, 1984) was conducted to define the stratigraphy and hydrogeology along the approximately 5,000 ft of the Landfill Section 1/9 boundary that abuts Veterans Avenue West. This study identified several areas of leachate seeps, believed to be representative of water table and perched conditions. Lateral flow was estimated to comprise 95 percent of total groundwater flow.

2.2.4 Gibbs & Hill (1989)

In March through June 1989, NYCDOS and Gibbs & Hill, Inc. supervised the advancement of a total of 48 borings at landfill Sections 1/9 and 6/7. The investigation included the installation of shallow monitor wells in the unconfined aquifer zone and the advancement of deep boreholes into rock, along both the perimeter and interior portions of the fill areas. Of the 48 shallow borings, 21 were completed as 4-in. PVC monitoring wells, 18 were completed as 2-in. PVC piezometers, and 9 were completed as multi-level cluster piezometers. The investigation also included subsurface sampling and testing, as well as in-situ hydraulic testing. No formal report of the investigation, beyond preparation of field boring and hydraulic testing logs, was prepared.

2.2.5 Woodward Clyde (1990)

Woodward Clyde Consultants (WCCI) performed a preliminary geotechnical evaluation of the Fresh Kills Landfill between 1989 and 1990. Field investigations conducted by WCCI included the performance of 18 piezo electric cone penetration tests (P-ECPTs) and 22 test borings in Landfill Sections 1/9 and 6/7 during September 1989 and January 1990. The primary goals of this study were to:

- Evaluate the stability of the landfill at various elevations, and under various site conditions.
- Predict appropriate rates of refuse loading.
- Develop specific "alarm values" for critical parameters, i.e., displacement and pore water pressure.
- Establish remedial protocols.

WCCI's first task on the project was the performance of a preliminary geotechnical evaluation of the site. The basic objectives of the task were to assess the suitability of the available geotechnical data and to establish the requirements of field investigations and laboratory testing necessary to obtain additional data. To that end, the evaluation included preliminary engineering analyses to: (a) corroborate the results of previous studies; (b) provide some initial insight into

the controlling factors in the stability of the landfill and assess the suitability of the existing data as they relate to these controlling factors; and (c) develop a detailed field investigation program for obtaining additional data necessary for final analyses and design of the landfill.

All borings drilled at Landfill Sections 1/9 and 6/7 prior to September 1989 were cataloged and referenced to a common coordinate system (Richmond County) as part of WCCI's Preliminary Geotechnical Evaluation Report (1990b). Log data were simplified for geotechnical interpretation, and entered into a database for storage and uniform output log generation. Virtually all of the test holes were advanced through refuse and Recent deposits into glacial till. Piezo cone test results and boring logs were contained in WCCI's Field Investigation Report (1990a).

2.2.6 Wehran EnviroTech (1991)

A hydrogeologic/geotechnical site investigation was performed at the site of the formerly proposed Fresh Kills Ash/Residue Landfill (PASNY) located west of Fresh Kills Landfill Section 3/4 [Figure 1.2] (Wehran EnviroTech, 1991). The overall objectives of the investigation were to provide the information required to support the design of the proposed facility and the preparation of a NYCRR Part 360 Permit Application package for the project. In addition to a regional well survey and literature review, the investigation included the installation of test borings, piezometers, wells and the performance of piezo electric cone penetration tests to define the geology and hydrogeology of the unconsolidated and bedrock strata present beneath the site. A program of continuous groundwater and surface water level measurement collection was also performed, to define the vertical and lateral direction of groundwater flow at the site, and evaluate the influence of tidal changes on the flow gradients.

The investigation identified the following sequence of geologic units beneath the site:

- Ten to 30 ft of fill, including both soil fill and municipal solid waste
- Tidal marsh deposit consisting of peat and organic silts and clays (Recent silt and clay)
- Recent sands

- Lacustrine deposits consisting of laminated silts and clays with some sand seams (Glaciolacustrine silt and clay)
- Glacial till
- Sedimentary rocks belonging to the Newark supergroup, including sandstones, siltstones, shales and claystones.
- Diabase.

Based on the results of in-situ and laboratory determined hydraulic conductivity testing, the refuse, Recent sands, and bedrock were identified as the primary water yielding units on site. The till and glaciolacustrine units confined the bedrock. The tidal marsh deposits appeared to act as a confining layer between the refuse and the Recent sands.

The direction of groundwater flow at the ash/residue site was estimated to be from the east to the west, towards the Arthur Kill. The flow was predominantly horizontal. The tidal influences on the water producing units were not considered to be significant. The most prominent effect was seen in several bedrock wells, and was believed to be due to the pressure effect of tidal loading, rather than direct connection with the adjacent Fresh Kills.

2.2.7 Woodward Clyde (1991)

The most recent report on subsurface investigations at the Fresh Kills Landfill is the Geotechnical Site Characterization Report (Woodward Clyde Consultants, 1991). WCCI reported an identified geologic stratification as follows:

- Recent deposits
  - Recent silt and clay
  - Recent sand
- Glacial deposits
  - glacial sand
  - glaciolacustrine clay
  - glacial till

- Cretaceous sequence
- Residual clay
- Weathered bedrock

The Recent silt and clay and glaciolacustrine clay were concluded to be the most critical units relative to structural stability. An interesting finding of this report, potentially relevant to the Hydrogeologic Investigation, concerns laboratory determination of a significant pressure related decrease in refuse hydraulic conductivity with depth within the landfill mounds. Additional piezometer installation and hydraulic conductivity testing within and below the refuse was performed by Woodward-Clyde during 1992 relative to ongoing slope stability investigations in support of Consent Order Appendix A-10.

3.0 SITE INVESTIGATION PLAN

The Hydrogeological Site Investigations Plan (SIP) was prepared in accordance with the requirements of Appendix A-6 to the Consent Order and 6 NYCRR Part 360-2.11(a), to provide a comprehensive approach to the investigation of geology, hydrogeology, and water chemistry at the Fresh Kills landfill site. The SIP (IT Corporation, 1990a; Attachment 42) was completed and submitted to NYSDEC on December 31, 1990 in accordance with the stipulated Consent Order Milestone schedule. Regulatory agency review of the document resulted in an acceptable determination dated February 4, 1991. The Consent Order Appendix A-4 Landfill Leachate Mitigation Investigation Work Plan (LLMIWP), largely equivalent in scope to the SIP, was submitted to NYSDEC simultaneously with the SIP. The LLMIWP (IT Corporation, 1990b) was determined to be unacceptable due to minor deficiencies by NYSDEC in correspondence dated February 4, 1991. These deficiencies were satisfactorily addressed in a series of clarifications submitted to NYSDEC by NYCDOS on February 22, 1991.

This report section summarizes the content of the SIP, and due to their similarity in scope, the LLMIWP. Reference is provided for the few areas where additional investigation was incorporated into the LLMIWP due to the particular specifications of Consent Order Appendix A-4. These additional investigations have been integrated into the reporting scope of the Hydrogeological Investigation.

3.1 Objectives of the SIP

The SIP defined the objectives of the Hydrogeological Investigation, the scope of all tasks to be performed as described in Consent Order Appendix A-6, the methods and procedures to be used for data collection and analysis following the requirements described in 6 NYCRR 360-2.11, and the deliverables for each task. Table 3.1 summarizes the relationship between the SIP and tasks in Consent Order Appendix A-6 and the requirements of 6 NYCRR-Part 360 - 2.11 (a), (b), (c). Data collected as a result of SIP implementation was identified to be utilized to fully characterize the hydrogeologic conditions at the entire Fresh Kills Landfill and, in part, support the evaluation and design of selected leachate mitigation strategies at Landfill Sections 1/9 and 6/7. In order to meet this purpose, specific objectives were identified in the analysis of site conditions, as follows:

- Define the hydrostratigraphic units beneath the landfill site
- Assess the regional geologic setting of the landfill
- Develop a glacial depositional model that describes the glacial history of the landfill site and local environment, and defines the origin and interrelationship of these glacial deposits, along with their thickness and lateral extent
- Develop a three-dimensional model of the distribution of Cretaceous deposits including thickness, vertical and lateral extent, potential for hydraulic intercommunication, and variation in Cretaceous depositional facies beneath the landfill
- Assess underlying bedrock characteristics including surface configuration, lateral distribution, and nature of primary and secondary features such as fractures, joints, and weathered surfaces
- Develop a regional model of groundwater flow for the defined hydrostratigraphic units beneath the entire Fresh Kills Landfill
- Develop localized models of groundwater flow to evaluate the surface/ground water interaction between tidally-influenced water bodies and defined hydrostratigraphic units and surface water bodies.
- Determine and assess the potential for offsite migration of landfill leachate within the defined hydrostratigraphic units and surface water bodies.
- Develop a geochemical process model for the defined hydrostratigraphic units describing changes in the chemical quality of the ground water as it migrates beneath the landfill site
- Develop information sufficient to support recommendations for design of a long-term monitoring plan.

3.2 Generic SIP Components [SIP Section 3.0]

In addition to those site activities explicitly required by the Consent Order or 6 NYCRR Part 360, other plan components were identified as necessary to complete the required field investigation and data analysis activities. These included such items as site mobilization/ demobilization,

phasing and scheduling of site activities, data management, and implementation of a health and safety plan. These activities were addressed as generic plan components in the SIP.

3.2.1 Mobilization and Scheduling

Mobilization activities were identified to include construction of a field office complex at landfill Section 6/7 consisting of (1) a double-wide trailer serving as office and meeting space for secretarial, data entry, and dedicated field staff as well as site visitors; (2) a single-width trailer serving as a field geotechnical laboratory and for sample storage; and (3) freight containers serving as storage for field equipment and overflow storage for geotechnical samples. Electrical, telephone, water, and sewer service was identified for connection to the on-site field office complex. Additional mobilization/storage areas were identified in other sections of the landfill complex for potential future usage.

Because of the importance of the subsurface investigation program to the successful completion of all project activities, optimal utilization of staff and equipment resources was considered essential to allow for timely completion of field activities and supporting data analysis tasks. This optimization requirement was addressed by (1) identification of site access constraints and proposal of alternative installation strategies, (2) phasing of the borehole and well installation programs to allow for ongoing data review and plan modification, and (3) prioritization of various aspects of the drilling program to allow for the timely initiation of design activities associated with the requirements of Consent Order Appendix A-4. Key activities of the Hydrogeological Investigation were phased to insure for the timely transfer of data to the engineering and surface water investigation teams, afford the opportunity for regulatory review and input into interpretation of field data at successive milestones throughout the drilling program, and allow for sequential modification of subsurface investigation activities to maximize the effectiveness of recovered data.

3.2.2 Data Management

Data management activities were identified to consist of site survey activities, development of a unique sample location and numbering system, implementation of a database management system, and provisions for data transfer. The site survey component was designed to consist of

an initial staking of all boring and well locations, periodic survey of completed installations during drilling and well installation activities, and a final site survey to include locations of new and pre-existent borings, wells, and the land surface along the proposed path of the leachate containment and collection system. All surveying activities were identified to be performed by individuals licensed to perform land surveys in the State of New York.

The SIP detailed a borehole numbering and location system for assignment to all sampling locations (defined in Section 4.0 of this report). This numbering system was developed to allow for tracking and retrieval of information regarding a particular sample or sample location, and to insure that all samples or sample locations were uniquely identified as to the landfill section, year of installation, and organization responsible for the initial installation of the well or boring. The IT Corporation ITEMS database management system was identified to be used to store and process all discrete data collected during the drilling and ground water monitoring portions of the Hydrogeological Investigation. The ITEMS system is a custom application designed around the ORACLE relationship database management system with linkages to common computer software applications such as Lotus 1-2-3, Microsoft Excel, and AutoCAD.

3.2.3 Health and Safety

All field operations have certain associated hazards which may pose significant risks to the health and safety of on-site field personnel. The Health and Safety Plan (HSP) was developed to help identify the potential hazards associated with activities conducted at the site and to provide guidance on reduction of the risk of mishap or injury. The HSP addressed applicable regulations and requirements, scope of work, definition of duties, training and medical surveillance requirements, hazard assessment, hazard control procedures, drilling safety, site entry and security, personnel protection, decontamination, air monitoring, heat and cold stress, and an emergency response plan.

3.3 Boring Program [SIP Section 4.0]

The SIP discussed in detail the installation protocol for the deep center boring program. In addition, sampling, logging, and geotechnical testing protocols for both the center boring and perimeter deep cluster well boring programs were identified.

A total of 50 deep borings within the central portions of the landfill sections are required under the terms of the Consent Order; 15 each in sections 1/9 and 6/7, and 10 each in sections 2/8 and 3/4. Boring locations were selected so as to provide uniform coverage over each of the landfill sections and to take maximum advantage of the presence of existing deep borings. A phased installation approach was identified for the deep boring program at each section to allow for initial stratigraphic correlation activity to proceed with geostatistical analysis of sediment thickness. This approach was designed to allow for repositioning of second phase borings to areas where stratigraphic relationships appear inconsistent or anomalous, or for the elimination of redundant or unnecessary borings. Due to the thickness of the fill throughout the landfill complex and the presence of multiple confined aquifer units underlying it, a combination of hollow stem auger and mud rotary drilling techniques were proposed. Casing-off of refuse deposits would be implemented prior to advancement of the borehole through underlying native deposits. In order to allow for the collection of hydraulic head data from the central portions of the landfill sections, up to three borings in each section were identified to be completed as temporary nested piezometers.

Specific to Consent Order Appendix A-4 requirements, the LLMIWP additionally identified performance of a perimeter boring program around the exterior of Landfill Sections 1/9 and 6/7 (LLMIWP Section 4.1.3). Piezo electric cone penetration testing (P-ECPT) was proposed in lieu of conventional borings for performance of this work, subject to NYSDEC approval following agency review of interim and final piezo cone/lithologic correlation reports.

A soil sampling plan was identified to support lithostratigraphic and hydrogeologic unit characterization, as well as the engineering design component of the LLMIWP. Two-foot soil samples were identified to be collected continuously through Holocene and Cretaceous deposits at all boring locations. Samples were identified to be collected at five foot intervals and at stratigraphic changes in Pleistocene (glacial) deposits. Undisturbed sample collection was specified from each confining unit in all soil borings. Several methods were identified to allow

for undisturbed soil collection, including split spoon, thin wall (Shelby tube), piston type, "Osterberg", Denison, or pitcher type samplers. A geologist was specified to be present at each drilling rig during all drilling, sampling, well construction, and finishing activities. The geologist was required to maintain a detailed boring log for each test hole, as well as a detailed daily completion log to identify and confirm the quantity of contract specified bid items expended each day for cost control and invoicing purposes.

The rationale for selection of soil samples obtained through installation of the center borings and deep perimeter well cluster borings for geotechnical property testing was identified. Test indices included grain size distribution, Atterberg liquid and plastic limits, horizontal and vertical hydraulic conductivity, moisture content, and specific gravity.

Because correlation of individual strata between boreholes using conventional means is often ambiguous, analysis of microfossil data from selected borehole samples was identified as a supplemental tool for stratigraphic analysis. Microfossil investigations were identified to consist of palynological and foramineferal analyses of Quaternary and Cretaceous sections. Downhole geophysical logging of selected deep boreholes (electromagnetic induction [EMI] and natural gamma) was also identified as a further means to assist in the cross-correlation of stratigraphic units between boreholes.

A borehole abandonment specification was identified for implementation following advancement of each deep center borehole to its design depth, and performance of downhole geophysical logging.

3.4 Monitor Well Installation Program [SIP Section 5.0]

With the exception of temporary pump test wells and nested piezometers, all monitor well installation was designed to occur along the perimeter of the four landfill sections. As with the boring program, well installation was designed to proceed in a phased approach. Complete well construction details and design schematics were identified. During Phase I, virtually all shallow well installation was identified to be associated with cluster well installations at 1500 ft intervals around each landfill section. Since adjacent deep borings would have been previously advanced with continuous sampling, sample retrieval was identified to be performed only adjacent to the

screen interval and at changes in stratigraphy within shallow well installations. In the few instances where shallow well construction was not associated with a well cluster, continuous sampling was identified to be performed across the entire length of the borehole.

Based on data available at the time of preparation, intermediate depth perimeter cluster wells were identified to be associated primarily with Landfill Sections 1/9 and 2/8, with screened intervals set into the center of the identified Pleistocene or Cretaceous sand units. Two wells in the same unit were required for installation where the unit thickness exceeded 50 ft.

Deep bedrock cluster wells were identified to be constructed as open boreholes 15 ft into competent bedrock. Downhole geophysical logging of the deep bedrock borehole though native sediments was identified for performance prior to the setting and grouting of permanent casing at depth.

Following installation, a procedure for development of all monitoring wells was identified, based on the measurement and interpretation of water chemistry data obtained over the development interval. Several methods of well development were identified for implementation, including overpumping, overpumping with backwashing, mechanical surging, and air lifting. A standard well development form was identified for the documentation of all development activities and the results of well head water analysis.

In-situ hydraulic conductivity testing was proposed to be conducted in all monitoring wells and piezometers following development using instantaneous discharge (slug) testing methodology. Additionally, a maximum of three long term (24 - 72 hours) aquifer tests were identified for performance at each landfill section. All in-situ test results would be performed to support development of conceptual and numerical ground water flow models for the Fresh Kills Landfill site.

3.5 Ground Water Monitoring [SIP Section 6.0]

The groundwater monitoring program was identified to consist of water level monitoring, water quality analysis, and groundwater temperature monitoring.

The use of dedicated pressure transducers and automatic dataloggers (supplemented by periodic manual measurements) were identified as the means to monitor water levels in the surface water, the water table aquifer, and confined aquifers. In addition to the nested piezometers in the central fill areas, transducers were proposed to be placed in all depth zones of all Phase I cluster well locations. Stilling towers were identified for installation at three locations in waterways adjacent to the fill areas. A minimum of thirty days of synchronous, continuous water level data was proposed to be collected for all monitoring locations during recharge and discharge periods of the annual hydrologic cycle. Periodic data collection form selected locations was additionally proposed to be performed to allow for ongoing ground water flow model development and analysis of diurnal variability and seasonal recharge/discharge variability. Continuous data were identified to be used to develop hydrographs at selected locations for each hydrostratigraphic zone monitored.

Sampling and analytical protocols were identified to perform the two quarterly sampling programs identified in Consent Order Appendix A-6: (1) quarterly sampling and analysis of NYCDOS wells installed in 1989, wells identified through the performance of the Groundwater Monitoring Well and Piezometer Survey Report (IT Corporation, 1990c, 1991b; Attachment 43), and all newly-installed wells for Part 360 Expanded parameters until the development of a long-term monitoring program, and (2) one year quarterly sampling of all NYCDOS piezometers installed in 1989 and off-site water supply wells identified through performance of the Supply Well Survey Report (IT Corporation, 1991a; Attachment 45) for Part 360 Baseline parameters. The quarterly monitoring programs represent a baseline data collection phase in support of the development of a long-term quarterly ground water monitoring program.

Specific to Consent Order Appendix A-4 requirements, the LLMIWP additionally identified a one year quarterly sampling program for Part 360 Expanded parameter analysis at two leachate pumping stations associated with the Veterans Avenue leachate collection system at Landfill Section 1/9.

All samples were identified to be analyzed by the Edison, NJ IT Corporation Analytical Services (ITAS) laboratory for Part 360 Expanded or Baseline Parameters. A Quality Assurance Program Plan (QAPP), analytical Quality Assurance Project Plan (QAPjP), and SIP specific QAPjPs were prepared to address program and project specific procedures for data management, sample

collection, sample custody, analytical protocols, data quality objectives and identification of critical analytical parameters.

In addition to the required Consent Order and 6 NYCRR Part 360 sampling programs, an additional water chemistry sampling program was identified for geochemical analysis. This program was designed to allow for performance of geochemical characterization and flow path analysis, as well as support analyses of the spatial variability of water chemistry in support of the design of the Phase II well installation program.

Temperature measurements were proposed to be obtained within the landfill refuse mound and the underlying hydrostratigraphic units into bedrock for the purpose of evaluating whether temperature variations could effect groundwater flow through variations in density and viscosity. Vertical temperature profiles were identified to be developed for the refuse and in underlying lithologic units to bedrock.

3.6 Data Analysis [SIP Section 7.0]

Four primary areas of data analysis were identified in the SIP: (1) statistical/geostatistical analysis, (2) stratigraphic correlation, (3) water quality characterization, and (4) groundwater flow modeling.

The objectives of the statistical analysis component was identified to fall within two groups. The first concerned those objectives that specifically required the use of statistical or geostatistical tools for their performance. These were identified as (1) estimation of optimal monitor well placement as a result of ongoing geostatistical analysis of water level and chemistry data and the results of preliminary ground water flow modelling, (2) minimizing spatial data variance, (3) periodic computation of information potential maps, and (4) evaluating the nature of variability in leachate character across the site.

The second group of statistical analysis objectives consisted of those analyses for which statistical guidance could improve the quality and interpretation of related investigations. These were identified to include (1) review of preliminary hydrogeological data, (2) determination of sitewide stratigraphic correlation, (3) leachate characterization, (4) distinguishing natural ground water

quality from contamination due to leachate, and (5) statistical and geostatistical analysis to develop strategies for optimizing the scope of sampling design.

The lithologic evaluation of stratigraphy was identified to be accomplished through interpretation of descriptive and downhole geophysical borehole logs, geostatistical modeling of log data, and the results of microfossil analysis. Logs from previous investigations as well as those from the current investigation were proposed to be incorporated in the analysis. Graphical formats to be produced from comprehensive analyses were identified to include cross-sections, structural contour maps, surface contour maps, isopach maps, and paleogeologic maps for all stratigraphic units identified in the field.

Characterization of ground water and leachate was proposed to be performed through the preparation of summary tables culled from the full ITEMS water quality data set. These tables would be prepared for each landfill section and the Fresh Kills complex as a whole. Evaluation of data between monitoring zones, and against regulated standards would be provided. The results of geochemical and indicator parameter analysis would be used to supplement the findings of the water quality based analyses.

A final component of water quality data analysis concerned development of a long-term monitoring program. Plan development was identified to consist of three components: (1) the spatial location of sampling points, (2) the aquifer zones to be monitored, and (3) the analytical parameters to be monitored.

Numerical models of ground water flow were identified for development in order to (1) assist in the design of optimal well spacing and distributions for the long term ground water monitoring program, (2) aid in the leachate mitigation design, and (3) support the development of the three dimensional conceptual model of flow for the entire landfill and underlying hydrostratigraphic units to bedrock.

3.7 Reporting [SIP Section 8.0]

The SIP identified preparation of six documents in accordance with the task and milestone schedule of Consent Order Appendix A-6, as follows: (1) Hydrogeological Literature Review

Report, (2) Monitoring Well and Piezometer Survey Report, (3) Water Supply Well Survey Report, (4) Interim Hydrogeological Report, (5) Draft Final Hydrogeological Report, and (6) Final Hydrogeological Report.

The Hydrogeological Literature Review Report was proposed to consist of a compilation of all available existing information on surface and subsurface conditions at and around the site. The report was identified to form the regional framework within which site-specific information obtained during execution of the SIP would be interpreted, and proposed remedial actions evaluated. (The completed report, with addendum, is contained in this document as Attachment 44.)

The Monitoring Well and Piezometer Survey Report was proposed to consist of a literature and field survey of existing wells and piezometers previously installed throughout the Fresh Kills Landfill, in order to determine the integrity of these wells relative to their continued use in the Hydrogeologic Site Investigation. Pertinent data from each located well would be recorded and compared to existing logs. Only those wells and piezometers for which boring logs and/or monitoring well installation logs were available would be selected for incorporation into the proposed ground water monitoring network. (The completed report, with addendum, is contained in this document as Attachment 43.)

Associated with development of the Water Supply Survey Report, a systematic water supply well survey was proposed to identify all public and private wells and commercial water supply systems located within one mile of the site. Well data would be obtained initially through review of construction logs at appropriate state and local agencies, and the U.S. Geological Survey. (The completed report is contained in this document as Attachment 45.)

The Interim Hydrogeological Report (IT Corporation, Wehran Envirotech, and O'Brien & Gere, 1992a) was identified to include an evaluation of all hydrogeological and geological data obtained prior to the date of report preparation. The report would identify potential gaps in the developing data base, and include recommendations for the scope of additional site investigations that are deemed necessary to satisfy the reporting requirements set forth in 6 NYCRR Part 360. Recommendations for modification of the groundwater monitoring program were proposed for inclusion, based on review of analytical data collected to date.

The content of the Draft Final Hydrogeological Report (IT Corporation, Wehran Envirotech, and O'Brien & Gere, 1993a) was identified to satisfy all reporting requirements of Consent Order Appendix A-6, and 6 NYCRR Part 360-2.11 . The report was stipulated to include the evaluation and interpretation of all data and information gathered during the performance of the Hydrogeological Investigation, incorporating data presented within the Interim Hydrogeological Report and the Literature Review Report. In addition, recommendations for implementation of a long term monitoring program were identified for incorporation in the Draft Final Report.

The Final Hydrogeological Report (this document) was identified to be prepared subsequent to regulatory agency review and comment on the Draft Final document. The final report would incorporate appropriate modifications resulting from the technical evaluation of issues raised during the review process.

4.0 HYDROGEOLOGICAL INVESTIGATION

This report section describes in detail the implementation of field investigation and data recovery tasks identified for performance in the project Hydrogeological Site Investigation Plan (IT Corporation, 1990a), and Landfill Leachate Mitigation Investigation Work Plan (IT Corporation, 1990b). Field investigations included preparation of on and off-site well survey reports, and performance of the deep center boring, perimeter boring (piezo cone), and perimeter well installation programs. Data recovery tasks included soil sampling and geotechnical laboratory analysis, in-situ hydraulic testing, performance of downhole geophysical logging, sampling and analysis of water quality and geochemistry, and collection of continuous surface water level and continuous and manual ground water level (head) data. Prior to initiating the discussion of project task execution, the well/boring numbering system, which forms a consistent basis for location reference throughout this report, is described.

As identified in the Hydrogeological Site Investigation Plan (SIP) and Landfill Leachate Mitigation Investigation Work Plan (LLMIWP), a location numbering system was developed as part of this investigation to accommodate boring and well/piezometer identifiers from all prior subsurface investigations at the landfill, as well as the current Consent Order drilling programs. The location identifier consists of a prefix providing general installation information, and a suffix providing the unique installation identifier.

The numbering system prefix consists of three components: a landfill section identifier, an installation type identifier, and the year of the installation. The first digit identifies the specific section of the landfill within which the boring, well, or piezometer was installed, as follows: 1 = Section 1/9, 2 = Section 2/8, 3 = Section 3/4, 6 = Section 6/7, A = Fresh Kills Ash/Residue Landfill (PASNY) Site (Figure 1.2), B = Brookfield Avenue Landfill (Figure 1.2), and R = Regional boring identified in the Hydrogeological Literature Review (IT Corporation and Wehran Envirotech, 1991a). The second character refers to the type of installation, as follows: B = boring, Z = cone penetration test (piezo cone) boring, W = well, and P = piezometer. The last two digits of the year of installation represent the third and fourth digits of the prefix. The prefix term is separated from the following unique location identifier by a colon (:).

The suffix term consists of the unique location identifier. For all previously installed borings, wells and piezometers, the existing designation has been used. For Consent Order installations completed as part of this investigation, the letters "IT" followed by a three digit number has been used to consecutively number borings, wells and other installations, as follows:

Well/Piezometer:	001-150 = Section 1/9
	151-300 = Section 6/7
	301-400 = Section 2/8
	401-500 = Section 3/4
Boring/P-ECPT:	501-650 = Section 1/9
	651-800 = Section 6/7
	801-900 = Section 2/8
	901-999 = Section 3/4

Within a cluster well location, the numerical code for all installations is the same. However, a letter designation is added after the three digit number to distinguish between shallow ('S'), intermediate depth ('I'), and deep ('D') bedrock wells. At locations where two or more intermediate wells were installed, a sequential number was added to the 'I' designation to distinguish the installations (shallowest intermediate well = 1). In a few cases, a piezometer was installed within a well cluster group; in this case the letter "Z" was appended to the numerical location code.

Examples of the location numbering system are provided below:

1W89:XW9 = Monitor well installed in Landfill Section 1/9 during 1989 with Woodward Clyde/NYCDOS designation of XW9.

6B91:IT651 = Boring installed by IT Corporation in Landfill Section 6/7 during 1991.

1W91:IT005I3 = Monitoring well installed by IT Corporation in Landfill Section 1/9 during 1991. The well is the third (deepest) intermediate well installed at cluster location IT005.

1P91:IT013Z = Piezometer installed by IT Corporation in Landfill Section 1/9 during 1991 adjacent to well cluster IT013.

6Z91:IT731S = Shallow Piezo Electric Cone Penetration Test (P-ECPT) performed in Landfill Section 6/7 during 1991.

The only exceptions to this numbering system are represented by a series of aquifer test wells installed in 1992, which use a unique location identifier (suffix) of "ATW" followed by the letter codes "S", "I", or "D" depending on depth (refer to report section 4.3.2).

4.1 Survey Reports

Tasks (8), (9), and (10) of Appendix A-6 to the Consent Order require literature review and performance of field reconnaissance to support development of a series of reports ancillary to the Hydrogeological Investigation Report, as follows: Hydrogeological Literature Review Report, Supply Well Survey Report, and Groundwater Monitoring Well and Piezometer Survey Report. The Hydrogeological Literature Review Report (IT Corporation and Wehran EnviroTech, 1991a; Attachment 44) was completed on March 15, 1991 in accordance with the Consent Order Milestone schedule, and accepted with a series of clarification requests by NYSDEC in correspondence dated May 13, 1991. These clarifications were addressed through preparation of an addendum literature review report dated September 13, 1991 (IT Corporation and Wehran EnviroTech, 1991c). This document was accepted by NYSDEC in correspondence dated September 26, 1991. It should be noted that the scope of the Appendix A-6 Task (8) Hydrogeological Literature Review additionally satisfies the LLMIWP requirements of Consent Order Appendix A-4, Task (11).

Due to the volume and detailed technical nature of the Hydrogeological Literature Review Report, its content is not fully summarized within this document. Excerpts from the literature review have, however, been incorporated previously under Section 2.0 (Overview of Pertinent Literature), and are integrated where appropriate in the technical presentations contained in Sections 5.0 (Geology) and 6.0 (Hydrogeology) of this investigation report. Summary discussions of the Groundwater Monitoring Well and Piezometer Survey and Supply Well Survey Reports are provided below.

4.1.1 Ground Water Monitoring Well and Piezometer Survey Report

In accordance with Task (10) of Appendix A-6 to the Consent Order, a survey of all wells and piezometers installed in Sections 1/9, 6/7, 3/4 and 2/8 of the Fresh Kills Landfill, was performed. A report on the investigation (IT Corporation, 1990c; Attachment 43) was prepared and submitted to

NYSDEC on December 31, 1990 in accordance with the Consent Order milestone schedule. As a result of this study, 41 of the 143 wells and piezometers scheduled for investigation were located and 38 were verified destroyed by a combination of a literature review, fill progression assessment, and ground survey. The remaining 64 wells and piezometers were not located and were assumed destroyed. Of the 41 wells located through the survey, 37 represent wells and piezometers installed by NYCDOS in 1989. The remaining four located installations represent piezometers installed in 1981 and 1982 by NYCDOS in Landfill Sections 6/7 and 3/4. All located wells/piezometers were screened either within refuse or silt and clay.

Review of this document by NYSDEC resulted in the issuance of an acceptable determination on February 4, 1991, contingent upon performance of additional field reconnaissance to locate wells and piezometers not verified destroyed in the original report. Some of the wells originally considered to be "verified destroyed" were re-evaluated during this supplemental investigation, since this designation included some wells/piezometers that had been eliminated based only on visual reconnaissance. While all well and piezometer locations had been field checked in the original survey, additional field reconnaissance during the winter months was identified as an appropriate action to minimize the effects of high vegetation that may have obscured well identification during the initial survey.

For the purpose of the addendum survey only unlocated wells screened in natural overburden soils or bedrock were scheduled for additional field reconnaissance (wells screened in refuse were excluded from the addendum survey as there is no potential for downward migration of leachate into underlying soils through these wells or their annular space and consequently, no need for formal abandonment.). As a result, a subset of 33 on-site wells/piezometers and 4 off-site wells were identified for further investigation. Field reconnaissance was performed over the period February - May, 1991. After identifying the general location of each well, the field crew performed a thorough search of the immediate area. As with the initial survey, if the well was located, it was opened and field measurements were recorded. These measurements included height of outer protective casing above ground surface (stickup), difference in height between inner and outer casings, depth to bottom of the well/piezometer, and depth to water.

The results of the supplemental survey were documented in an addendum report completed on August 31, 1991 (IT Corporation, 1991b; Attachment 43). An additional 7 of the 37 wells/piezometers selected for additional reconnaissance were located. Five of these wells, located

within Landfill Sections 1/9, 6/7 and 3/4, were recommended for abandonment (abandonment was performed during February and October 1992). The remaining two wells, located off-site, were identified for potential use in the collection of water level data to support groundwater flow modeling investigations.

Of the 30 wells/piezometers not located in the addendum survey, 20 were verified destroyed by field reconnaissance and published reports. The remaining 10 wells/piezometers continued to elude detection following the intensive, supplemental field reconnaissance. While tangible evidence regarding their destruction was not found, the intensity of the search, the date and method of construction of the wells/piezometers, and the nature of site activities argue strongly against their existence. Acknowledgement of the conclusions of the addendum survey report were provided by NYSDEC in correspondence dated September 27, 1991.

4.1.2 Supply Well Survey Report

In accordance with Task (9) of Appendix A-6 to the Consent Order a supply well survey was conducted for the area within a one mile radius of the Fresh Kills Landfill. The purpose of this survey was to identify public or private potable water supply wells capable of providing representative sample (and incorporation into the Consent Order Appendix A-6, Subject 12, one year quarterly sampling program) that may be potential receptors of contamination migrating from the landfill. Well permit records of the New York City Department of Health - Bureau of Engineering, and New Jersey Department of Environmental Protection - Division of Water Resources were reviewed and screened for inclusion in the survey. In addition, literature review and contact with major land owners in the Staten Island project area was performed in an attempt to identify non-permitted wells.

A total of 356 well permits or records were initially reviewed. Of these, only 12 were identified as potentially applicable for inclusion in this survey due to construction and location within the one mile survey boundary. Information obtained from direct contact with (or unsuccessful attempts to locate) the owners of each of these wells, resulted in the identification of only two viable and potentially accessible supply wells. These wells are: (1) an industrial supply (truck wash water) well operated by the NYCDOS at the Muldoon Avenue garage on Fresh Kills Landfill property (Section 1/9) that draws water from the Triassic Stockton bedrock formation (identified as well No. 12 in the survey report), and (2) an inactive pond supply (irrigation) well owned by the South Shore Golf Course

(located approximately one half mile south of Landfill Section 1/9), believed to be screened in the Cretaceous sand (identified as well No. 11 in the survey report; location R-101 on Sheet 5.1 in this report).

The Golf Course well is of special interest to the hydrogeological investigation since, based on discussions with facility operations personnel, it was abandoned after several years of operation due to increasing chloride content. The irrigation well was equipped with a 475 pgm turbine pump. Its operation would have resulted in significant drawdown within the Cretaceous sand unit, affecting lateral and vertical groundwater flow over a large surrounding area (including the Fresh Kills Landfill area). As discussed in more detail in Sections 6.0 and 7.0 of this report, it is likely that pumpage of the irrigation well is at least partly responsible for the presence of saline intrusion within the Cretaceous sand unit underlying Landfill Section 1/9 (i.e., induced recharge of saline surface waters through the Arthur Kill river channel and vertically interconnected Recent/glacial sand deposits to the Cretaceous sand).

The Supply Well Survey Report (IT Corporation, 1991a; Attachment 45) was completed on March 15, 1991, and accepted by NYSDEC in correspondence dated April 12, 1991, with a request for several minor clarifications. Clarification responses were submitted by NYCDOS to NYSDEC on May 13, 1991. One year of quarterly sampling of the NYCDOS industrial supply well was initiated during the July 1991 sampling quarter. Additional field assessment of the South Shore Golf Course well indicated that the configuration of internal pump components, the method of abandonment, and the subsurface location of the pumpworks and well head would not allow for sample collection.

4.2 Boring/Nested Piezometer Program

In accordance with Task (6) of Appendix A-6 and Task (1) of Appendix A-4 to the Consent Order, an exploratory "deep center" boring program was implemented to provide lithologic data beneath each of the four Fresh Kills landfill sections. Installation of a total of 50 borings was stipulated in the Consent Order; 15 each in Landfill Sections 1/9 and 6/7, and 10 each in Sections 2/8 and 3/4. As discussed in detail in the following subsections, the boring program followed a phased installation approach to allow for preliminary data analysis, and the incorporation of regulatory agency input into the design of the final installation plan. As a result of this process, the location of a number of borings was shifted to improve data recovery, and 5 borings were eliminated from the program as

unnecessary. All drilling in both phases of this program was performed by Empire Soils Investigations, Inc. using Failing F-10, CME-75, and Mobile B-61 drilling rigs.

Figure 4.1 illustrates the typical drilling specification for installation of the deep center borings. In accordance with the SIP, boreholes were advanced through the refuse mound with 10 1/4 or 11 7/8 in. OD hollow stem auger equipment. Stabilizers were used periodically in order to maintain a straight hole alignment. Five, six or eight in. temporary steel or PVC casing was set and grouted with bentonite slurry five ft into the first confining layer below refuse prior to advancement to bedrock. Beneath the refuse, boreholes were advanced with 2 15/16 or 3 1/4 in. roller bits using water or Wyoming bentonite mud as the drilling fluid. An organic drilling mud (Revert) was occasionally used in the drilling fluid for the piezometer installations, where borehole collapse was anticipated in the screen interval. The soil sampling protocol (Section 4.4.1) was initiated at the refuse/native sediment interface, and continued to bedrock. Subsequent to reaming of the borehole to a 5 1/4 in. diameter, and the installation of temporary 4 in. steel casing, 15 ft of rock core was generally obtained using wire line techniques. At selected locations, downhole geophysical logging (Section 4.6) was performed prior to the initiation of rock coring. Depending on the cohesiveness of the soil, logging was performed either before or after borehole reaming.

Following rock core recovery the borehole was abandoned, as follows: (1) tremie grouting of the borehole in bedrock and through overlying sediments into the lower 10 ft of refuse with a cement/bentonite grout mix (5 percent bentonite maximum), (2) grout set-up period (generally overnight), and (3) backfilling of the remaining borehole through the refuse mound with previously excavated materials. Where temporary casing could not be removed from the refuse mound borehole, the exposed casing was cut at or below the ground surface.

At selected locations within each landfill section, one or more borings were converted to piezometers or nested piezometers for the purpose of recovering hydraulic head (water level) information from within the refuse mound, and native sediments underlying the mound. Figure 4.2 illustrates the drilling specification for the most complex (3 stage) nested piezometer installation. Due to difficulties encountered during drilling and the setting of casing, many of the piezometers were installed in nests of two, or as single installations.

The locations of all borings and nested piezometers installed as part of the deep center boring program are indicated on Figures 4.3 (Section 6/7), 4.4 (Section 1/9), 4.5 (Section 2/8), and 4.6

(Section 3/4)[1]. These figures also indicate the initial proposed location for all installations, as identified in the SIP. Modifications to the SIP location plan were the result of the referenced phased installation plan; the rationale for plan modifications are provided in the landfill section specific discussions below. Table 4.1 is a summary presentation of pertinent construction data for all boring and nested piezometer installations. These data include installation date, depth, and horizontal/vertical survey control for borings, and additionally, screen interval depth and elevation, screened interval stratigraphic unit, and screen diameter for nested piezometer installations. Final boring logs of all installations, corrected for uniformity with areal stratigraphic interpretations, are contained in Appendix B. Original field logs are contained in Attachment 1, and a photographic log of recovered bedrock core is contained in Attachment 2.

4.2.1 Phase I Drilling Programs

With several exceptions, installation of Phase I borings closely followed the location plan identified in the SIP. Minor adjustments were routinely made in the field based on access and terrain considerations; major adjustments were occasionally necessary due to the constraints imposed by ongoing landfilling activities. All modifications to the Phase I location plan were evaluated in the field with regulatory agency oversight personnel prior to initiation of drilling activity.

During each phase of the drilling program, the nature of encountered subsurface materials or equipment/borehole stability problems periodically resulted in necessary modification to the drilling/sampling protocol. Where implemented, such modifications are described in each of the following landfill section discussions.

4.2.1.1 Landfill Section 6/7

The Phase I center boring program was initiated at Landfill Section 6/7 on January 17, 1991, and completed on February 20, 1991. Eight borings were completed during this phase, as follows: IT651, IT652, IT655, IT656, IT659, IT660, IT663, and IT665. [The location code prefix for all of these

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[1]Figures 4.23 through 4.26 provide more detailed location maps of these and all other installations performed under the Consent Order.

locations is: 6B91.] Boring IT659 was completed as a nested piezometer, with screened communication zones within the serpentinite bedrock, and approximately five ft below the water table in the refuse mound.

Downhole geophysical logging was performed in all borings except IT656 and IT659. A total of 26 disturbed (split-spoon) samples and 13 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered during this phase. Ten to 16 ft of rock core was obtained at all borings except IT652, where only 6.5 ft of core was obtained due to poor recovery.

4.2.1.2 Landfill Section 1/9

The Phase I center boring program was initiated at Landfill Section 1/9 on February 15, 1991 and completed on June 6, 1991. Eight borings were completed during this phase, as follows: IT501, IT503, IT505, IT506, IT509, IT510, IT511, and IT514. [The location code prefix for all of these locations is: 1B91.] Boring IT510, initially identified as a Phase I nested piezometer, could not be completed due to the presence of a thick layer of metallic debris at depth below the area identified for installation. After several attempts, the location of boring IT510 was shifted to the southwest, and nested piezometer installation was deferred to Phase II, where IT507 was substituted as the piezometer location for IT510. Boring IT506 had to be terminated at 150' due to a broken auger; the boring was abandoned, moved 20 ft north, and redrilled.

Downhole geophysical logging was performed in all eight boreholes. A total of 37 disturbed (split-spoon) samples and 13 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered during this phase. Twelve to 16 ft of rock core was obtained from all boreholes except IT501, where only six feet of core was obtained due to poor recovery. Drilling/sampling program modification was required as follows:

- IT509 and IT511: Loss of circulation in the overburden material encountered below the depth of the 4-in. temporary surface casing necessitated placement of a 3-in. temporary steel casing through the 4-in. casing. The smaller diameter of the steel casing precluded collection of undisturbed (shelby tube) sample.

- IT510: A 4-in. temporary steel casing was set through the 5-in. temporary surface casing to a depth of 129 ft. The inner casing was installed to prevent refuse from entering the borehole, which had previously inhibited soil sample recovery. Soil samples from the 103' - 129' depth interval were difficult or impossible to recover due to the presence of the refuse in the bottom of the borehole.

4.2.1.3 Landfill Section 2/8

The Phase I center boring program was initiated at Landfill Section 2/8 on April 22, 1991 and completed on May 8, 1991. Four borings were completed during this phase, as follows: IT801, IT802, IT805, and IT809. [The location code prefix for all of these locations is: 2B91]. The fifth scheduled Phase I boring (IT806), designated as a nested piezometer, could not be installed during spring 1991 due to the location and high level of activity of landfill operations occurring at Section 2/8 within that time frame.

Downhole geophysical logging was performed in all four boreholes. A total of 9 disturbed (split-spoon) samples and 6 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered during this phase. Ten to 16 ft of core was obtained from all boreholes except IT805, where no core was recovered due to casing breakage in the borehole.

4.2.1.4 Landfill Section 3/4

The Phase I center boring program was initiated at Landfill Section 3/4 on April 8, 1991 and completed on April 30, 1991. Four borings were completed during this phase, as follows: IT901, IT903, IT908, and IT909. [The location code prefix for all of these locations is: 3B91]. The fifth scheduled Phase I boring (IT907), designated as a nested piezometer, could not be installed during spring 1991 due to the location and high level of activity of landfill operations occurring at Section 3/4 within that time frame.

Downhole geophysical logging was performed in all four boreholes. A total of 8 disturbed (split-spoon) and 7 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered during this phase. Approximately 15 ft of rock core

was obtained from borings IT901, IT903 and IT909. No core was recovered from boring IT908 due to casing collapse and breakage in the borehole. No undisturbed (shelby tube) sample was obtained from IT903 because of the need to place a 3-in. temporary steel casing through the temporary 4-in. PVC casing. This was done because the PVC casing broke during the drilling operation.

4.2.2 Phase II Drilling Programs

Following completion of Phase I borings at each landfill section, newly recovered sample data was combined with the results of prior subsurface investigations (and perimeter Phase I well borings where available) to develop preliminary stratigraphic interpretations of the lateral and vertical distribution of encountered geologic units. The results of these analyses were then discussed with oversight regulatory agency personnel in order to define a location strategy for Phase II boring installation. Phase II installations were designed to address identified data gaps or anomalies identified through performance of the Phase I program, or inconsistencies noted between the results of current and prior investigations. Formal modification plans were developed for the Phase II boring programs at Sections 6/7, 2/8, and 3/4, and included the modification of Phase II boring locations identified in the SIP, as well as the elimination of borings in selected areas due to the consistency of the subsurface lithology. As a result of the complexity of the stratigraphy underlying Section 1/9, no formal modification to the SIP location plan was identified; however, several of the Phase II borings were shifted in the field to improve data recovery following stratigraphic analysis of Phase I borings and completed perimeter deep well borings.

4.2.2.1 Landfill Section 6/7

Modifications to the SIP Phase II installation plan for this landfill section was identified in the "Phase I Milestone Report: Center Boring Program-Landfill Section 6/7" (IT Corporation, Wehran Envirotech, IDT, Inc.,1991). This report documented the continuity and thickness of the primary confining unit (low hydraulic conductivity glaciolacustrine silt and clay) underlying this landfill, and identified two anomalous areas requiring further investigation:

(1) A bedrock "saddle" in the southernmost portion of the site in the vicinity of a contact between serpentinite and schist bedrock. South of this saddle, depth to bedrock was

noted to increase significantly, and the presence of Cretaceous deposits (not identified elsewhere under the landfill section) were encountered.

(2) A rise in bedrock elevation corresponding with a thinning of the glaciolacustrine clay in the northeast-central area of the landfill section, in the presumed vicinity of a contact between sandstone and serpentinite bedrock. While a general rise in bedrock surface elevation to the east was apparent, the identified area was anomalous through comparison with adjacent borings oriented along a north-south axis.

Installation plan modifications consisted of the following components, as illustrated on Figure 4.7: (1) elimination of borings IT653, IT658, IT661, and IT662 due to the documented continuity of the glaciolacustrine confining layer, (2) shifting of the location of borings IT654, IT657, and IT664 to "bracket" the anomalous bedrock high in the northeastern area of the landfill section and improved spatial coverage in areas of eliminated borings, and (3) addition of new boring (IT666) in the southern portion of the landfill in the vicinity of the identified bedrock "saddle"

The Phase II center boring program was initiated on May 1, 1991, and completed on June 21, 1991. Four borings were completed during this phase, as follows: IT654, IT657, IT664, and IT666. Boring IT664 was completed as a nested piezometer with communication zones in the serpentinite bedrock and approximately five ft below the water table in the refuse. Boring IT654 was completed as a deep piezometer screened in sandstone; a separate shallow piezometer screened in the refuse was constructed adjacent to this installation due to upper borehole collapse and casing lodgement encountered during deep boring advancement (caused by the presence of a gravel/cobble layer). Abandonment of the IT654 deep piezometer was performed during February 1992 as a result of casing breakage believed to have been caused by the shifting of fill deposits.

Downhole geophysical logging was performed in borings IT655, IT657, and IT664. A minimum of 14 ft of core was obtained at all boring locations. A total of 6 disturbed (split-spoon) and 8 undisturbed (shelby tube or tube lined spoon) samples were selected from all samples recovered during this phase for geotechnical laboratory analysis.

4.2.2.2 Landfill Section 1/9

As noted earlier, no formal plan for modification of Phase II boring locations identified in the SIP was developed for Section 1/9 due to the complexity of the stratigraphy underlying the landfill, and the consequent need for extensive and uniform coverage in the subsurface investigation. A number of boring locations were shifted in the field to avoid areas where drilling difficulties were encountered repeatedly at depth, or to improve areal coverage in regions where ongoing landfill activities had previously constrained access during the Phase I installation program.

The Phase II center boring program was initiated on April 30, 1991, and completed on September 19, 1991. (Due to access constraints, several Phase II borings were initiated prior to the completion of the Phase I installation program.) Seven borings were completed during this phase, as follows: IT502, IT504, IT507, IT508, IT512, IT513, and IT515. Boring IT504 was completed as a nested piezometer with communication zones in the sandstone bedrock, Cretaceous sand, and approximately five feet below the water table in the refuse mound. Boring IT507 was completed as a deep piezometer in the sandstone bedrock. Breakage of interior temporary casing during removal precluded installation of additional piezometers in the deep borehole. Consequently, an intermediate depth piezometer screened in a thin Cretaceous sand lens, and a refuse zone piezometer were nested in an adjacent borehole. Boring IT515 was completed as a nested piezometer with communication zones in the sandstone bedrock and a lower Cretaceous sand. A second nested piezometer screened in an upper Cretaceous sand and the refuse mound was installed adjacent to the deep piezometer nest.

Downhole geophysical logging was performed in borings IT502, IT504, IT507, IT508, and IT512. A total of 29 disturbed (split-spoon) samples and 11 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered during this phase. Ten to 19 ft of rock core was obtained from all boreholes except IT504 where only 7 ft of core was obtained due to poor recovery. In addition, no core was obtained from boring IT513 due to failure of the drilling rig drive mechanism.

4.2.2.3 Landfill Section 2/8

Modifications to the SIP Phase II installation plan for this landfill section was identified in the "Phase I Milestone Report: Center Boring Program-Landfill Sections 2/8 and 3/4" (IT Corporation and Wehran Envirotech, 1991b). This report identified the presence of thick glacial deposits (lacustrine silts and clays and till) in the northern and eastern areas of the section. These deposits thin to the

south and west, and are largely replaced by a gradually thickening sequence of Cretaceous sediments (silt, clay, and sand). An anomalous condition was identified in the north-central area of Section 2/8, where glacial lacustrine deposits appear to thin rapidly with a corresponding rapid increase in the Cretaceous sequence. Unlike the strategy implemented for program design at Section 6/7, a two stage approach to the design of the Phase II program was followed for Section 2/8 due to the additional lithologic complexity of this landfill.

Interim installation plan modifications consisted of the following components, as illustrated on Figure 4.8: (1) elimination of borings IT803, IT807, and IT810 due to control provided by existing Phase I installations and perimeter cluster well installations proposed for this area, (2) shifting of boring IT808 to the southwest to provide additional data in the area of the sharp contact between glacial and Cretaceous deposits, and (3) addition of a new boring (IT811) in the southwest portion of the landfill to provide lithologic control in this area (associated with this action was the shifting of well cluster IT307 to the southeast, along Arthur Kill Road).

The interim Phase II center boring program for Section 2/8 was initiated on July 3, 1991, and completed on August 13, 1991. Four borings were completed during this phase, as follows: IT804, IT806 (a deferred Phase I boring), IT808, and IT811. Boring IT806 was completed as a nested piezometer with communication zones in the serpentinite bedrock, Cretaceous sand, and approximately five feet below the water table in the refuse mound.

Downhole geophysical logging was performed in borings IT804, IT806, and IT808. A total of 21 disturbed (split-spoon) and 5 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered during this phase. A minimum of 12 ft of core was obtained from borings IT804 and IT811; approximately 9 ft of core was obtained from borings IT806 and IT808 due to poor recovery.

Analysis of data recovered from the interim Phase II program confirmed the results of earlier section-wide analyses, including the presence of a (presumed) sharp erosional surface in the north-central area of the landfill, and a potential contact between refuse deposits and Cretaceous sand. In order to evaluate the potential for leachate migration across this contact, boring IT803 was identified for installation in this area, as indicated on Figure 4.8. Installation of this boring was completed on September 10, 1991. No rock core was obtained from this location, as the rationale for installation focused on unconsolidated sediment lithology.

4.2.2.4 Landfill Section 3/4

Modifications to the SIP Phase II installation plan for this landfill section was identified in the "Phase I Milestone Report: Center Boring Program-Landfill Sections 2/8 and 3/4" (IT Corporation and Wehran Envirotech, 1991b). This report identified the presence of continuous or nearly continuous deposits of Recent sand (below refuse), glaciolacustrine silt and clay (below the Recent sand), and residual clay (overlying the bedrock). An anomalous condition was noted in the southeast/central portion of the site, where Recent sand and glaciolacustrine clay are absent from the stratigraphic column near the presumed location of a subsurface till mound (identified as an upland area surrounded by marsh in historical topographic maps). As with Section 2/8, a two stage approach to the design of the Phase II program was followed for Section 3/4 due to the additional lithologic complexity of this landfill.

Interim installation plan modifications consisted of the following components, as illustrated on Figure 4.9: (1) elimination of borings IT905, and IT906 due to observed lithologic continuity provided by previously installed Phase I borings IT903 and IT909, (2) shifting of boring IT907 (deferred Phase I boring) west to the area vacated by elimination of IT905 and IT906, shifting of boring IT910 to the northeast, and shifting of boring IT904 to the west/southwest to the vicinity of the postulated till mound, where stratigraphic discontinuities were noted.

The interim Phase II center boring program for Section 3/4 was initiated on June 24, 1991, and completed on August 12, 1991. Four borings were completed during this phase, as follows: IT902, IT904, IT907 (deferred Phase I boring), and IT910. Boring IT910 was completed as a nested piezometer with communication zones in the sand/siltstone bedrock, and approximately five feet below the water table in the refuse mound. A separate intermediate depth piezometer was installed adjacent to the deep installation, screened in the Recent sand.

Downhole geophysical logging was performed in borings IT902 and IT904. A total of 15 disturbed (split-spoon) and 3 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered during this phase. Thirteen to 24 ft of core was obtained from borings IT902, IT904, and IT910; approximately 7 feet of core was obtained from boring IT907 due to poor recovery.

Analysis of data recovered from the interim Phase II program confirmed the results of earlier section-wide analyses, including discontinuity in the stratigraphic sequence in the southeastern area of the landfill. In order to further evaluate the extent of this discontinuity (and the potential for vertical leachate migration), boring IT906 was identified for installation in this area, as indicated on Figure 4.9. Installation of this boring was completed on August 28, 1991. No rock core was obtained from this location, as the rationale for installation focused on unconsolidated sediment lithology.

4.2.3 Piezo Electric Cone Penetration Testing

Task (1) of Appendix A-4 to the Consent Order requires the installation of shallow and deep exploratory borings along the perimeter of Landfill Sections 1/9 and 6/7. Shallow exploratory borings are specified to be installed at 200 linear foot intervals and to penetrate to a minimum of five feet into the uppermost confining layer. Deep exploratory borings are specified to be installed at 1000 linear foot intervals and are to penetrate to a minimum of five feet into the second uppermost continuous confining layer.

The objective of the perimeter boring program is to provide detailed lithologic control along the alignment of stipulated perimeter leachate control facilities, with special consideration given to the areal continuity of the uppermost confining unit(s), as well as the depth, thickness, and permeability of the confining unit(s). Discussion of the perimeter boring program has been integrated into the Hydrogeologic Report to improve the interpretation and presentation of stratigraphic relationships beyond that feasible from data derived from the Consent Order Appendix A-6 investigation programs alone. This integrated analysis benefits the objectives of both the Appendix A-6 Hydrogeological Investigation and the Appendix A-4 Landfill Leachate Mitigation Investigation.

In accordance with the Landfill Leachate Mitigation Investigation Work Plan (IT Corporation, 1990b), piezo electric cone penetration testing (P-ECPT) was proposed in lieu of the drilling of soil borings along the Landfill Section 6/7 and 1/9 perimeters. Piezo electric cone penetration techniques have previously been used successfully by NYCDOS at Landfill Section 1/9 in work performed in 1989 under the direction of Woodward-Clyde Consultants by Applied Research Associates (ARA) of South Royalton, VT (Woodward-Clyde, 1990a, 1990b, 1991). The P-ECPT technique in lieu of soil borings for this investigation was provisionally accepted by NYSDEC, pending review of the results of correlation testing between P-ECPT's and soil boring logs derived from the perimeter well

installation program. In December 1992, a detailed review of the stratigraphic correlation of P-ECPT data with control borings installed during Phase I and II of the well installation program was performed with NYSDEC. With the exception of approximately 15 locations, where P-ECPT test logs provided incomplete or ambiguous data, the cone penetration test program was identified as complete relative to the requirements of the Consent Order Appendix A-4 perimeter boring program. Drilling of conventional borings to address data gaps identified through stratigraphic and engineering review was performed during March and April 1993.

The alignment of the piezo electric cone penetration tests performed for this investigation generally followed the trace of containment facilities proposed in the 1985 Landfill Operations Plan prepared for NYCDOS by Wehran Engineering, exclusive of the area represented by the Marine Terminal Plant 1 in the northwestern corner of Landfill Section 1/9. In addition, the location of the piezo electric cone penetration tests around the southeastern section of Landfill Section 6/7 and two areas along the northern perimeter of Section 1/9 were adjusted to accommodate the revised grading plan for these landfills developed by SCS Engineers (1991) for NYCDOS. Along perimeter zones that border on tidal streams or wetlands, elevation 10 (Richmond County High Water datum) was selected as a guide to represent the boundary along which all testing was performed, with the exception of areas that presented severe access constraints. Elevation 10 generally represents the limit between uplands and wetlands, the intertidal zone, and the floodway, as well as the exterior footprint of the landfill.

The final correlation test report for Landfill Sections 6/7 and 1/9 is contained in Appendix C, and the final report of the complete perimeter piezo electric cone penetration test program is contained in Appendix D. In addition to detailing test log, texture analysis, and physical property data, the final report also provides the results of pore pressure dissipation testing, and tabulates formation hydraulic conductivity estimates derived from these tests. A summary of installation details for all penetration tests is contained in Table 4.2. Final logs of conventional borings installed along the perimeter of the landfill sections to supplement the test penetration data are contained in Appendix B.

4.2.3.1 Piezo Electric Cone Penetration Test Technology

An electric cone penetrometer consists of an instrumented probe which is forced into the ground using a hydraulic load frame mounted on a truck. Ballast in the form of steel weights is added to the truck frame to serve as a reaction mass. The basic probe consists of a conical tip and friction sleeve

which provide independent measurements of vertical tip resistance and frictional resistance on the sides of the probe as a function of depth. Internal strain-gaged load cells measure the vertical and frictional resistances. The ARA equipment has been modified to include a pressure transducer mounted in the cone of the probe to measure pore water pressure as the probe is pushed into the ground (Figure 4.10). The probe or cone design conforms to ASTM D3441-86 allowing ready comparison of acquired data to published information. The generated data is displayed on a computer screen during acquisition, and recorded on a computerized data storage system for subsequent processing. Typical processed piezo cone test output is illustrated on Figure 4.11.

The advantages of the piezo cone test technique during geological and environmental subsurface investigations include: a relatively non-destructive, low impact test procedure; immediate, computerized data reporting and interpretation; continuous profiling; high degree of personal safety; and a lower cost and higher productivity as compared to traditional boring techniques.

Data acquired with the pore pressure modified electric cone penetrometer can be utilized to estimate soil classification and stratigraphy, as well as a wide range of in-site soil characteristics, including shear strength, consolidation properties, and lateral permeability. Specifically, the equipment can yield the following data:

- Cone resistance or end-bearing resistance q_c - The resistance to penetration developed by a 1.4 in. diameter, 60° cone, equal to the vertical force on the cone divided by its horizontally projected area. As soil bearing capacity is primarily dependant on grain size, this data is commonly utilized to classify soil texture and estimate a wide range of in-situ soil properties, including shear strength.

- Friction resistance, fs - the resistance to penetration developed along the sides of a 1.4 in. diameter, 5.25 in. friction sleeve, equal to the vertical force applied to the sleeve divided by its surface area. This resistance is a function of friction, and adhesion. This data is utilized for the classification of soil texture.

- Friction ratio, R_f - the ratio of friction resistance to cone resistance expressed as a percent. This data is utilized for the classification of soil texture. A low ratio is an indication of sands due to the very high cone resistance; the friction ratio is high in clays.

- Pore pressure, u - the soil water pressure response to penetration. In order to perform pore pressure measurements, a low compressibility, viscous, fluid saturates a cavity beneath the transducer and a teflon filter assembly. Pressure changes in the

pore fluids cause nearly simultaneous pressure changes in the pore pressure transducer. The pressure response to penetration depends on soil saturation, permeability and compressibility. Pressure changes measured during penetration are a result of the volumetric distortion of the soils induced by penetrometer advancement. The dissipation rate and time is a function of the static pore fluid pressure and the lateral permeability of the soil strata encountered.

For a sandy layer, the dynamic pore pressure approximates the static pore pressure because the high permeability of the sand allows rapid dissipation of any excess pore fluid pressure caused by penetration. In a clayey soil, an increase in dynamic pore fluid pressure will be observed as a result of volumetric distortion induced by penetrometer advancement. Because the permeability of the formation is low, dissipation cannot occur as rapidly.

These test data enhance the ability to distinguish individual soil strata. They allow for identification of extremely thin strata that may not appear using conventional drilling and sampling techniques.

- Dissipation Testing - A dissipation test measures pressure decay over time with the cone in a stationary position. Over time, the pressure measured will approach the static pressure of the formation fluid. In a silty sand, the excess pressure normally dissipates in a matter of minutes. However, in a tight clay layer, pressure dissipation may take hours. This test can be used to estimate the in-situ static pore fluid pressure as well as lateral permeability, drainage conditions, and consolidation properties;

- Pore pressure ratio, B_q - the ratio of the generated pore pressure to the cone resistance. This ratio is useful in the estimation of soil compressibility and permeability effects. Low pore pressure ratios will be generated for sandy soils and higher ratios will be generated for higher compressibility clay soils. These data are most useful for the classification of lower permeability soils.

4.2.3.2 Test Program

The Piezo-Electric Cone Penetration Test (P-ECPT) program was initiated on July 17, 1991 and was conducted during several time periods through March 27, 1992. A total of 191 P-ECPT's were completed, including 14 correlation P-ECPTs, seven each in Section 6/7 and Section 1/9. An additional nine conventional borings complimenting the P-ECPT program were completed in April and October, 1992. The locations of all P-ECPTs and conventional borings installed as part of this program are indicated on Figures 4.12 (Section 6/7) and 4.13 (Section 1/9).

A truck mounted cone penetration testing (CPT) unit was utilized to initiate the program. This unit is capable of accessing areas with a relatively level grade and firm subgrade. An all terrain unit was used for areas that presented difficult access or poor subgrade bearing capacity. The all terrain unit consists of a light panel side truck fitted with tracks mounted on the rear dual wheels. A bulldozer was used to improve grade and pull the truck onto test locations in areas of difficult access.

Section 6/7 correlation penetration tests accessible by truck were completed first. The correlation P-ECPTs were performed adjacent to perimeter cluster well installations to demonstrate the effectiveness of the piezo cone technique in meeting or exceeding the information gathering objectives of the Consent Order perimeter boring program. Correlation penetration tests were performed at least 25 well diameters away from existing well installations as required by ASTM D3441. During the correlation testing program, piezo cone pore pressure dissipation tests were performed at all vertical intervals within which undisturbed samples had been collected for laboratory hydraulic conductivity testing during the well installation program.

Following completion of the Section 6/7 correlation P-ECPTs, the shallow 200 linear ft interval P-ECPTs and deep 1000 linear ft interval P-ECPTs accessible by the truck mounted CPT unit in Section 6/7 were completed. Correlation, shallow 200 linear ft interval, and deep 1000 linear ft interval P-ECPTs in Section 1/9 accessible by the truck mounted CPT unit were then completed. After a three month period of correlation P-ECPT data analysis, the remainder of the P-ECPTs in Sections 6/7 and 1/9 were completed with an all terrain vehicle mounted CPT unit. All correlation P-ECPTs were incorporated into the 1000 linear ft interval perimeter deep boring program as required under Consent Order Appendix A-4, Task (1).

- ***Landfill Section 6/7***

In Section 6/7 both the truck mounted and all terrain core penetration testing (CPT) units were utilized. A total of 4,560 feet of penetration testing and 683.6 minutes of dissipation testing was completed. The truck mounted CPT unit portion of the Section 6/7 P-ECPT program was initiated on July 17, 1991 and was conducted during two different time periods through October 31, 1991. Over these periods, a total of 83 P-ECPTs were completed (location codes 6Z91:IT701 through 780, and 800A, 800B). These tests included 18 deep tests at 1000 linear foot intervals, including 7 correlation P-ECPTs, and 65 shallow tests at 200 linear foot intervals. The truck mounted CPT program resulted in a total of 3,777 feet of penetration testing and 488.5 minutes of dissipation

testing. The correlation P-ECPTs were incorporated into the 1000 linear foot interval deep boring program; test locations were adjusted to place deep P-ECPTs adjacent to truck accessible cluster well installations. This adjustment resulted in a final deep test spacing interval of approximately 750 linear ft for the northern and western perimeter of Section 6/7. Testing along the southeast portion of the landfill perimeter was adjusted to accommodate the revised site grading plan developed by SCS Engineers (1991); i.e., the P-ECPT alignment was relocated to the west of the adjacent wetlands area.

Testing along the northeast portion of Section 6/7 was performed using an all terrain vehicle mounted CPT unit during March 1992. During this period, a total of 18 P-ECPTs were completed (location codes 6Z92:IT781 through 799). These tests included 5 deep and 13 shallow P-ECPTs. The all terrain CPT portion of the program resulted in a total of 783 feet of penetration testing and 195.1 minutes of dissipation testing. Testing along the eastern portion of the landfill perimeter followed the 10 to 14 ft elevation contour between tests IT780S and IT787S. North of IT787S, the test locations were adjusted to the west, to approximately the 30 ft elevation contour, due to access constraints.

Following detailed stratigraphic correlation, 9 of the 101 P-ECPT's completed in Section 6/7 were determined to have not reached or sufficiently penetrated the uppermost confining layer, or the P-ECPT responses were ambiguous within certain zones of the test profile. Three conventional borings (6B92:IT770, IT790 and IT796) were drilled during March and October 1992 to address the most significant data gaps. Eight supplemental borings (6B93:IT722, 770B, 776, 783, 791, 792, 793 and 795) were performed in March and April 1993 to address the remaining data deficiencies summarized below.

IT722S: Qgl (glaciolacustrine silt and clay, uppermost confining layer) not encountered, boring terminated in Qrsc (Recent silt and clay).

IT770S: Qgl not encountered, boring terminated in Qgs (glacial sand). Conventional boring IT770 completed 54 ft to the south of P-ECPT IT770 encountered Qgl at -0.4.

IT776S: Qgl penetration <5 ft (3.5 ft).

IT791S: Test data ambiguous (Qgl possibly Qrc).

IT792S: Qgl not encountered.

IT795S: Qgl not encountered.

- ***Landfill Section 1/9***

In Section 1/9, both the truck mounted and all terrain cone penetration testing (CPT) vehicles were utilized. A total of 5,093 feet of penetration testing and 1956.4 minutes of dissipation testing was completed. The truck mounted CPT portion of the P-ECPT program for Section 1/9 was initiated on November 11, 1991 and continued through December 12, 1991. During this phase, a total of 53 P-ECPTs were completed (location codes 1Z91:IT525 through 576). These P-ECPTs included 38 shallow, 200 linear foot interval tests and 15 deep, 1000 linear foot interval penetrations, including 7 correlation P-ECPTs. Truck mounted CPT testing resulted in a total of 2,735 feet of penetration testing, and 1,549.4 minutes of dissipation testing.

The locations of correlation P-ECPTs in the north and east area of Section 1/9 were adjusted so they were adjacent to cluster well installations, in order to incorporate these tests into the 1000 linear foot interval deep boring program stipulated under the Consent Order. This adjustment resulted in a final deep test spacing interval ranging from approximately 500 ft to 1000 ft, depending on cluster well spacing. In order to be consistent with the revised grading plan provided by SCS Engineers (1991), the P-ECPT test alignment was adjusted in two areas. The first area is located near the NYCDOS Muldoon Avenue maintenance garage, where the test alignment was relocated to the east, adjacent to the Highway 440 service road. The second area is located near the Section 1/9 scale house. In this area the test alignment was relocated to the north and west. With the exception of P-ECPT 1Z91:IT533D, all truck accessible P-ECPTs were completed to the confining layer required in the Consent Order. P-ECPT 1Z91:IT533D ended in refusal above the second uppermost confining layer in a very dense sand at 69 ft below grade.

Testing along the southeast, south and west portion of Section 1/9, between cluster well installations 1W91:IT006 and 013, was performed using an all terrain vehicle mounted CPT unit during March 1992. During this period, a total of 37 P-ECPTs were completed (location codes 1Z92:IT577 through 613). These tests included 4 deep and 33 shallow penetration tests, totalling 2,358 feet of penetration testing and 407.0 minutes of dissipation testing. Deep monitor well information was used in conjunction with the perimeter P-ECPT program to meet the deep boring requirements of the Consent Order, maintaining a deep testing interval of approximately 1000 ft.

On Section 1/9, three P-ECPTs were not performed due to severe access problems, despite several attempts to access these locations. Ten P-ECPTs did not fully penetrate or encounter a confining layer due to the presence of overlying dense sands not penetratable by the CPT equipment. These locations are identified below:

IT526S:	Penetration test terminated before encountering uppermost confining layer, (Kc, Cretaceous clay).
IT580D:	Penetration test ended in refusal above the second uppermost confining layer (residual clay), however, 70 feet of penetration was achieved into the uppermost confining layer (Kc).
300 ft south of IT009:	Test not performed due to access difficulties.
IT592S:	Confining layer penetration limited to 3.0 ft of Kc prior to refusal in sand.
IT587S:	Confining layer penetration limited to 2.9 ft of Kc prior to refusal in sand.
IT588S:	Penetration test ended in refusal before encountering uppermost confining layer, (Kc or residual clay).
IT590D:	Penetration test ended in refusal above the second uppermost confining layer (residual clay).
IT603S:	Penetration test ended in refusal before encountering uppermost confining layer (residual clay).
IT604S:	Penetration test ended in refusal before encountering uppermost confining layer (residual clay).
IT613S:	Penetration test ended in refusal before encountering uppermost confining layer (residual clay).
IT612S:	Penetration test ended in refusal before encountering uppermost confining layer (residual clay).
600 ft. north-east of IT012:	Test not performed due to access difficulties.

IT610S: Two testing attempts failed due to equipment problems. Subsequent test not performed due to access problems.

P-ECPTs were not attempted between 1Z92:IT604S and 613S, based on the testing results of P-ECPTs 1Z92:IT603S, 604S, 612S and 613S, which indicated the lack of a shallow confining layer in this area. These P-ECPT's penetrated between 72 to 82 feet of soil before terminating in dense sands overlying the uppermost confining layer, (residual clay).

During October 1992, six conventional borings (1B92:IT610, 614, 615, 616, 617 and 618) were completed on the west side of Section 1/9 in place of the P-ECPTs that were not performed due to access problems or due to the likelihood that the upper confining layer would not be penetrated by the CPT equipment. Nine supplemental borings (1B93:IT526, 542, 544, 545, 546, 547, 548, 582 and 598) were performed in March and April 1993 to address remaining deficiencies in the perimeter test program.

4.3 Monitoring Well Program

Tasks (1) and (2) of Appendix A-6 and Tasks (4) and (5) of Appendix A-4 to the Consent Order, specify installation of a perimeter monitoring well array to consist of: (1) shallow (water table) well installations at 500 ft intervals around each landfill section, (2) confined water bearing unit (cluster well) installations at 750 ft intervals around the downgradient and cross gradient perimeters of each landfill section, and (3) confined aquifer (cluster well) installations at 1500 ft intervals around the up gradient perimeter of each landfill section. The objective of this installation program is to provide for characterization and long term monitoring of water quality laterally across and vertically beneath the Fresh Kills landfill complex, as well as collection of lithologic data to supplement that obtained from the center boring program in support of sectional and site-wide stratigraphic characterization.

As with the center boring program, the well installation program was designed to proceed in a phased manner, allowing for the incorporation of the results stratigraphic analysis, numerical ground water flow modeling, and spatial variability (geostatistical) analyses of water chemistry into the design of the final installation plan. As identified in the SIP (IT Corporation, 1990a), the Phase I program consisted of the installation of cluster wells (shallow, intermediate depth, and bedrock wells) at 1500 ft intervals around each landfill section. This pattern of well installation was identified as an

appropriate strategy to allow for a comprehensive initial characterization of water chemistry and the dynamics of the groundwater flow system. As discussed subsequently, specific recommendations for the Phase II well installation program were then developed for each landfill section based on the results of such characterization.

Well construction specifications incorporated into the SIP and implemented in the field were designed to address the specific requirements of Appendix A-6 Task (3) and Appendix A-4 Task (6) to the Consent Order, notably in regard to minimization of the potential for vertical leachate transport through the well bore and annulus and optimizing the filtration characteristics of the sand pack and well screen. As noted in Section 4.3.3, the latter objective proved difficult to achieve in the case of shallow wells, due to the nature of encountered sediments (fine grained fluvial deposits and/or refuse).

A great deal of care and considerable expense was expended during the field program to insure for sanitary well construction through a staged installation process. This process is designed to preclude vertical migration of leachate from shallow horizons to deeper monitoring zones by isolating a series of telescoping casing segments (through progressive casing placement and grouting) in low permeability materials encountered at depth, prior to successive advancement of the borehole.

Typical as-built construction schematics for the range of well installations completed in the field are illustrated on Figures 4.14 (shallow well/above-ground completion detail), 4.15 (2 stage intermediate depth well), 4.16 (3 stage intermediate depth well), 4.17 (2 stage bedrock well), and 4.18 (3 stage bedrock well). The number of required installation stages was a function of the number of confined water bearing units present between the water table and the bedrock. Two stage installations were the most frequently employed, with three stage installations associated primarily with Landfill Sections 1/9 and 2/8.

Except for several cases where shallow wells were installed out of sequence to maintain the efficiency of the drilling operation, the deep well boring was drilled first at each cluster location. A small diameter pilot hole (typically 2 15/16 or 3 1/4 in. roller bit) was initially drilled with mud and/or water to bedrock to allow for improved sample recovery, and identification of intermediate depth confined aquifer units and the number of interior casing stages required for final installation. Prior to commencement of rock coring, downhole geophysical logging (Section 4.6) was performed in selected boreholes. In some cases, this required installation of temporary PVC riser to prevent borehole caving.

Subsequent to logging, the borehole was reamed and interior casing was placed and grouted in stages, as appropriate. Upon encountering bedrock, permanent 4 in. steel casing was set and either pressure or tremie grouted to the surface in one or two lifts depending on the depth of the hole. Following overnight grout set-up, 3 in. temporary steel casing was then emplaced in the borehole, the hole was flushed, and either wire line or conventional rock coring was initiated. Typically 15 ft of NX or HX rock core was recovered from each installation. NX boreholes were reamed with a 3 7/8 roller bit and completed as open borehole wells (additional reaming was not required where HX coring was performed). Occasionally, 2 in. PVC wells were constructed in the open borehole, where formation caving was apparent. Following deep well completion, any required intermediate and shallow depth wells were installed. Soil sampling in these adjacent boreholes was performed only at changes in stratigraphy, intervals where poor or no recovery occurred, in the deep boring, and in the screened interval. Intermediate depth wells were constructed of either Schedule 40 or 80 PVC, depending on the depth of installation (deeper installations used Schedule 80 PVC to avoid riser pipe deformation resulting from the heat of hydration associated with long grout emplacement runs in the annulus). Shallow wells were constructed of Schedule 80 PVC to provide added strength in the potentially unstable surficial deposits.

The locations of all wells installed in the Phase I installation program during 1991 are indicated on Figures 4.3 (Section 6/7), 4.4 (Section 1/9), 4.5 (Section 2/8), and 4.6 (Section 3/4). These figures also indicate the cluster well locations proposed in the SIP; only minor adjustments to the proposed locations were implemented in the field (due primarily to terrain or severe access constraints). Figures 4.19 (Section 6/7), 4.20 (Section 1/9), 4.21 (Section 2/8) and 4.22 (Section 3/4) illustrate the location plan for Phase II wells installed during 1992. As discussed subsequently in Section 4.3.2, siting of Phase II well clusters was based on collection and analysis of water level data to define the orientation of hydraulic gradients in confined water bearing units. For this reason, and constraints imposed by the actual installed location of Phase I wells (between which Phase II wells were installed along the landfill perimeters), the location of installed Phase II wells differ in certain areas from tentative locations identified in the SIP. Figures 4.23 through 4.26 provide detailed maps of the location of all well installations, as well as boring and piezometer installations also performed under the Consent Order.

Table 4.3 is a summary compilation of pertinent construction data for all Phase I and Phase II well and piezometer installations. These data include installation date, depth, horizontal and vertical survey control, screen interval depth and elevation (relative to the Richmond County High Water

Datum), screened interval stratigraphic unit, and screen diameter. Final well construction/boring logs for all installations, corrected for uniformity with areal stratigraphic interpretations, are contained in Appendix E. Original field logs are contained in Attachment 3, and a photographic log of recovered bedrock core is contained in Attachment 2.

Due to the staged construction design implemented for deep wells installed during this project, and the abandonment of monitoring wells from previous investigations screened in confined water bearing units (identified in the Groundwater Monitoring Well and Piezometer Survey Report, IT Corporation, 1990c), the opportunity for leachate migration to deep water bearing zones as a result of the subsurface investigation and well installation process has been precluded. A potential exception relative to this issue is the NYCDOS Muldoon Avenue garage facility well, a deep (580 ft) industrial supply well used periodically for the washing of Sanitation Department trucks. Staged construction was not used in its installation, resulting in the potential for vertical contaminant migration through the well annulus. To address this concern, NYCDOS has scheduled this well for abandonment during January of 1994. Casing removal, or casing perforation and pressure grouting, will be required to adequately seal this well.

4.3.1 Phase I Drilling Programs

A total of 99 wells and one piezometer were installed at the four landfill sections during the Phase I installation program, consisting of 28 shallow wells, 31 intermediate (confined sand) wells, 40 deep (bedrock) wells, and one deep piezometer. Deep ('D') wells were installed at all cluster well locations with the exception of 009 at Section 1/9, which was designated as a shallow installation only in the SIP. Intermediate depth ('I') wells in confined aquifer units were installed as appropriate, based on review of lithology documented during drilling of the deep well borehole.

Shallow ('S') wells were installed at all cluster well locations except where surficial deposits were unsaturated and/or comprised of a silt/clay matrix (cluster locations 005 and 006 in Section 1/9, 163 in Section 6/7, and 304, 305, and 307 in Section 2/8), or where existing NYCDOS wells were located proximal to the cluster location and were substituted for new well installation (6W89:YW8 at location 162, and 6W89:YW6 at location 159 in Section 6/7). Due to access difficulties, the installation of the shallow well at cluster location 303 in Section 2/8 was deferred until Phase II. Additionally, shallow wells associated with locations 153, 154, 155, and 156 at Section 6/7 were deferred until the Phase II installation program to await finalization of the revised grading plan for

this section; deep wells were installed to the east of the tidal tributary and wetlands lying along the eastern margin of the section (inside the Richmond Avenue berm) along areas accessible by the heavy drilling equipment required to install bedrock wells.

All drilling during this phase was performed by EMS (WC Services) Inc., the IT Corporation Drilling Services Division, and Empire Soils Investigations, Inc. using Failing 1250 HM, Failing F-10, CME-75, Ingersol Rand TH-60, Mobile B-61, Gus Pech Brat 22-R, and Speedstar drilling rigs. Periodically, the nature of encountered subsurface materials, or equipment/borehole stability problems resulted in necessary modification to the drilling/sampling protocol. Where implemented, such modifications are described in each of the following landfill section specific discussions as well as report Section 4.4 and Table 4.5.

4.3.1.1 Landfill Section 6/7

The Phase I perimeter well installation program was initiated at Landfill Section 6/7 on February 14, 1991, and completed on June 26, 1991. Twenty four wells were installed during this phase, as follows: IT151S,D; IT152S,D; IT153D; IT154D; IT155D; IT156I,D; IT157S,I,D; IT158S,I,D; IT159D; IT160S,D; IT161S,D; IT162I,D; and IT163I,D. [The location code prefix for all of these locations is: 6W91]. All of the intermediate and deep wells were constructed as two stage installations (i.e., PVC screen and riser or 4 in. steel bedrock casing set through and below larger diameter outer surface casing).

Downhole geophysical logging was performed in all deep well boreholes except IT153D, IT154D, IT155D (due to their shallow depth), and IT162D. A total of 22 disturbed (split-spoon) samples, and 24 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered. Twelve to 16 ft of rock core was recovered from all deep well boreholes with the exception of: (1) IT153D, and IT156D where only six feet of core was obtained from each location due to poor recovery, and (2) IT158D where only one ft of core was obtained due to repeated damage to the core barrel cutting head.

4.3.1.2 Landfill Section 1/9

The Phase I perimeter well installation program was initiated at Landfill Section 1/9 on March 18, 1991, and substantially completed by July 26, 1991. Several final installations were completed during September 1991. Thirty nine wells were installed during this phase, as follows: IT001S,I,D; IT002S,D; IT003S,D; IT004S,I,D; IT005I1,I2,I3,D; IT006I,D; IT007S,I,D; IT008S,I,D; IT009S; IT010S,I1,I2,D; IT011S,I1,I2,I3,D; IT012S,I1,I2,D; and IT013S,I,D,Z. [The location code prefix for all of these locations is: 1W91, with the exception of 1P91:IT013Z (piezometer)]. Wells IT005D, IT007I, IT007D, IT008D, IT010I2, IT011I3, IT011D, and IT012D were constructed as three stage installations (i.e. PVC screen and riser or 4 in. steel bedrock casing set through and below large diameter intermediate depth and outer surface steel casings). All remaining intermediate and deep wells were constructed as two stage installations.

A deep bedrock piezometer as well as a shallower weathered bedrock well was installed at cluster location IT013 due to the extensive thickness of the weathered bedrock zone at this location. Two installations were deemed necessary to allow for: (1) consistency with water level measurements at surrounding cluster well locations, and (2) evaluation of vertical head distribution within the weathered bedrock/bedrock aquifer. A two in. PVC well screen and riser was installed within the bedrock borehole at locations IT013D, IT013Z and IT012D, due to extensive sidewall caving observed following completion of coring activities.

Downhole geophysical logging was performed in all deep well boreholes except IT001D. A total of 72 disturbed (split-spoon) samples, and 21 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered. Ten to 15 ft of rock core was obtained from IT003D, IT004D, IT005D, IT007D, IT008D, IT010D, IT011D, and IT013Z. Approximately five feet of rock core was obtained from IT001D and IT002D due to poor recovery. No core was obtained from IT006D due to the cracking and jamming of the core barrel at depth; no core was obtained at IT013D due to prior recovery at IT013Z. Only one foot of core was recovered at IT012D due to extensive caving; as noted above, this condition necessitated installation of a well screen within the corehole. Modification of the drilling/sampling program was required, as follows:

- IT007I1: Based on the drilling log from IT007D, two intermediate depth wells were scheduled for installation at this location. The well boring for the shallow intermediate depth well was advanced into and ten feet beyond the design interval for

screen placement without encountering the sand unit identified in the deep borehole log. Consequently, the IT007I1 borehole was abandoned, and the identification number of the deep intermediate well installation was revised from IT007I2 to IT007I.

- IT013D: Due to the excessive loss of drilling fluids while drilling through refuse at IT013D, polymer drilling mud was used when drilling through the refuse (above the first stage casing seal) in place of the specified bentonite drilling mud, following consultation with NYSDEC. The polymer drilling mud created a faster and more durable mud cake in the borehole then the bentonite drilling mud allowing for advancement of the borehole.

4.3.1.3 Landfill Section 2/8

The Phase I perimeter well installation program was initiated at Landfill Section 2/8 during March 1991, with the installation of several shallow wells. The majority of well installation was completed during the period July 25 through October 30, 1991. Eighteen wells were installed during this phase, as follows: IT301S,D; IT302S,D; IT303D; IT304D; IT305I,D; IT306S,I1,I2,D; IT307I,D; and IT308S,I1,I2,D. [The location code prefix for all of these locations is: 2W91]. Wells IT306I2 and IT306D were constructed as three stage installations. All of the remaining intermediate and deep wells were constructed as two stage installations.

Downhole geophysical logging was performed in the IT301D and IT302D boreholes. A total of 26 disturbed (split-spoon) samples, and 12 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered. Ten to 17 ft of rock core was obtained from IT302D, IT304D, IT305D, IT306D, and IT307D. Five or less feet of core was obtained at IT303D and IT308D due to poor recovery. No core was obtained at IT301D due to extensive caving of the corehole sidewall; this necessitated reaming and installation of a 4 in. diameter well screen and riser to complete the installation.

4.3.1.4 Landfill Section 3/4

The Phase I perimeter well installation program was initiated at Landfill Section 3/4 during March 1991, with the installation of several shallow wells and one deep well. The majority of well

installation was completed during the period June 27 through October 3, 1991. Eighteen wells were installed during this phase, as follows: IT401S,D; IT402S,D; IT403S,D; IT404S,I,D; IT405S,I1,I2,D; IT406S,I,D; and IT407S,D. [The location code prefix for all of these locations is: 3W91]. All of the intermediate and deep wells were constructed as two stage installations.

Downhole geophysical logging was performed in the IT405D and IT406D boreholes. A total of 26 disturbed (split-spoon) samples, and 12 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered. Twelve to 15 ft of rock core was obtained from all deep boreholes except IT405D, where only six feet of core was obtained due to poor recovery. Additionally, monitoring well IT407D was abandoned at 88 ft and had to be redrilled due to the loss of a wire line cable down the borehole that could not be retrieved.

4.3.2 Phase II Drilling Programs

Design of the Phase II well installation program was initiated during the months of December 1991 and January 1992, with the collection of continuous water level measurement data from the majority of monitoring wells installed during the Phase I program across the four landfill sections. These data provided the basis for the development of a series of equipotential maps of time averaged hydraulic head (Report Section 6.0), allowing for an assessment of groundwater flow gradients in the water bearing units underlying the project area. Estimation of flow gradients in confined water bearing units is a fundamental component of Phase II program design, as the location of wells in these units (i.e., intermediate depth and bedrock wells) is a function of the orientation of the groundwater flow system. (In accordance with the requirements of Appendix A-6 Task (1), and Appendix A-4 Task (4) of the Consent Order, confined aquifer wells are specified at 750 ft intervals (i.e., between existing Phase I installations) along the cross and down gradient margins of each landfill section.) Gradient estimation is not a factor in design of the Phase II program for shallow (unconfined) well installation, as the Consent Order (Appendix
A-6 Task (2), Appendix A-4, Task (5)) specifies a uniform 500 ft spacing for these wells based on an assumption of radial flow from the landfill refuse mounds.

A total of 118 wells and 26 piezometers were installed at the four landfill sections during the Phase II installation program in 1992, consisting of 76 shallow wells, 21 intermediate depth (confined sand) wells, and 21 deep (bedrock) wells. Piezometers were installed for hydraulic monitoring/testing purposes within the refuse, bedrock and glacial till. Installation details for the piezometers (including

aquifer test wells) are outlined in the following landfill section specific discussions are presented in Table 4.3 together with the monitoring well data. Additional discussion regarding piezometer and test well installation program is contained in Section 4.5.2.

Deep ('D') bedrock wells were installed along the landfill perimeters at all cluster well locations indicated on Figures 4.19 through 4.22 with the exception of location 014 at Section 1/9 (locally upgradient in the flow system), and 1W92:IT044D, IT045D, which were placed to the south and east of Landfill Section 1/9 to avoid a very low permeability region of the bedrock and provide an "off-site" perspective on the groundwater flow system and water chemistry. Intermediate depth ('I') wells were installed in encountered sand units adjacent to bedrock wells at all cluster well locations with the exception of location 014 at Section 1/9 (regionally upgradient with respect to Cretaceous sand; no Recent/glacial sand encountered in test boring), location 169 at Section 6/7 (no Recent/glacial sand encountered in the test boring), and 1W92:IT044I1, 044I2, 044I3, 045I1, 045I2. These latter intermediate depth monitoring wells were installed adjacent to the landfill perimeter while the deep (bedrock) wells were constructed to the south and east within the Landfill Section 2/8 "pan handle", as noted above.

Shallow ('S') wells were installed at 500 ft intervals around the margin of each landfill section, accounting for the existing 1500 ft spacing of Phase I installations, except where surficial deposits were unsaturated and/or comprised of a silt/clay matrix (cluster location 017 in Section 1/9 and locations 304, 314, and 322 in Section 2/8), or where existing NYCDOS wells were appropriately located for inclusion in the perimeter monitoring well array (6W89:YW1, YW2, YW3, YW4, YW5, YW7, YW9, and YW10).

All drilling during this phase was performed by Empire Soils Investigations, Inc. using Failing F-10, CME-75, CME-550, and CME-850 drilling rigs. Downhole geophysical logging was not performed during the Phase II well installation program. In addition, following extensive technical consultation with NYSDEC, borehole soil sample collection frequency was reduced
during this phase due to the extensive stratigraphic control provided by interpretation of Phase I data. Similarly, the target run of rock core required from each deep well boring was reduced to 5 ft from 15 ft. The Phase I soil geotechnical testing protocol was maintained without modification throughout the Phase II program. Periodically, the nature of encountered subsurface materials, or equipment/borehole stability problems resulted in necessary modification to the drilling/sampling

protocol. Where implemented, such modifications are described in each of the following landfill section specific discussions, as well as Report Section 4.4 and Table 4.5.

4.3.2.1 Landfill Section 6/7

The Phase II perimeter well installation program was initiated at Landfill Section 6/7 on March 11, 1992, and completed on September 3, 1992. Thirty-four wells were installed during this phase, as follows: IT163S; IT164D; IT165I, D; IT166I1, I2, D; IT167I, D; IT168D; IT169D; IT170D; IT171S, D; IT172S; IT173S; IT174S; IT175S; IT176S; IT177S; IT178S; IT179S; IT180S; IT181S; IT182S; IT183S; IT184S; IT185S; IT186S; IT189S; IT190S; IT191S; IT192S [The location code prefix for all of these locations is: 6W92]. During installation of IT169D, a potential confined water bearing unit was identified at depth in the overburden. The adjacent intermediate well boring was advanced and continuously sampled through the overburden, and was subsequently abandoned when no sand unit of a thickness suitable for well screen placement was encountered. All of the intermediate and deep wells except one (IT166D), were constructed as two stage installations (i.e., PVC screen and riser or 4 in. steel bedrock casing set through and below larger diameter outer surface casing). Well IT166D was constructed as a three stage installation (i.e., 4 in. steel casing set through and below larger diameter intermediate depth and outer surface steel casings). The shallow wells were constructed with 4 in. schedule 80 PVC screen and riser.

A total of 27 disturbed (split-spoon) samples, and 10 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered. Five to 9.5 ft of rock core was recovered from all deep well boreholes, with the exception of: (1) IT167D and IT171D where only 2.25 ft of core was obtained from each location, and (2) IT170D where only 3.75 ft of core was obtained, all due to poor recovery.

During March 1992, four shallow piezometers were installed adjacent to existing deep well clusters along the eastern side of Section 6/7 (6P91:IT153, 154, 155, 156) to allow for further vertical definition of the shallow flow system to the east and west of the unnamed stream (tidal tributary) located inside the eastern landfill boundary. These piezometers were constructed with 2 in. schedule 80 PVC screen and riser.

Three test wells were installed in Section 6/7 during June and July, 1992, with three additional test wells being completed in September and October, 1992, as follows: 6P92:ATW-S, ATW-S2, ATW-I, ATW-D, ATW-S3, and ATW-S4. Wells ATW-S, S2, I and D were constructed at a single cluster location in the refuse mound, with the 'S' well installed within shallow saturated refuse deposits, the 'S2' well installed at the base of the refuse, the 'I' well installed in glacial till, and the 'D' well within the bedrock. Test wells S3 and S4 were installed approximately 1500 ft to the southwest of the initial test well cluster as a shallow/deep refuse well couplet. The deep and intermediate test wells were constructed as two stage installations (i.e., 4 in. PVC screen and riser or 4 in. steel bedrock casing set through and below outer surface casing). The shallow test wells were constructed with 2 in. schedule 80 PVC screen and riser. ATW-D was completed with 55 ft of open bedrock borehole; 4.25 ft of rock core was recovered over a 25 ft interval from the top, and 4 ft of core was recovered from the bottom of the open bedrock borehole.

4.3.2.2 Landfill Section 1/9

The Phase II perimeter well installation program was initiated at Landfill Section 1/9 on March 31, 1992, and was completed on September 29, 1992. Thirty eight wells were installed during this phase, as follows: IT009I1, I2, D; IT014S; IT015S, I, D; IT016S, I1, I2, D; IT017I, D; IT020S; IT021S; IT022S; IT023S; IT024S; IT025S; IT026S; IT027S; IT028S; IT029S; IT030S; IT031S; IT033S; IT034S; IT035S; IT036S; IT039S; IT040S; IT044I1, I2, I3, D; IT045 I1, I2, D [The location code prefix for all of these locations is: 1W92]. One well borehole, IT014I, was advanced as a pilot hole to determine if a glacial sand, determined to be cross gradient at this location, was present. No glacial sand was encountered and the borehole was subsequently abandoned. Wells IT044D and IT045D were installed in the southwest portion of Section 2/8 but are considered part of the Section 1/9 monitoring program due to their location relative to the refuse mound. Wells IT016D, IT044I3, and IT044D were constructed as three stage installations (i.e., 2 in. PVC screen and riser or 4 in. steel bedrock casing set through and below larger diameter intermediate depth and outer surface steel casings). All remaining intermediate and deep wells were constructed as two stage installations (i.e., 2 in. PVC screen and riser or 4 in. steel bedrock casing set through and below larger diameter outer surface steel casing). A 2 in. PVC well screen and riser was installed in the bedrock core hole at locations IT016D and IT017D due to extensive sidewall caving observed during and after coring activities. All shallow wells were constructed with 4 in. schedule 80 PVC screen and riser.

A total of 39 disturbed (split-spoon) samples, and 7 undisturbed (shelby tube or tube lined spoon) samples were selected for geotechnical laboratory analysis from all samples recovered. Five to 9.5 ft of rock core was recovered from all deep well boreholes with the exception of IT017D, where only three feet of core was obtained due to poor recovery associated with highly fractured bedrock.

Three temporary shallow piezometers were installed in the elevated areas of the refuse mound at Section 1/9 between March 25 and March 30, 1992 as follows: 1P92:IT041Z, 042Z, and 043Z. The piezometers were constructed with 2 in. schedule 80 PVC screen and riser. These piezometers were installed to provide additional data regarding the relationship between landfill mound and leachate mound elevation.

Four test wells were installed in Section 1/9 for hydraulic testing purposes during June, July and September 1992, as follows: 1P92:ATW-Z, ATW-S, ATW-I, ATW-D. Wells ATW-Z, S, and D were constructed at a single cluster location in the refuse mound, with the 'Z' well installed within shallow saturated refuse deposits, the 'S' well installed at the base of the refuse, and the 'D' well within the bedrock. ATW-I was installed at the northeastern margin of the landfill within glacial till. ATW-D was constructed as a three stage installation with 50 ft of open borehole in the bedrock. Five feet of core was recovered over a 12 ft interval from the top, and four feet of core was recovered from the bottom of the 50 ft bedrock borehole. The deeper of the shallow wells (ATW-S) was constructed with 4 in. steel screen and riser; ATW-Z and ATW-I were constructed with 2 in. schedule 80 PVC screen and riser.

4.3.2.3 Landfill Section 2/8

The Phase II perimeter well installation program was initiated at Landfill Section 2/8 on April 20, 1992 and was completed on September 15, 1992. Twenty-two wells were installed during this phase, as follows: IT303S; IT309I, D; IT310I1, I2, D; IT311S, I1, I2, D; IT312S; IT313S; IT315S; IT316S; IT317S; IT318S; IT319S; IT320S; IT321S; IT323S; IT324S; IT325S [The location code prefix for all of these locations is: 2W92]. Three proposed shallow well locations (IT304S, 314S and 322S) were drilled and subsequently abandoned when no saturated refuse zone amenable for well screen placement was encountered. Wells IT309D, IT310I2, IT310D, and IT311D were constructed as three stage installations (i.e., PVC screen and riser or 4 in. steel bedrock casing set through and below larger diameter intermediate depth and outer surface steel casings). A 2 in. PVC screen and

riser was installed in the open hole portion of the bedrock core hole at location IT310D due to the presence of swelling clays in the open hole. All remaining intermediate wells were constructed as two stage installations (i.e., PVC screen and riser set through and below larger diameter outer surface steel casing). The shallow wells were constructed with 4 in. schedule 80 PVC screen and riser.

A total of 17 disturbed (split-spoon) samples, and 1 undisturbed (shelby tube or tube lined spoon) sample were selected for geotechnical laboratory analyses from all samples recovered. Five and one quarter to 10 ft of rock core was recovered from all deep well boreholes.

Three temporary shallow piezometers (2P92:IT327Z, IT328Z, IT806Z) were installed in the elevated area of the refuse mound at Section 2/8 during Phase II of the drilling program during March 1992. IT806Z was installed adjacent to Phase I nested piezometer cluster 806 as a replacement for piezometer 2P91:IT806S. The piezometers were constructed with 2 in. schedule 80 PVC screen and riser. These piezometers were installed to provide additional data regarding the relationship between landfill mound and leachate mound elevation.

Two test wells (2P92:ATW-I, ATW-D) were installed in Section 2/8 during July and September, 1992. The intermediate depth well was constructed with 2 in. schedule PVC screen and riser in a manner similar to shallow well installation, and screened in glacial till. The deep well was installed to bedrock within the refuse mound, and experienced a series of hole collapse problems during bedrock drilling and coring operations. Approximately 9 ft of rock core was recovered from the central portion of the 70 ft open borehole section before final hole collapse and loss of drilling tools precluded further coring or hydraulic testing.

4.3.2.4 Landfill Section 3/4

The Phase II perimeter well installation program was installed at Landfill Section 3/4 on May 27, 1992, and was completed on September 23, 1992. Twenty-four wells were installed during this phase, as follows: IT408S, D; IT409D; IT410D; IT411S; IT412S; IT413S; IT414S; IT415S; IT417S; IT418S; IT419S; IT420S; IT421S; IT422S; IT423S; IT424S; IT425S; IT426S; IT427S; IT428S; IT422S, D; IT434I [The location code prefix for all of these locations is: 3W92]. All of the deep wells were constructed as two stage bedrock well installations (i.e., 4 in. steel bedrock casing set through and below larger diameter surface steel casing). The intermediate depth well was

constructed with 2 in. schedule 80 PVC screen and riser. The shallow wells were all constructed with 4 in. schedule 80 PVC screen and riser.

A total of 18 disturbed (split-spoon) samples, and 5 undisturbed (shelby tube or tube lined spoon) samples were selected for laboratory analysis from all samples recovered. Five to 11 ft of rock core was recovered from all deep well boreholes.

Three temporary shallow piezometers were installed in the elevated areas of the refuse mound at Section 3/4 between March 31 and April 6, 1992, as follows: 3P92:IT430Z, 431Z, and 432Z. The piezometers were constructed with 2 in. schedule 80 PVC screen and riser. These piezometers were installed to provide additional data regarding the relationship between mound and leachate mound elevation.

One test well (3P92:ATW-D) was installed in Section 3/4 during July and August 1992. The well was constructed as a three stage installation with 50 ft of open borehole in the bedrock. Three and one half feet of core was recovered from the top, and 5 ft of core was recovered near the bottom of the open hole.

4.3.3 Consistency of Monitoring Well Array with 6 NYCRR Part 360 and Consent Order Requirements

The perimeter monitoring well array installed at Fresh Kills Landfill Sections 1/9, 2/8, 3/4, and 6/7 is indicated by monitoring zone on Figures 4.27 through 4.30. In addition to well locations, these figures depict the mean direction of groundwater flow inferred from Map Sheets 6.32 through 6.40 (indicating down and cross gradient landfill margins), and the distribution of sand units in the intermediate depth monitoring zone. As indicated on Figures 4.28 and 4.29, the intermediate depth monitoring zone has been divided into two water bearing units (i.e., shallow Recent/glacial sands and deep Cretaceous sands) for the purpose of this analysis.

With two minor exceptions, the existing monitoring well array is consistent with the specifications of the Consent Order and Part 360 relative to site stratigraphy and the mean hydraulic head distribution within each water bearing zone. These exceptions relate to the Recent/glacial sand horizon within portions of Landfill Sections 1/9 and 3/4. Final stratigraphic interpretations (Section

5.0) indicate that Recent and glacial sands associated with these areas are more areally correlative than initially believed during the Phase I and II well installation programs. To address these data gaps, additional well installation is proposed in these areas as a component of (and in support of) the Long Term Groundwater Monitoring Program.

Four wells are proposed to be installed within the intermediate depth Recent sand horizon at Section 3/4, as indicated on Figure 4.28 (i.e., IT407I, 428I, 435I and 436I). These wells will complete perimeter coverage of this horizon in areas where the Recent sand has been mapped as thick and laterally correlative.

To complete the monitoring well array in the kame deposit glacial sands present in the northeastern area of Section 1/9, three wells are proposed: an intermediate depth well (IT025I) at well location 1W92:IT025S, and an intermediate depth well cluster (IT046) approximately 750 ft north of IT025S. The proposed locations are indicated on Figure 4.28. It is interpreted that the upper glacial sand unit screened in IT025S is correlative with the glacial sand screened in 2W91:IT308I1 in Section 2/8. The proposed intermediate well IT025I will be screened in a lower glacial sand unit which is interpreted to be correlative with the glacial sand screened in 2W91:IT308I2 in Section 2/8. Wells will be installed in glacial sands determined to be correlative with the IT025 and IT308 glacial sands at the proposed IT046 well cluster location.

It should be noted in review of the perimeter intermediate well array within Recent and glacial sands on Figure 4.28 that the distribution of sands within this monitoring zone is highly variable laterally and vertically, and the sands are not present in all mapped areas. Consequently, while the intermediate depth well array may appear sparse in this monitoring zone, well installation was attempted at all perimeter well cluster locations, and wells were not installed where sand thicknesses were insufficient to support well construction, or where sand units were not encountered in the soil column at the cluster well locations. The additional well installation locations identified above and indicated on Figure 4.28 represent those areas where a high degree of confidence exists relative to the presence of thick, laterally correlative sand units within this monitoring zone.

In addition, several shallow wells at Landfill Sections 2/8 and 3/4 have consistently failed to yield sufficient water for groundwater sampling since their installation (2W92:IT321S, 322S, 325S; 3W92:IT413S, 414S). As part of the supplemental well installation activity identified above,

abandonment and replacement of these wells with deeper installations will be attempted, as feasible given site lithology.

4.3.4 Monitoring Well Development

In accordance with Task (5) of Appendix A-6 and Task (8) of Appendix A-4 to the Consent Order, development of all perimeter monitoring wells is required subsequent to installation. Well development is performed to achieve three objectives (USEPA, 1987; Driscoll, 1986):

- Repair damage to the formation (smear or mud "cake" of fine grained materials formed on borehole wall) caused by the drilling process, in order to facilitate entry of water into the well;
- Remove fluids (primarily water) introduced into the formation during the drilling process; and
- Minimize the suspended sediment load in the formation water to reduce bias in the chemical analysis of sample collected from the well.

These objectives are attained through the cycled application of energy (represented by rising and falling water level) to the well screen, filter pack, and surrounding formation resulting in a breakdown of the mud cake, and the drawing of finer materials into the hole for removal. This process also helps remove the finer fraction of formation materials in proximity to the borehole, resulting in a "natural" pack of coarser grained materials. One of two methods of well development were applied to all wells installed under this project: Air lift, and over pumping with back washing/flushing.

Air lift development was performed initially in all wells by introducing compressed air to the well screen interval, causing water to be lifted above the static level and either discharging from the well head, or falling back into the water column. A double air filtration system was used on all air compressors associated with the well development program to preclude introduction of organic contamination (lubrication oil) into the monitoring wells.

Over pumping with back washing consists of the cycling of pump discharge from a well to allow water to periodically fall back into the water column. This technique, combined with the addition of

potable water for flushing purposes, was applied to the redevelopment of a number of bedrock wells exhibiting very low yield and extremely turbid discharge, and several shallow wells determined to be dry upon completion of installation. It was also applied in concept where bailers were used to develop extremely low yielding shallow wells or piezometers.

Prior to and during the well development process, a series of hydraulic and chemical parameters were monitored to track the effectiveness of the activity, including water level, discharge rate/volume, temperature, pH, conductivity, salinity, and turbidity. Following initial documentation of parameters, measurements were taken at 15 minute intervals. Development activity was stipulated in the SIP to proceed until stabilization (< 10 percent variation) of field measured chemical parameters (exclusive of turbidity) was achieved. In wells completed in refuse or fine grained fluvial deposits, stabilization of turbidity was not anticipated. Consequently, development relative to this parameter was stipulated to proceed until a marked reduction from initial sample readings was noted, or a measure of inherent variability was documented.

At installations where potable water was introduced into the well for flushing purposes, water chemistry was generally not recorded; at these installations flushing and purging until dewatering occurred proceeded in a series of cycles. Table 4.4 is a summary compilation of well development data recorded from all monitoring wells (chemical parameter data is presented from the final monitoring interval only from each development event). These data were derived from the completed Well Development Logs compiled in Attachment 4 to this document. As indicated from review of Table 4.4, elevated turbidity was exhibited in many of the installed wells (primarily low yielding shallow wells and bedrock wells), and was a chronic problem persisting after several attempts at redevelopment. In certain cases, the lack of stabilization of measured parameters was not identified as a cause for additional redevelopment, including falling pH (identified as acceptable once in the neutral range), and rising temperature (where heat was noted to be introduced into the discharge water from the elevated temperature of the compressed air source).

A difficulty encountered with the well development process during Phase I of the well installation program was an operational constraint, resulting from negotiated union labor staffing of drilling rigs that precluded well drilling activity during the well development process. In order to balance the requirements of the drilling schedule with the need for a reasonable level of development activity, a one hour time frame was established for each development activity. This periodically resulted in insufficient time for stabilization of indicator parameters, or optimal reduction of turbidity. In most

cases, redevelopment was performed at least once to address this problem. During the Phase II well installation program, independent development crews were established to allow for an appropriate time frame for well development activity at each locations. Due to the presence of a number of very poorly yielding wells, multiple development episodes, including flushing and purging activity, were still required during the Phase II program.

4.4 Soil Sampling and Testing

In accordance with Task (6) of Appendix A-6 and Task (2) of Appendix A-4 to the Consent Order, soil sample was recovered from all boreholes advanced during performance of the stipulated drilling programs. A subset of samples recovered from the drilling programs were then processed for geotechnical laboratory analysis, in accordance with Task (7) of Appendix A-6 and Task (3) of Appendix A-4 to the Consent Order. The following report sections detail the methods of soil sample retrieval, the sample selection protocol for laboratory testing, geotechnical test protocols, and the results of the testing program on the specified suite of geotechnical index parameters.

4.4.1 Soil Sample Recovery

During the center boring program and Phase I of the well installation program, soil sampling generally occurred continuously through Recent (Holocene) and Cretaceous deposits, and at five ft intervals through glacial (Pleistocene) deposits in all center borings and in the deep well boreholes associated with each perimeter well cluster. At shallow and intermediate depth wells within each well cluster, sampling was performed at changes in stratigraphy, at intervals of poor or no recovery in the adjacent deep boring, and in the screened interval. Subsequent to the initial stages of the drilling program, continuous sampling was implemented through glacial sand units in deep boreholes to determine if well screen placement was necessary. In addition, sampling through residual clay deposits was generally performed at five to ten foot intervals rather than continuously, due to the uniformity of this material and its known location within the stratigraphic column. Following extensive technical consultation with NYSDEC, sample collection frequency was modified to five foot intervals through all deposits during the Phase II well installation program, due to the extensive stratigraphic control provided by interpretation of the Phase I data. Continuous sampling was performed at stratigraphic changes, screened intervals, and sand zones where the potential for screen placement existed during

Phase II well installation. The target run of rock core required from deep well borings was similarly reduced from 15 ft to 5 ft during the Phase II program.

Soil samples recovered for laboratory hydraulic conductivity analysis were obtained using 4 in. diameter thin walled shelby tube or denison samplers (ASTM D1587). Where these methods were repeatedly unsuccessful, plastic or brass tube lined three in. split spoon samplers were used. Undisturbed sample recovery with shelby tubes was typically unsuccessful in hard, stiff soils such as Cretaceous clays or glacial till. Denison tube samplers were only marginally successful in these soils; consequently, most of the sample recovered in difficult soil horizons was obtained using the tube lined split spoon samplers. Disadvantages associated with the use of the tube lined split spoon samples included increased sample disturbance and a general inability to perform laboratory horizontal hydraulic conductivity testing due to limitations imposed by the tube diameter.

Soil samples recovered for stratigraphic analysis, archival purposes, and all other laboratory testing were obtained with two or three in. diameter split spoon samplers. All recovered sample was sealed in sampling jars or tubes, labelled, and processed for storage and/or geotechnical testing (sample jar/tube labels are illustrated on Figure 4.31). With the exception of the tube samples, a minimum of one jarred sample from each sampled unit was logged into the on-site sample archive (located at the project trailer complex in the northeastern area of Landfill Section 6/7, adjacent to Richmond Avenue). Any tube sample remaining after laboratory analysis was jarred and returned to the on-site archive. The sample archive and tracking logs for sample recovered from the drilling program are contained in Attachment 5.

The subset of soil sample recovered from the drilling programs to be processed for geotechnical laboratory analysis was identified in accordance with the following selection protocol:

- Center boring program: (1) one or more samples from each encountered fine grained (confining) unit analyzed for hydraulic conductivity and index parameters, (2) one or more samples from each encountered coarse grained unit for grain size analysis.

- Perimeter well installation program: (1) one or more samples from encountered surficial fine grained (silt/clay/peat) units analyzed for hydraulic conductivity, index parameters, and organic content, (2) two samples from encountered uppermost confining unit analyzed for hydraulic conductivity and index parameters, (3) one or more samples from each encountered coarse grained unit for grain size analysis, and

(4) one or more samples from encountered lower confining units analyzed for hydraulic conductivity and index parameters.

More than one sample within each encountered unit was processed for testing only if noticeable changes in material composition were noted.

Collection of soil sample according to the prescribed protocol was not always possible due primarily to formation characteristics and occasionally to equipment or casing placement difficulties. Some of the most common formation sampling problems included sloughing of refuse into the borehole, and the presence of running sands, large cobbles, or extremely soft soils. Table 4.5 identifies the significant sampling intervals, by boring location, where either disturbed (split spoon) or undisturbed (tube) sample recovery was not accomplished. In many cases, analysis of downhole geophysical logs, piezo-electric cone penetration test (P-ECPT) data, or sampling during adjacent intermediate depth well installation allowed for interpretation of lithology across intervals that could not be sampled during deep borehole advancement.

4.4.2 Geotechnical Laboratory Analysis

Geotechnical analyses of soil samples were analyzed both at the project site in a geotechnical laboratory established for this investigation, and at the Wehran Envirotech geotechnical laboratory in Tuxedo, NY. Geotechnical analyses conducted in the field at the project site during performance of the center boring program, and Phase I well installation program (February - August 1991) included:

Determination of Moisture Content	ASTM D2216
Particle Size Analysis of Soil	ASTM D422
Liquid Limit and Plastic Limit	ASTM D4318
Specific Gravity of Soil	ASTM D854

Test equipment installed at the on-site laboratory during its period of operation included: two ovens (3.3 ft^3 capacity air circulation, 1.5 ft^3 capacity convection), two scales (electronic O HAUS E-4000D, 36 pound capacity mechanical), sieve shaker, vacuum pump, liquid limit device, desiccator,

water bath for hydrometer jars, and a set of 8 in. diameter sieves from 2 in. - #200 (2 in., 1 1/2 in., 1 in., 3/4 in., 1/2 in., 3/8 in., #4, #10, #30, #40, #60, #100, #200, and #200 for sample washing). The presence of on-site equipment capable of particle size analysis was useful on a number of occasions during the drilling program, when expedited textural classification of selected soil sample was required by field personnel in support of sampling or screen placement determinations. Following completion of the Phase I well installation program in the fall of 1991, the on-site testing laboratory was decommissioned.

During both phases of the center boring and well installation program, all undisturbed (shelby tube) samples were tested at the Tuxedo, NY laboratory for the following analyses:

Determination of Moisture Content	ASTM D2216
Particle Size Analysis of Soil	ASTM D422
Liquid and Plastic Limit	ASTM D4218
Specific Gravity of soil	ASTM D854
Organic Content	ASTM D2974
Vertical Permeability	EM-110-2-1906
Horizontal Permeability	EM-110-2-1906
Logging of Shelby Tube Samples	ASTM STP479

Table 4.6 is a summary compilation of the results of all soil sample processed through the on and off-site geotechnical laboratories for analysis. The table includes sample designation, and sample depth and elevation interval, as well as the analytical results of the suite of index parameter tests. Test results were obtained for a total of 382 disturbed and 163 undisturbed samples through performance of all drilling programs. Table 4.6 also provides additional test data for borings performed to support the design of the Landfill Section 1/9 Veterans Avenue Leachate Treatment Plant (VALTP borings). Full geotechnical laboratory analytical data reports are contained in Attachment 6.

4.4.2.1 Laboratory Test Protocols

Laboratory tests were performed according to applicable test procedures following the guidelines set forth by the American Society of Testing of Materials as well as by the United States Corps of Engineers.

- ASTM D2216 Determination of Moisture Content:
  This test method covers the laboratory determination of moisture content of soil. A representative portion of the split-spoon sample or the Shelby tube sample is placed in a container and oven-dried at 110° +/- 5°C to constant mass. Samples containing organic materials were dried in the drying oven at 60° C. The moisture content expressed as a percentage is the ratio of mass of water to the mass of dry soil.

- ASTM D422 Particle Size Analysis of Soil:
  This test is the quantitative determination of the distribution of particle size in soils. A representative portion of the split-spoon jar sample or the Shelby tube sample required to be tested is selected. The portion of the sample retained on #200 sieve is analyzed by sieving and the portion of the sample passing #200 sieve is determined by hydrometer analyses.

- ASTM D4318 Atterberg Limits (Liquid and Plastic Limit):
  A representative portion of the sample to be tested is air dried. The sample is processed to remove any material coarser than #40 sieve. Liquid limit tests are performed in a liquid limit test device; liquid limit is the water content of a soil at the arbitrarily defined boundary between the liquid and plastic states. This water content is defined as the water content at which a part of soil placed in a standard cup and cut by a groove of standard dimensions will flow together at the base of the groove for a distance of 1/2 in. when subjected to 25 shocks from the cup being dropped 10 mm in a standard liquid limit device. Plastic limit is the water content in percent of a soil at the boundary between the plastic and brittle states. The water content at this boundary is defined when a soil can no longer be deformed by rolling into 1/8 in. diameter threads without crumbling.

- ASTM D854 Specific Gravity:
  Specific gravity is the ratio of weight in air of a given volume of solids at a stated temperature to the weight in air of an equal volume of distilled water at a stated temperature. A representative portion of the sample is oven dried overnight at 110° +/- 5° C, and subsequently cooled in a desiccator. Organic material is oven dried at 60° C. The oven dried sample is placed in a pyrometer, distilled water is added, and the material soaked over night. Entrapped air is removed by subjecting the pyrometer content to a partial vacuum. The pyrometer is filled with distilled water, the exterior cleaned and dried, and the weight and temperature of the sample is measured. Specific gravity values reported are based on water at 20° C.

- ASTM D2974 Organic Content:
  A representative portion of the sample is oven dried at 105° +/- 5° C and subsequently cooled in a desiccator; part of the oven dried material is placed in a porcelain dish and is subjected to a temperature of 750° C until the specimen is completely ashed. Organic

content is computed based on the loss on ignition and the oven dry weight of the specimen.

- Vertical and Horizontal Permeability:
  Permeability Tests With Back Pressure Saturation In Triaxial Cell Constant Head Test Method (Nominal Compliance, method suggested in Engineer Manual, Engineering and Design Laboratory -- Soils Testing EM 1110-2-1906, Department of Army, Office of Chief Engineers; USEPA Method 9100). This method differs from ASTM D5084-90 primarily in that permeants other than pure water may be tested.

  Vertical Permeability:
  Specimens obtained by the Shelby tube sampling are tested without trimming except for cutting a representative portion and squaring the ends. Care is taken to reduce as much as possible the remolding of the soil sample surface.

  Horizontal Permeability:
  Samples obtained by the Shelby tube sampling are cored, ends are squared and tested. Prepared specimens are set in a triaxial cell with porous end pieces with porosity greater than that of the specimen tested. The flexible membrane is placed around the specimen with the help of a membrane expander and the ends are sealed with "O" rings, two at each end, cap and base. The triaxial cell assembled with the specimen is filled with water and attached to the test control panel. Confining pressure of 5 psi is applied to the cell and the water flushed through the flow system. Chamber or cell pressure and back pressure is increased simultaneously in increments, maintaining the back pressure at about 5 psi less than the chamber pressure. The size of each increment is usually 5, 10, 15, or 20 psi depending upon the type of sample. Generally, back pressure of 90 psi and effective confining pressure of 1/2 psi is applied. The specimen is left in the test cell under pressure for a minimum of 12-16 hours. During the saturation period, the height of the specimen is monitored and if there is any significant change, it is applied to the initial length of the specimen. The initial dimensions are measured with a caliper reading to 1000th of an inch. The purge valves are operated to flush any free air bubbles out of the system. Permeability tests are performed with the head pressure applied. The burette readings and times are recorded. The last four trials and the average of the four trials are reported with details such as specimen dimensions, moisture content, densities, time, quantity of flow, difference in hydraulic head, temperature, etc. The difference in hydraulic head across the specimen is generally half of the effective confining pressure.

- Extrusion of Shelby Tube Samples:
  The samples are removed from the Shelby tube with a motorized hydraulic sample ejector; the hydraulic cylinder, driven by an electric pump, has a full 36" travel, long enough to extrude the full length of a Shelby tube. To regulate speed of ejection, a flow control valve is provided with the system which is helpful in situations when a sample requires special handling.

- Logging of Shelby Tubes:
  Shelby tube samples are logged with the description of the material. Description of the material is based on the suggested methods of test for identification of soils according to: Special Procedures for Testing Soil and Rock for Engineering Purposes ASTM STP479, American Society for Testing and Materials.

4.5 In Situ Testing

In the context of this investigation, in situ testing refers to the in place hydraulic testing of saturated subsurface soil materials through removal or injection of water into a well and subsequent monitoring and analysis of changes in water level over time. The derivation of aquifer characteristics from these tests (e.g., hydraulic conductivity) supplement the results of geotechnical laboratory analysis of soil samples, and provide basic input into the conceptual and numerical analysis of groundwater flow. A continuum of in situ testing approaches is available for application, ranging from instantaneous discharge (slug) tests, through short term single well, to long term multiple well pump tests. Further variation is afforded through implementation of a packer pump testing approach, in which a small zone or series of zones within a large test interval is isolated for independent testing. Slug tests influence only a small radius of saturated soils in the vicinity of the test well; consequently, hydraulic conductivity data derived from them is limited to that region. Pump tests influence a wider area (the actual extent dependent on the pump rate, length of test, and hydraulic properties of the soil material), with estimated aquifer hydraulic parameters representative of mean conditions throughout the larger region. Performance of the in situ testing program during the Phase I and II well installation programs of the Hydrogeological Investigation is detailed in the following report sections.

4.5.1 Instantaneous Discharge (Slug) Testing Program

Hydraulic conductivity tests were performed at all newly-installed monitoring wells/piezometers and existing monitoring wells/piezometers identified in the Groundwater Monitoring Well and Piezometer Survey Report (IT Corporation, 1990c), in order to evaluate the in-place hydraulic conductivity and water-bearing characteristics of the saturated materials. The information obtained from these tests, together with knowledge of local groundwater gradients provide a comprehensive analysis of groundwater fluxes within and away from the site. Moreover, hydraulic conductivity data assist in the identification of hydrostratigraphic units, in the interpretation of groundwater quality sampling

results, and in the delineation of potential contaminant migration pathways. Accordingly, following the development of the monitoring well and piezometer installations, in situ tests were conducted at wells/piezometers screened in the fill, Recent sand, glacial sand, Cretaceous sand, residual clay, weathered bedrock and bedrock units. Table 4.7 provides a summary of the wells/piezometers included in the in situ field testing program, as well as the saturated thickness of the test zones, screened stratigraphic unit(s), and the estimated horizontal hydraulic conductivity (Kh) derived from these tests.

4.5.1.1 Test Protocol

The instantaneous discharge method was utilized to determine in situ hydraulic conductivity of the various water-bearing units underlying the site. This technique, known as the slug test, was modeled after the work of Ferris and Knowles (1964). With this particular method, an instantaneous change in water level is produced in the monitoring well/piezometer by either introducing a measured quantity of water (slug injection) or by removal of a measured quantity of water (slug withdrawal). The changes in water level over time are then monitored and the resulting data are interpreted to determine the hydraulic conductivity of the materials screened by the monitoring well/piezometer. The criteria for performing either the slug injection or slug withdrawal test was dependent on the water level relative to the screen intake. If the screen was fully saturated at the time of the test, a slug injection was performed. If the static water level was located within the screened interval, a slug withdrawal test was performed.

Prior to each test, the general condition of the well was recorded, the static water level was measured, and the depth to the bottom of the well was sounded. This information, as well as the top of casing reference point were recorded in a field notebook. The measured static water level was compared to the as-built well construction logs to determine which type of slug test was required. An In Situ, Inc. 30 psi pressure transducer was then lowered into the well. The transducer was typically submerged a minimum of 10 ft below the static water level to insure that the unit remained submerged throughout the testing and to allow for subsequent water level recording. Once in place, the pressure transducer was connected to a data logger and referenced to zero so that water level fluctuations would be recorded directly as changes in head from static. The data logger utilized was either an In Situ, Inc. Hermit Environmental Data Logger, capable of reading and storing water level changes in a logarithmic time sequence, or a Telog Inc. system data logger that recorded at a linear rate. Prior

to and upon completion of testing, the head or column of water above the installed transducer was recorded.

- ***Slug Injection***

Slug injection tests were performed in wells whose screens were fully submerged beneath the water table. In order to accomplish an instantaneous slug injection, a device capable of delivering a known volume of water was utilized. The device was constructed of a 2.5 ft length of 6 in. inside diameter schedule 40 PVC pipe with a bottom cap which acted as the water reservoir. A check valve was then connected to the cap via a 2 in. coupling. To funnel the water into the well, a 1 in. inside diameter schedule 40 PVC leader pipe was attached to a ball valve. Figure 4.32 presents a schematic diagram of the slug testing device.

- ***Slug Withdrawal***

Slug withdrawal tests were performed in wells installed in unconfined aquifer units exhibiting partially saturated well screens. In order to withdraw a known volume from the water column, a bailer attached to a nylon cord was lowered beneath the water surface. Time was allowed for the well to return to a static equilibrium condition. Following equilibrium, the bailer was removed simultaneously with the start of the electronic data logger, thus removing a measured volume of water from the well.

- ***Monitoring Head Changes with Electronic Data Loggers***

Changes in water levels during both slug injection and withdrawal tests were automatically recorded by utilizing electronic data loggers and calibrated pressure transducers. The type of data recorder and transducer used was dependent upon the responsiveness of the water-bearing formations. In many wells, where a rapid response of the water-bearing formation was anticipated, the water level changes were electronically monitored at a logarithmic rate. This was accomplished using an In Situ, Inc. Hermit Environmental Data Loggers (Model Numbers SE1000 and SE2000) and Hermit precalibrated pressure transducers to record head changes with time. The Hermit Data Loggers were set to record data initially at a logarithmic rate from 0.33 seconds for the first 10 minutes of the test. Thereafter, water levels were automatically recorded at 2 minute intervals until the wells stabilized to approximately 90 percent of the original static levels recorded prior to the start-up of the test.

Most of the tests for which the logarithmic rate was used (typically wells screened in refuse or sand units) were completed in less than 10 minutes.

In other cases, where the anticipated response of the water-bearing formation was considerably slower (typically wells screened in fluvial deposits or bedrock), changes in water level were automatically recorded at a linear rate. Telog Inc. data recorders and calibrated transducers were utilized to electronically record the water level changes over time at 30-minute intervals.

- ***Decontamination***

All field equipment was decontaminated prior and subsequent to testing. Decontamination procedures involved an initial rinse with deionized water, followed by a rinse in methanol, and completed with another deionized water rinse. This procedure was followed for all water level indicators, pressure transducers, bailers and probes. Following performance of each slug withdrawal test, the nylon bailer suspension cord was detached and replaced with a new cord.

4.5.1.2 Data Evaluation

Digital time drawdown/recovery data recorded in the field were transferred to a portable computer using the In Situ, Inc. Hermit Data Manager (DM) and Telog Inc. system software. Data analysis (curve matching) was performed in accordance with the Cooper, Bredehoeft, and Papadopulos (1967) method, using Graphical Well Analysis Package (GWAP) software (Dansby and Price, 1987). The estimate of horizontal hydraulic conductivity (K_h) was determined from:

$$K_h = T/b$$

Where:

K_h	=	horizontal hydraulic conductivity (gpd/ft^2)
T	=	transmissibility (gpd/ft)
b	=	length of the saturated screen (ft)

The results of the in situ testing program are summarized in Table 4.7. Attachment 7 contains the field data (head changes) used in the type curve analysis, and the appropriate graphical type curve match utilized in each solution.

4.5.1.3 Deviations from Standard Slug Test Protocol

Deviations from the standard slug testing protocol were required at several of the on-site wells. Due to slow aquifer response time in conjunction with interruptions from sampling events or non-recording dataloggers, recovery testing was performed in several instances. In addition, at several refuse well locations where the screened interval did not intercept the water table, dry well slug tests were performed.

- ***Recovery Testing***

At several of the deep bedrock wells, recovery testing was performed in conjunction with groundwater sampling events. This method was employed in wells that exhibited extremely slow response time, and whose water columns were lowered below the elevation of the permanently installed Telog, Inc. pressure transducers. The variable head borehole or recovery test technique developed by Hvorslev (1951) for the United States Army Corps of Engineers and summarized in Cedergren (1977) was implemented in performance of these tests. Such tests were conducted as follows:

- The static water level and bottom depths of the monitoring well were measured and recorded in a field notebook.
- The monitoring well was then evacuated by pumping with submersible or bladder pump, followed by bailing with a teflon bailer.
- Upon the removal of the evacuation device, the depressed water level in the well was measured and a starting time recorded, constituting the beginning of the recovery period.
- The water level was recorded at frequent time intervals thereafter, until the well recovered to the elevation of the installed pressure transducer, which then provided water level recording at 30 minute intervals.
- The test was continued until the recovered water level reached approximately 90 percent of the static water level measured prior to the sampling event.

The method of analysis assumes that the rate of inflow to the monitoring well after evacuation is proportional to the horizontal hydraulic conductivity (K_h), expressed in cm/sec, and to the unrecovered head distance. A plot of the unrecovered head distance or head ratio versus time (t) indicates an exponential decline in the recovery rate with time:

$$K_h = \left[\frac{r^2 \ln(h_1/h_2)}{2 L (t_2-t_1)} \right] \ln (L/R)$$

Where:

R = sandpack radius, cm

r = riser radius, cm

L = length of sandpack, cm

t_1 = time interval corresponding to h_1, sec

t_2 = time interval corresponding to h_2, sec

h_1 = head ratio at t_1, dimensionless

h_2 = head ratio at t_2, dimensionless

- ***Dry Well Slug Test***

Due to the presence of a dry screen interval at 1P89:XP-2 and 3W92:IT414S, a slug injection test was performed at these installations in accordance with the protocol identified in report Section 4.5.1.1. For a slug test performed in a dry well, the technique summarized in Cedergren (1977) makes the assumption that the monitoring well can be represented as an open-ended pipe. Lateral hydraulic conductivity was calculated as follows:

$$K_h = \frac{d^2}{11D (t_2-t_1)} \times \ln \frac{h_1}{h_2}$$

Where:

d = diameter of the riser pipe, cm

D = diameter of the riser pipe, cm

t_1	=	time interval corresponding to h_1, sec
t_2	=	time interval corresponding to h_2, sec
h_1	=	head ratio at t_1, dimensionless
h_2	=	head ratio at t_2, dimensionless
K_h	=	horizontal hydraulic conductivity expressed in cm/sec

Since performance of such testing in a dry borehole results in a solution of marginal accuracy, these data have been qualified on Table 4.7, and have not been incorporated within the more extensive hydraulic conductivity database presented in Report Section 6.0.

4.5.2 Aquifer Test Program

A series of long term aquifer pump tests were identified for performance within each landfill section in the SIP (IT Corporation, 1990a). The purpose of these tests was to provide additional data regarding the hydraulic characteristics of the saturated water bearing units underlying the landfills to supplement that provided from in-situ instantaneous discharge (slug) tests and laboratory soil geotechnical analyses. The quantity and location of these tests was qualified in the SIP due to anticipated difficulties with piezometer and test well installation through thick refuse deposits.

As planning for the performance of the pump test program proceeded during the Phase II well installation program, a series of practical and technical considerations acted to mitigate against the general strategy outlined in the SIP. Practical issues included: (1) severe constraints on the siting and installation of deep piezometers/wells through the refuse at Sections 2/8 and 3/4 due to active filling, (2) extreme difficulty associated with construction of all deep installations through the refuse mound, precluding implementation of the "telescoping" construction strategy outlined in the SIP, and (3) progressive deterioration of most of the temporary deep piezometers installed through the refuse, due primarily to riser pipe damage resulting from the shifting of refuse deposits. Discussions regarding the technical rationale for modification of the pump testing program within the refuse and confined water bearing units, as well as the ultimate design and implementation of these programs, is provided below.

4.5.2.1 *Refuse Water Bearing Unit*

In order to supplement limited Phase I information regarding leachate mound head and refuse hydraulic conductivity distribution in the central areas of the landfill mounds, a series of shallow piezometers were installed as an initial component of the test well program at three landfill sections during March 1992: 1P92:IT041Z, 042Z, 043Z at Section 1/9; 2P92:IT327Z, 328Z, 806Z[2] at Section 2/8; and 3P92:IT430Z, 431Z, 432Z at Section 3/4. Four piezometers were installed to the east of the tributary stream lying adjacent to the eastern limit of fill at Section 6/7 to provide a shallow head distribution in this area in support of analytical and numerical analyses of groundwater flow (6P92:IT153Z, 154Z, 155Z, 156Z). Additional shallow piezometers were not installed within the refuse mound at Section 6/7 during this phase due to the subdued configuration of the leachate mound in that landfill relative to the other Sections.

In most cases, screen lengths were extended to 40 ft during installation of the shallow refuse piezometers, in an attempt to account for ambiguity in identification of the upper saturated zone (i.e., to allow for averaging of head across perched, saturated horizons). In general, the longer screen lengths acted to provide a conduit for the release of gas pressure within the refuse, and precluded accurate water level measurement; this condition also forestalled additional planning relative to pump testing within the upper zone of the refuse mounds. For these reasons, and to supplement limited data regarding a reduction in the hydraulic conductivity distribution of refuse at depth (Woodward Clyde, 1991), additional test well installation within the refuse was directed to the basal saturated horizons of the waste mounds.

Based on sample moisture descriptions obtained during the drilling of the deep aquifer test wells through the refuse (Section 4.5.2.2, below), screen intervals for deep refuse wells were selected at Sections 1/9 and 6/7, as follows: (1) 1P92:ATW-S, elevation 36 - 31 ft (100 - 105 ft below grade) above a basal unsaturated zone identified in the deep well boring at Section 1/9, (2) 6P92:ATW-S2, elevation -13 - -18 ft (80 - 85 ft below grade) at the base of the refuse below an upper unsaturated zone identified in the deep well boring at Section 6/7, and (3) 6P92:ATW-S4, elevation -7 - -12 ft

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[2]Test well 2P92:IT806Z was installed adjacent to Phase I piezometer 1P91:IT806S following abandonment of that installation due to uncertainties regarding screen integrity based on review of measured head data. While identified as a shallow installation, this piezometer is actually screened at the base of the refuse, as no saturated waste materials were encountered above the lower 10 ft of the boring (which was advanced to the refuse/native soil interface).

(65 - 70 ft below grade) at the base of the refuse below an upper unsaturated zone identified during drilling of the refuse well borehole.

Shallow piezometers (1P92:ATW-Z, 6P92:ATW-S, 6P92:ATW-S3) were installed adjacent to each of the basal refuse test wells to provide a means to evaluate the effect of identified unsaturated zones on the vertical hydraulic head distribution. Heads in the deep refuse piezometers are approximately 30 - 60 ft lower than those in the shallow installations. Basal refuse piezometers installed by Woodward Clyde at Landfill Sections 2/8 and 3/4 in connection with Consent Order Appendix A-10 slope stability investigations also indicate refuse heads significantly lower than those measured in shallow piezometers installed within refuse in those landfill sections (Attachment 29).

As noted in Table 4.7, the hydraulic conductivity of the basal refuse deposits measured through the performance of instantaneous discharge (slug) tests was very low at 1P92:ATW-S (1.83×10^{-7} cm/sec) and 6P92:ATW-S2 (8.19×10^{-6} cm/sec), and within the range of shallower deposits at 1P92:ATW-S4 (7.64×10^{-3} cm/sec). These data correlate well with the findings of additional in-situ testing of basal refuse deposits performed by Woodward Clyde Consultants during 1992 (Attachment 29), as follows: Section 1/9 test location = 1.0×10^{-3} cm/sec, Section 2/8 test location = 2.0×10^{-5} cm/sec, and Section 3/4 test locations = 2×10^{-6} and 4×10^{-6} cm/sec. Due to the generally very low hydraulic conductivity of the basal refuse deposits, pump testing of wells installed in them was not pursued.

In should be noted that the variance in measured hydraulic head between the shallow and deep refuse piezometers, head data recorded from basal refuse piezometer 2P92:IT806Z, and the identification of significant thicknesses of unsaturated refuse deposits in the drilling of the deep (bedrock) test well installations at Sections 2/8 and 3/4 led to the subsequent numerical evaluation of the effect of these zones on vertical flux as part of the hydrogeological investigation component of this report (Section 6.0).

4.5.2.2 Confined Water Bearing Units

A review of the hydrogeological database following completion of the Phase I Well Installation Program indicated a number of data gaps relative to the definition of hydraulic characteristics for selected lithologic units. Other than the issues discussed previously in Section 4.5.2.1, these data

gaps related primarily to: (1) hydraulic conductivity distribution of low permeability materials (residual clay, glacial till), and (2) vertical hydraulic conductivity distribution, base of flow system, and head (underlying the refuse mounds) of the bedrock. As supplemental data regarding these issues would not be recovered through strict adherence to the specifications of the SIP, the test well installation/testing program was modified to address them. Specifically, test well installation and hydraulic testing was focused on a more extensive cross-section of the bedrock unit and the glacial till unit, in lieu of pump testing of permeable deposits (confined sand units) for which an adequate description of the hydraulic conductivity distribution was available from in-situ testing performed during the Phase I and Phase II well installation programs.

One bedrock test well was installed within each of the four landfill sections (1P92:ATW-D within the Stockton Formation, 2P92:ATW-D within the serpentinite, 3P92:ATW-D within the Stockton Formation, and 6P92:ATW-D within the Stockton Formation). The open borehole at each location was drilled/cored to a depth of 50 - 70 ft, to allow for discrete zone packer pump testing across a section approximately three times longer than that available from perimeter bedrock boreholes completed in accordance with the specifications of the Consent Order and SIP. Wells were located within the refuse mounds to additionally allow for collection of water level data within areas of limited bedrock hydraulic head information. As noted in Section 4.3.2.3, test well 2P92:ATW-D experienced a series of hole collapse problems during borehole drilling and coring operations due to formation instability. This condition ultimately led to the shearing and loss of drilling tools, precluding the ability to perform downhole packer testing. Instantaneous discharge (slug) testing of the open borehole interval and water level monitoring was, however, performed at this installation.

The complete report of the packer pump testing program in the bedrock test wells is contained as Attachment 8 of this report. At 1P92:ATW-D, seven discrete zones were tested (including six 10 ft borehole intervals) as well the entire borehole length. At 3P92:ATW-D, five discrete zones were tested (including four 10 ft borehole intervals) as well as the entire borehole. At 6P92:ATW-D, eight discrete zones were tested (including five 10 ft borehole intervals) as well as the entire borehole. The permeability of all tested bedrock intervals within all test well boreholes was extremely low based on the results of initial slug testing performed in each zone. This finding precluded the performance of long term pump testing within any of the test intervals. As noted in Table 4.7, the range of hydraulic conductivity for the full length of the open boreholes at all test well locations is 2.47×10^{-8} to 7.78×10^{-6} cm/sec.

A total of three test wells were installed within glacial till at Sections 1/9, 2/8 and 6/7 (1P92:ATW-I, 2P92:ATW-I, and 6P92:ATW-I). As noted in Table 4.7, the range of hydraulic conductivity in this unit derived from instantaneous discharge (slug) testing is 4.9×10^{-6} to 5.4×10^{-4} cm/sec.

4.5.2.3 Proposed Supplemental Testing

Notwithstanding the considerations noted above, estimates of bulk hydraulic conductivity of the refuse may be useful relative to continuing engineering planning and design for leachate containment and collection at the landfill. To address the potential need for such data, performance of three pump tests will be attempted within the refuse units at Sections 1/9, 2/8, and 3/4, where substantial refuse mound thicknesses exist. These tests are scheduled for the spring of 1994, and will be performed in accordance with the specifications outlined in Sections 5.3.2.3 (Aquifer Test Procedures) and 5.3.2.4 (Data Analysis) of the Hydrogeological Site Investigation Plan (IT Corporation, 1990a; Attachment 42).

Locations for these tests have been identified to maximize use of existing monitoring points (i.e., refuse piezometers), and in consideration of observed relationships between refuse thickness and basal hydraulic conductivity (i.e., Figure 6.2B). These locations are: (1) adjacent to piezometer 1P89:XP-7 in the southern area of Landfill Section 1/9, (2) adjacent to piezometer 2P92:CP-C201 in the eastern area of Section 2/8, and (3) adjacent to piezometer 3P92:CP-D103 in the western area of Section 3/4. All cited piezometer locations are indicated on Map Sheet 5.1.

At each pump test location, an observation piezometer fully screened through the saturated refuse deposits will be installed to supplement the existing monitoring point. The pumping well will be constructed of pre-packed well screen (to allow for reduction in borehole size diameter, and maximize efficacy of the well development process). The diameter of the pumping well and the spatial location of the pumping well relative to the observation piezometers will be determined through consideration of the observed refuse saturated thickness, and the results of hydraulic testing of the installed piezometer prior to pump test well installation.

4.6 Borehole Geophysics

The objectives of the geophysical log acquisition program were to utilize downhole geophysical data in conjunction with descriptive downhole lithologic (soil sample) data to enhance stratigraphic unit characterization and allow for refinement of stratigraphic boundaries defined by review of recovered soil sample. These objectives were accomplished through quantitative evaluation of geophysical log responses to lithology using statistical analyses of acquired digital log data.

As specified in the SIP (IT Corporation, 1990a), downhole conductivity or focused electromagnetic induction (EMI) and natural gamma (NG) logging was conducted in selected center borings and Phase I deep perimeter well boreholes at the site. The following additional logs, in varying combinations, were also acquired in selected boreholes:

- Spontaneous Potential (SP)
- Single-point Resistance (SPR)
- 16-inch Normal Resistivity (16NR)
- 16-inch Normal Conductivity (16NC) [Reciprocal of 16NR Logs]
- 64-inch Normal Resistivity (64NR)
- Lateral Resistivity (LATR)
- Fluid Resistivity (FLR)
- Inverse EMI (i.e., Resistivity) (EMIR)
- Temperature (TMP)
- Delta Temperature (DTMP)
- Single Long-arm Caliper (CAL)

Downhole geophysical logging of boreholes provides continuous objective records of geophysical parameters that are spatially and temporally consistent. Table 4.8 presents a brief compilation of common parameters that can be measured or inferred from downhole geophysical logs. The effective volume of soil material in the vicinity of the borehole amenable to investigation with each type of log varies with respect to the physical and chemical properties of the formation and borehole fluid, and is also affected by borehole diameter and downhole probe configuration. To obtain valid responses for electrical logs (i.e., SP, SPR, 16NR, 64NR, LATR and FLR), the borehole interval to be logged must be open to the formation and filled with a conductive fluid such as mud or water. Natural gamma (NG) logs are the only logs acquired in this investigation that are valid in both open boreholes

and over borehole intervals cased with steel, and NG and EMI logs are the only logs valid over borehole intervals cased with PVC.

4.6.1 Borehole Geophysical Techniques

- ***Electromagnetic Induction Logging (EMI)***

EMI logs measure conductivity, which is the reciprocal of resistivity. They are generally used to determine lithologic unit boundaries and formation resistivities (i.e., the ability of the formation to conduct an electric current). Since EMI logs detect variations in apparent formation conductivity/resistivity they can detect the presence of conductive contaminants in groundwater. Induction-logging tools originally were designed to solve the problem of measuring formation resistivity in oil-based drilling mud, where no conductive medium occurred between the tool and the formation. Induction tools provide formation resistivity measurements regardless of whether the borehole is filled with air, water or fresh mud. As noted previously, EMI logs are also accurate when run through plastic casing. These tools are designed to provide for good vertical resolution, reasonable lateral depth of investigation of formations, and insensitivity to conductive borehole fluid. A simple version of an induction tool contains two coils; one for transmitting an AC current into the surrounding formation and a second for receiving the returning signal. Two additional coils are employed in the multi-parameter tool used in this investigation (Century 9510) to focus the current. The magnitude of the received current is proportional to the electrical conductivity of the formation.

- ***Natural Gamma Logging (NG)***

NG logs, also called gamma logs, are the most widely used radioactive logs in groundwater applications. They are used to measure the amount of natural radiation emitted by soils and rocks. The NG log is an excellent indicator of the presence of clays or shales since clays and shales have a higher gamma ray emission level than sands or sandstones; therefore, the most common use of the gamma log is for identification of lithology and stratigraphic correlation. The NG log provides a record of the total gamma radiation detected in a borehole that is within a selected energy range. The logs provide valid data over a wide range of borehole conditions, including measurements through steel or plastic casing. In rocks that are not contaminated by artificial radioisotopes, the most significant naturally occurring gamma-emitting radioisotopes are the daughter products of the

uranium and thorium-decay series and potassium-40 -- hence the name natural-gamma log. In 200 shale samples collected from various localities in the United States, the uranium series contributed almost half the gamma radiation because of its high specific activity (Keys, 1990). Fine-grained detrital sediments that contain abundant clay tend to be more radioactive than quartz sands and carbonates, although numerous exceptions to this norm occur. Rocks can be characterized according to their usual gamma intensity, but knowledge of the local geology is needed to identify the relationship between lithology and radioactivity. Under most conditions, 90 percent of the gamma radiation detected probably originates from material within 6 to 12 in. of the borehole wall. The amplitude of gamma-log deflections is changed by any borehole conditions that alter the density of the material through which the gamma photons must pass or by the length of the travel path. Thus, casing and cement will reduce the recorded radiation, as will large diameter wells.

- ***Spontaneous-Potential Logging (SP)***

Spontaneous potential is one of the oldest logging techniques. The SP log is recorded by measuring the difference in potential between an electrode in the borehole and a grounded electrode at the surface. The SP measure a change in borehole potential as a function of depth; therefore, it can be a good indicator of the contacts between shale or clay beds and sand layers. The SP is a function of the chemical activities of fluids in the borehole and in adjacent rocks, the temperature, and the type and amount of clay present; it is not directly related to porosity and permeability. If the borehole fluid is fresher than the interstitial water in the rocks or sediments, a negative SP occurs opposite sand beds giving a response similar to the gamma log. If the salinities of the borehole and formation fluids are reversed, or if there is no salinity difference between borehole and formation fluids, the log will be a straight line, or in the case of fresh water sands, a positive SP deflection may occur.

- ***Single-Point Resistance Logging (SPR)***

The SPR log has been one of the most widely used in groundwater hydrology in the past; it is still useful in spite of the increased application of more sophisticated techniques for measuring resistivity. SPR logs are excellent for lithologic interpretation. SPR systems measure the resistance in ohms between two electrodes in the well. Because no provision exists for determining the length or cross-sectional area of the travel path of the current, the measurement is not an intrinsic characteristic of the material between the electrodes. Therefore, SPR logs cannot be related quantitatively to porosity or to the salinity of water in those pore spaces. SPR logs are greatly affected by changes in borehole

diameter, partly because of the relatively small volume of investigation. SPR logs have a significant advantage over multi-electrode logs in that they do not exhibit reversals as a result of bed-thickness effects. SPR logs deflect in the proper direction in response to the resistivity of formation materials adjacent to the electrode, regardless of bed thickness; thus, they have a very high vertical resolution.

- ***Normal-Resistivity Logging (16NR & 64NR)***

Among the various multi-electrode resistivity-logging techniques, normal resistivity is probably the most widely used in groundwater hydrology. The most important application of normal resistivity logs in groundwater hydrology is in evaluating water quality, although they may also be used for determination of salinity and lithology. The relation between corrected resistivity from normal logs and the concentration of dissolved solids in groundwater is valid only if the porosity and clay content are relatively uniform. Normal-resistivity logs can be interpreted quantitatively when they are properly calibrated in terms of ohm-meters. The normal logging systems employ two current electrodes, A and B, and two potential electrodes, M and N. The volume of investigation of the normal resistivity devices is considered to be a sphere, with a diameter approximately twice the AM electrode spacing. Thus, the long normal (64NR), usually 64 in, measures resistivity farther from the borehole than the short normal (16NR), which is usually 16 in. The difference between these two measurements may provide information on invasion by drilling fluids. Long normal (64NR) response is affected significantly by bed thickness effects, which are a function of electrode spacing; this problem can make the logs quite difficult to interpret.

- ***Lateral-Resistivity Logging (LATR)***

Lateral logs are performed with four electrodes like the normal resistivity logs, but with a different configuration of those electrodes. They measure the formation resistivity beyond the invaded zone. The most common uses are for determining lithologic contracts, and evaluating water quality, and salinity. The potential electrodes M and N are normally located 32 in. apart; the current electrode A is normally located 18 ft 8 in. above the center (O) of the MN spacing. Lateral logs are designed to measure resistivity beyond the invaded zone by use of very long spacing. They have several limitations that have restricted their use in water wells, primarily inhibition of response through PVC casing, and susceptibility to bed thickness effects. Best results are obtained when bed thickness is greater than twice the AO spacing, or more than 40 ft for the standard spacing. Anomalies are unsymmetrical about a bed, and the amount of distortion is related to bed thickness, as well as the effect of adjacent beds. The Century LATR log response is provided by a software transformation of 16NR and 64NR log response, so characteristics of the log are not well known.

- ***Fluid-Resistivity Logging (FRL)***

Logs of fluid resistivity, which is the reciprocal of fluid conductivity, provide data related to the concentration of dissolved solids in the fluid column. Although the fluid column may not reflect the quality of interstitial fluids in adjacent rocks, the information can be useful when combined with other logs. FLR logs are records of the capacity of the borehole fluid that enters the probe to transmit electrical current. The probe should not be affected by changes in the resistivity of adjacent fluids or solid materials because it is constructed with the electrodes inside a housing. Disturbance of the fluid column in the borehole can make fluid-resistivity logs difficult to interpret. It also may take a considerable time after drilling for the equilibrium fluid resistivity and temperature profiles to be established. Disturbance of an equilibrium salinity profile can be caused by the movement of logging probes or by convective cells. When both fluid conductivity and temperature are known, the equivalent sodium chloride concentration can be determined, but it may be necessary to correct this value for the presence of other ions. The logs can be used to monitor plumes of contaminated groundwater from waste-disposal operations. Another important use for fluid-resistivity logs is to aid in the interpretation of electric logs. Spontaneous potential, single-point resistance, and many types of multi-electrode-resistivity logs are affected by the salinity of the fluid in the borehole.

- ***Temperature Logging (TMP)***

Temperature logs can provide very useful information on the movement of water through a borehole, including the location of depth intervals that produce or accept water; thus, they provide information related to permeability. Temperature logs can be used to trace the movement of injected water or waste. Most of the temperature probes used in groundwater studies employ a glass-bead thermistor, mounted in a tube that is open at both ends to protect it from damage and to channel water flow past the sensor. Two general types of temperature logs are in common use: The standard temperature log (TMP) is a record of temperature versus depth; the differential-temperature log (DTMP) is a record of the rate of change in temperature versus depth. The differential temperature log can provide greater sensitivity in locating changes in gradient which can be related to intervals of increased groundwater flow. Temperature logs can aid in the solution of a number of groundwater problems if they are properly run under equilibrium conditions, as described under the above discussion on FRL. If there is no flow into, or adjacent to a well, the temperature gradually will increase with depth, as a function of the geothermal gradient. If vertical flow occurs in a well at a

high rate, the temperature log through that interval will show little change. Vertical flow, up or down, is very common in wells that are completed through several aquifers or fractures that have different hydraulic heads. Temperature logs can be used to locate plumes of wastewater that result from injection in wells or seepage from ponds or landfills.

- ***Caliper Logging (CAL)***

Caliper logs provide a continuous record of borehole diameter. Changes in borehole diameter may be related to both drilling technique and lithology. Caliper logs aid the interpretation of other logs since many log measurements are affected by changes in borehole diameter, and therefore should be corrected for borehole diameter to enhance accuracy. They also are useful in providing information on well construction, lithology, and secondary porosity. The most common type of probe used for logging water wells has three arms, approximately the diameter of a pencil, spaced 120 degrees apart. Arms of different lengths can be attached to this type of tool to optimize sensitivity over the borehole diameter range expected. Single-arm calipers are commonly used to provide a record of borehole diameter while running another types of logs, but may not be as sensitive as three-arm caliper logs. Notwithstanding the usefulness of the caliper log, it is often not obtained in environmental investigations where downhole logging is performed as a secondary or supplemental investigative tool, and where time critical drilling activity must be suspended to allow for log acquisition.

4.6.2 Borehole Geophysical Log Acquisition Program

Downhole geophysical data were acquired in selected Phase I and Phase II deep center boreholes, and selected Phase I perimeter deep cluster well boreholes prior to bedrock coring operations within landfill sections 1/9, 2/8, 3/4, and 6/7 (Table 4.9).

Downhole data were digitally acquired at the point of measure in each borehole at either a 0.1 or 0.5 ft digitization interval using a Century Geophysics, Inc. Compu-Log Portable borehole logging system, equipped with 9510, 9041, 9060, 0001 and 9032 multi-parameter tools, as well as a Robertson Geologging Ltd. Porta-Log borehole logging system equipped with an NG/EMI multi-parameter tool. All data acquired with the Century Compu-Log Portable borehole logging system were acquired at a constant rate of between 10 to 12 ft per min. A less constant rate was maintained with the Robertson Geologging, Ltd. Porta-Log borehole logging system due to the fact that the

system was outfitted with a manual drawworks. Paper records of each log were displayed in the field, and digital data were archived on the Compu-Log hard drive system, as well as 3.5-in. floppy diskettes. All down hole equipment and cables in contact with groundwater were steam cleaned prior to each logging operation.

The Compu-Log Portable geophysical logging system is fully self-contained and configured for portable operation, supporting a number of multi-parameter geophysical logging tools. These tools are lowered into the borehole via the Compu-Log drawworks, which is equipped with an electric motor drive, digital depth encoder with manual counter, automatic level wind and 600 ft of 3/16 in. diameter 4-conductor wire line cable. Multi-parameter data output from the downhole tool is converted into a frequency measured in counts per second (CPS), multiplexed, and telemetered at 2400 baud over the wire line cable every tenth of a second as a series of high and low frequency modulations used to represent the digital log data. This data transmission encoding scheme is based on Frequency Shift Keying (FSK) technology, and the digitally encoded signal contains all sensor readings for each tenth second, along with the tool's unique serial number. Once received by the Compu-Log computer, the attached tool is identified via its serial number and the multiplexed signal is interpreted via the tool interface board, utilizing First In, First Out (FIFO) and Universal Asynchronous Receiver Transmitter (UART) technologies. The corresponding depth reading is supplied to the interface board via the digital encoder on the drawworks that is coupled to a measuring wheel of known circumference, over which the cable is passed. Data are, therefore, digitized at the point of measure, thereby eliminating noise from the logging cable and insuring the integrity of data received at the surface.

The Century multi-parameter geophysical logging tools are designed to withstand a maximum pressure of 3000 psi within an operating temperature range of 32° to 176° F. The 9510, 9060, 9041 and 9032 tools are equipped with a scintillation type NAI crystal that provides for 90 percent of its response to a maximum radius of penetration of about 12 in. over an operating range of 0 - 600,000 CPS.

The Century 9510 tool measures 82.5 in. in length by 1.625 in. in diameter. It consists of a scintillation type NG detector and a four coil focussed EMI array driven by a 40 kHz sine wave with a constant current of 0.75 ampere peak. Approximately 50 to 90 percent of the total focussed EMI response derives from penetration radii of 5 to 24 in., with an accuracy of $\pm$5 millimho/meter (mmho/m). EMI readings below 5 mmho/m may not be considered accurate, and readings acquired

within formations with resistivities in excess of 200 ohm-m should not be used for quantitative purposes.

The Century 9060 tool measures 88 in. in length by 1.4 in. in diameter and is equipped with an NG detector that is smaller than that in the 9510 tool. The 9060 tool is also equipped with a downhole SP/SPR electrode that provides for 90 percent of its response to a maximum radius of penetration of about 10 in. SPR values in excess of 1000 ohms may be recorded but cannot be considered accurate and should not be used for quantitative purposes.

The Century 9041 tool measures 84 in. in length by 2.5 in. in diameter and is equipped with an NG detector that is approximately the same size as that in the 9510 tool, and a downhole SP/SPR electrode that is larger than that in the 9060 tool. The tool is also equipped with 16NR, 64NR potential and current electrodes that provide for maximum radii of penetration of 16 to 32 in., and 64 to 128 in., respectively. The LATR response is provided via a software transformation of the 16NR and 64NR response, providing for a maximum radius of penetration of about 48 in. SPR, 16NR, 64NR, and LATR values in excess of 2000 ohm-meters may be recorded, but cannot be considered accurate and should not be used for quantitative purposes. In addition to a downhole temperature thermistor that allows for the recording of fluid temperatures of between 50° and 122°F, the tool is equipped with an FLR detector.

The Century 0001 tool is designed to the same specifications as the 9060 tool, but the NG detector has been removed and replaced with a temperature thermistor designed to record fluid temperatures of between 32° to 122°F.

The Century 9032 tool used at the site measures 105 in. in length by 2.8 in. in diameter and is equipped with an NG detector that was smaller than that installed in the 9510 tool, as well as a single-long arm caliper designed to measure variations in borehole diameter ranging from 2.5 to 13 in.

The downhole NG/EMI tool used with the Robertson Geologging, LTD. Portalog system measures 96 in. in length by 1.7 in. in diameter and is equipped with an NG detector that is smaller than that in the 9510 tool. The tool is designed to withstand a maximum pressure of 2200 psi. within an operating temperature range of 32 to 158°F.

Century multi-parameter geophysical logging tools are calibrated in the laboratory by equating the counts per second (CPS) response of each sensor on a particular tool with known standards at two points, one at the high end and the other at a lower end of the sensor's sensitivity but within a normal range of radioactivity. The slope between the two points is assumed to be linear so that CPS values read by the sensor can be converted into engineering units. These conversion values are stored as calibration files on the hard drive of the Compu-Log computer. Whenever a tool is turned on, the system reads the tool's serial number and checks for the existence of a calibration file for the connected tool. Once existence has been verified, the system is capable of logging, and all downhole data are automatically converted from CPS response to engineering units before being archived and displayed.

The Compu-Log Portable System software, Personal Compu-Log (PCL), is a tree-structured, menu-driven program designed to allow the user to record, plot, save and process geophysical log data. The multi-tasking capability of PCL allows for more than one program function to be performed concurrently allowing for the plotting of a log file as it is recorded, providing a real-time plot of the borehole.

4.6.2.1 Borehole Geophysics Conducted in Landfill Section 6/7

Downhole geophysical data in Landfill Section 6/7 were acquired in boreholes 6W91:IT152D, 157D, 159D, 160D, and 6P91:IT664 with Century 9041, 9060 and 9010 multi-parameter tools; in boreholes 6B91:IT651, 652, 655, 660, 663, and 665 with Century 9041 and 9060 multi-parameter tools; and in boreholes 6W91:IT151D, IT156D, IT158D, IT160D, IT161D, IT163D, 6B91:IT657, 666, and 1P91:IT664 with Century 0001 and 9510 multi-parameter tools. All boreholes were logged from the maximum attainable depth to the surface and digitally recorded at 0.1 ft intervals, with the exception of boreholes 6W91:IT159D, IT160D, IT161D, and 6B91:IT657, which were recorded at 0.5 ft intervals. Temperature logs were acquired from the surface to depth on the first downhole run in each borehole so as to minimize borehole fluid (media) disturbance. Off-site manufacturer maintenance and recalibration of the 9510 tool prevented the acquisition of downhole conductivity data within PVC cased intervals of boreholes 6B91:IT651, 652, 644, 660, 663, and 665. A short in the Compu-Log surface ground cable prevented the acquisition of SP data in boreholes 6W91:IT160D and 161D. A steel stake attached to the drawworks via insulated copper wire was

used as the reference electrode during acquisition of downhole geophysical data in boreholes 6W91:IT151D, 156D, 163D, and 6B91:IT666.

The borehole fluid in borehole 6W91:IT152D was thickened with mud prior to geophysical logging in order to prevent caving. This factor coupled with the large borehole diameter resulted in attenuation of the geophysical logs, and further prevented the lowering of the 9510 tool past -30 ft, thereby precluding acquisition of NG/EMI data below this elevation[3]. Caving of borehole 6W91:IT160D after the first 0001 logging run prevented acquisition of data below an elevation of -55 ft on subsequent runs. Caving or borehole geometry prevented the acquisition of data with the 9041 tool below an elevation of -42 ft in borehole 6B91:IT651. During the construction of borehole 6B91:IT652, the drilling contractor noted that large quantities of drilling fluid began to enter the formation at an elevation of -67 ft. Mud thickened borehole fluid prevented the acquisition of data with the 9510 tool past an elevation of -50 ft in borehole 6B91:IT657. The casing bottom elevation reported by the drilling contractor appeared to be about 5 ft shallower than that indicated in the geophysical logs for borehole 6B91:IT663. Caving of borehole 6B91:IT665 prevented acquisition of data on the first 0001 logging run below an elevation of -38 ft. The borehole was re-drilled and flushed out with water, allowing for the borehole to be logged to total depth on subsequent 0001 and 9510 logging runs.

4.6.2.2 Borehole Geophysics Conducted in Landfill Section 1/9

Downhole geophysical data in Landfill Section 1/9 were acquired in boreholes 1W91:IT004D, 005D, 006D, and 1B91:501, 503, 505, 511, 514 with Century 9041, 9060, and 9510 multi-parameter tools; in boreholes 1W91:IT002D, 003D, 010D, and 1B91:IT506 with Century 9060 and 9510 multi-parameter tools; in boreholes 1W91:IT007D, 008D, 011D, 012D, 013Z, 1B91:IT502, 508, 509, 512, and 1P91:IT504, 507 with Century 0001 and 9510 multi-parameter tools; and in borehole IT510 with the Century 0001 multi-parameter tool. All boreholes were logged from the maximum attainable depth to the surface and digitally recorded at 0.1 ft intervals, with the exception of boreholes 1W91:IT011D and 1B91:IT509, which were recorded at 0.5 ft increments. Temperature logs were acquired from the surface to depth on the first downhole run in each borehole so as to minimize

[3]This and subsequent references to elevation within Section 4.6.2 refer to the Richmond County High Water Datum.

borehole fluid media disturbance. A short in the Compu-Log surface ground cable prevented the acquisition of SP data in borehole 1W91:IT011D and a tool transmission error prevented the acquisition of NG and EMI data in borehole 1B91:IT510. A steel stake attached to the drawworks via insulated copper wire was used as the reference electrode during the acquisition of downhole geophysical data in boreholes 1W91:IT007D and 1B91:IT510. A malfunction in the Century 9041 tool and lack of availability of a replacement 0001 tool prevented the acquisition of downhole TMP and DTMP data in boreholes 1W91:IT002D, 003D, 010D, and 1B91:IT506.

Borehole obstructions at approximate elevations of -13 and -29 ft necessitated several attempts at lowering of the 9060 tool to depth in borehole 1W91:IT005D. A borehole obstruction at an approximate elevation of -30 ft necessitated several attempts at lowering of the 9060 and 9510 tools to depth in the borehole 1W91:IT006D.

The mud thickened borehole fluid in borehole 1W91:IT008D was allowed to set-up for a few days prior to downhole logging. This prevented the lowering of logging equipment to depth in the borehole. The borehole was reamed prior to logging with the 0001 tool. Upon completion of the 0001 logging run, two-inch diameter Schedule 40 PVC riser was inserted to depth, the annulus flushed with water, and the borehole logged with the 9510 tool through the PVC riser. The drilling contractor noted that a large amount of metallic debris was encountered while drilling through refuse material in borehole 1W91:IT008D, some of which was believed to have been pushed down into the underlying sediments during borehole advancement. Metallic debris introduced into a borehole while drilling through refuse will produce low resistance, readily evident in electric logs.

The inaccessibility of borehole 1W91:IT011D due to terrain conditions necessitated that the Compu-Log surface unit and drawworks be located about 160 ft from the actual borehole location. Borehole obstructions at approximate elevations of -29, -46, -69, and -75 ft were noted while lowering the 0001 tool to depth in borehole 1W91:IT011D.

The top of the 9510 tool became hung-up on the bottom of the steel casing during the logging of borehole 1W91:IT012D, necessitating the tool to be fished out and relowered to the bottom of the casing, enabling the remainder of the borehole to be logged. The inaccessibility of borehole 1P91:IT013Z due to terrain conditions, and the location of drilling equipment, necessitated that the Compu-Log surface unit and drawworks be located about 30 ft from the actual borehole location.

Borehole 1B91:IT502 was first logged on July 12, 1991. After successful logging of the borehole with the 0001 tool, the 9510 tool became hung-up on the bottom of the steel casing and the run was aborted. Two in. diameter Schedule 40 PVC riser was inserted to depth in the borehole, the annulus was flushed out with water, and the borehole was re-logged with the 9510 tool on July 15, 1991. Borehole 1B91:IT502 was logged again with the 9510 tool on August 1, 1991 as a calibration check, and also to determine whether temporal changes in downhole conductivity due to formation fluid were occurring. No appreciable change in conductivity was noted.

SPR values in excess of the 0001 tool cut-off value of 1000 ohm-meters were noted below an elevation of -45 ft in borehole 1P91:IT504 during the first run with the 0001 tool. The borehole was, therefore, re-logged with the 0001 tool and the Compu-Log System set so as to record SPR data in CPS for later conversion to ohm-meters, via a software transformation.

Steam was noted to be rising from the top of protective casing during borehole logging operations in borehole 1B91:IT506, suggesting elevated temperature of the borehole fluid.

The lowering of the 9510 tool past an elevation of about -45 ft in borehole 1B91:IT509 was not possible due to borehole diameter effects preventing acquisition of downhole NG/EMI data below that elevation. Geophysical logs acquired in borehole 1B91:IT510 indicate the casing bottom elevation to be about 7 ft shallower than that reported by the drilling contractor.

The noisy appearance of the SP log acquired in the first 0001 tool logging run at borehole 1B91:IT510 is likely the result of activation of the drill rig water pump midway through the run.

SPR values in excess of the 0001 tool cut-off value of 1000 ohm-meters were noted below casing to an elevation of about -75 ft in borehole 1B91:IT512 during the first 0001 tool logging run. The borehole was re-logged with the 0001 tool and the Compu-Log System set so as to record SPR data in CPS for later conversion to ohm-meters, via a software transformation.

4.6.2.3 Borehole Geophysics Conducted in Landfill Section 2/8

Downhole geophysical data in Landfill Section 2/8 were acquired in boreholes 2W91:IT302D, 2B91:IT801, 802, 804, 805, 809 and 2P91:IT806 with Century 0001 and 9510 multi-parameter tools;

in borehole IT301D with the Century 9510 multi-parameter tool, and in borehole 2B91:IT808 with the Century 0001 and 9032 multi-parameter tools, as well as the Robertson Geologging Ltd. NG/EMI tool. All boreholes were logged from the maximum attainable depth to the surface and digitally recorded at 0.1 ft increments, with the exception of boreholes 2B91:IT801, 802, 805, and 2P91:IT806, which were recorded at 0.5 ft intervals. Temperature logs were acquired from the surface to depth on the first downhole run in each borehole so as to minimize borehole fluid media disturbance. A steel stake attached to the Compu-Log drawworks via insulated copper wire, was used as the reference electrode during acquisition of downhole geophysical data in boreholes 2B91:IT801, 802, and 805.

Borehole construction and monitoring well installation had been completed in borehole 2W91:IT301D prior to downhole geophysical logging operations, and one 9510 tool logging run was completed through the 4-in. PVC riser from depth to the surface.

A borehole obstruction in borehole 2W91:IT302D at an elevation of -45 ft was noted while lowering the 0001 tool downhole. Difficulty was encountered while lowering the 9510 tool through mud-thickened borehole fluid in boreholes 2B91:IT802 and 805. It was not possible to acquire NG and EMI data below an elevation of -55 ft and SP, SPR, TMP data below an elevation of -65 ft in borehole 2B91:IT805. A shelby tube was lost at an elevation of about -40 ft in borehole 2B91:IT802 and pushed to the side of the borehole annulus during construction.

A 5 ft section of 3 in. steel casing was lost within the refuse during the construction of borehole 2B91:IT808. The single long-arm caliper on the 9032 tool was calibrated on-site with 4 in. ID and 10 in. ID sections of pipe before being lowered into the borehole. Digital EMI data in borehole 2B91:IT808 was lost due to a computer malfunction.

4.6.2.4 Borehole Geophysics Conducted in Landfill Section 3/4

Downhole geophysical data in Landfill Section 3/4 were acquired in borehole 3W91:IT405D, 406D, and 3B91:IT904, 908 and 909 with Century 0001 and 9510 multi-parameter tools; in boreholes 3B91:IT901 and 903 with Century 9060, 9041, and 9510 multi-parameter tools; and in borehole 3B91:IT902 with the Century 0001 and Robertson Geologging, Ltd. NG/EMI multi-parameter tools. All boreholes were logged from the maximum attainable depth to the surface and digitally recorded

at 0.1 ft intervals, with the exception of boreholes 3B91:IT901, IT903, IT908 and IT909, which were recorded at 0.5 ft intervals. Temperature logs were acquired from the surface to depth on the first downhole run in each borehole so as to minimize borehole fluid media disturbance.

The drilling contractor noticed metal filings and debris within drill cuttings and borehole fluid during advancement of borehole 3B91:IT903, and suspected that metallic debris was dropped into the borehole during drilling. As previously noted, metallic debris within the borehole will produce low resistance readily evident in electric logs.

Running sands in borehole 3B91:IT904 necessitated that the borehole be logged in two stages. The first 0001/9510 tool logging runs were conducted with 4 in. steel casing set at an elevation of -52 ft. The 4 in. steel casing was then pulled up to an elevation of -9 ft and the second 0001/9510 tool logging runs were completed three days later. SPR values in excess of the 0001 tool cut-off value of 1000 ohm meters were noted throughout the first 0001 tool logging run. Calibration testing of the 0001 tool, as well as cable continuity checks performed upon completion of the run indicated the logging system to be operating properly and the high SPR values are attributed to borehole diameter effects.

4.7 Water Quality Sampling and Analysis

In accordance with Task (14) of Appendix A-6, and Task (9) of Appendix A-4 to the Consent Order, a program of groundwater sampling and analysis was implemented at the project site. Two quarterly monitoring programs are identified in Consent Order Appendix A-6: (1) Sampling and analysis of NYCDOS wells installed in 1989, additional existing wells identified through performance of the Groundwater Monitoring Well and Piezometer Survey Report (IT Corporation, 1990c) from which representative sample can be obtained, and all newly installed wells for 6 NYCRR Part 360 Expanded parameters, starting in January 1991 and continuing until the development of a long term monitoring program, and (2) sampling and analysis of NYCDOS piezometers installed in 1989 and off-site water supply wells identified through performance of the Supply Well Survey Report (IT Corporation 1991a) from which representative sample can be obtained for 6 NYCRR Part 360 Baseline parameters, starting in April 1991 and continuing for one year.

Table 4.10 provides a summary of all well sampling activity performed through 1992. Sampling was initiated on December 31, 1991 (in accordance with Milestone 12 of Appendix A-6) at existing wells in Landfill Sections 1/9 and 6/7. Sample analysis was performed by the IT Corporation Analytical Services (ITAS) Laboratory in Edison, NJ, with periodic support from ITAS Laboratories in Monroeville, PA and Cincinnati, Ohio. As described in more detail in Section 4.7.2, ongoing analytical program development between NYSDEC and NYCDOS resulted in the postponement of April 1991 quarterly sampling activities until the July 1991 sampling quarter. Program development during this period included expansion of the scope and content of Quality Assurance Program and Project Plan documents beyond the baseline requirements of 6 NYCRR Part 360, and identification of project specific analytical criteria, including groundwater constituent specific data quality objectives (Table 4.11) and initial project critical parameters defined by NYSDEC (Table 4.12).

The July 1991 sampling quarter was initiated on August 7, and completed on September 24. A total of 84 wells and 2 leachate collection pump stations were sampled for Expanded parameter analysis, and 5 wells and piezometers were sampled for Baseline parameter analysis. As noted on Table 4.10 sample recovery was not accomplished at a number of wells and piezometers. These generally included piezometers installed in 1989 by NYCDOS (which were not constructed as permanent installations), and a number of deep bedrock wells (primarily in Landfill Section 1/9) that exhibited extremely low yield and/or elevated pH. Subsequent intensive re-development (purging/surging/flushing) of these bedrock wells (Report Section 4.3.3) resulted in their rehabilitation for inclusion in the January 1992 sampling quarter.

Following independent validation of analytical data obtained from the July 1991 sampling quarter, review of parameter data and test method performance by NYSDEC and NYCDOS resulted in additional analytical program refinement through December 1991. These activities led to the deferment of the October 1991 sampling quarter to January 1992.

The January 1992 sampling quarter was initiated on January 20, and completed on February 27. A total of 121 wells and 2 leachate collection pump stations were sampled for Expanded parameter analysis, and 5 wells and piezometers were sampled for Baseline parameter analysis. Sample recovery was not achieved at two DOS 1989 wells and two Phase I bedrock wells due to a lack of yield. The previously noted bedrock well rehabilitation program was responsible for reducing the number of non productive bedrock wells from 12 to 2 between the July 1991 and January 1992 sampling quarters.

The April 1992 sampling quarter was initiated on April 20, and was completed on May 21. A total of 119 wells and 2 leachate collection pump stations were sampled for Expanded parameter analysis. A total of five wells and piezometers were sampled for Baseline parameter analysis. Poor recovery precluded sample collection from one DOS 1989 well and three Phase I bedrock wells. Due to repeated vandalism at cluster 402, these wells were abandoned and subsequently deleted from the sampling program.

The July 1992 sampling quarter was initiated on July 20, and was completed on September 9. A total of 144 wells and 2 leachate collection pump stations were sampled for Expanded parameter analysis. A total of five wells and piezometers were sampled for Baseline parameter analysis. Poor recovery precluded sample collection from 6 Phase I bedrock wells. Sample collection at the NYCDOS 1989 wells located on Section 1/9 ('XW' wells) was discontinued beginning with this quarter as they had achieved four quarters of Expanded Parameter analysis, and are not located appropriately for incorporation into the perimeter monitoring well array. NYCDOS 1989 wells located at Section 6/7 ('YX' wells) were maintained in the sampling program.

The October 1992 sampling quarter began on October 14 and was completed on December 17. A total of 219 wells and 2 leachate collection pump stations were sampled for Expanded parameter analysis. One well was sampled for Baseline parameter analysis. Poor recovery precluded sample collection from one Phase I bedrock well, one Phase II bedrock well, and nine Phase II shallow wells. In addition, two wells were not sampled due to bent or obstructed well casings. Beginning with this sampling quarter, sampling of the DOS 1989 piezometers on Sections 1/9 and 6/7 was discontinued because they had achieved four quarter of Baseline Parameter analysis as per the requirements of the Consent Order.

The January 1993 sampling quarter was initiated on January 18 and was completed on March 25. A total of 221 wells and 2 leachate collection pump stations were sampled for Expanded Parameter Analysis. Poor recovery obviated sample collection from four Phase I bedrock wells and five Phase II shallow wells. Additionally, sample collection was precluded from two locations previously identified as having bent or obstructed well casings. Because the NYCDOS 1989 wells on Section 6/7 ('YW' wells) were to be included in the Long Term Monitoring Program, sample collection from these locations was reinstituted during this sampling quarter.

As a supplement to the sampling programs stipulated under 6 NYCRR Part 360 and the Consent Order, a limited indicator parameter/geochemical sampling program was integrated into the larger water quality sampling program. This program entailed the collection of filtered sample to minimize the localized affects on turbidity of constituent concentration, and allow for the accurate calculation of sample ion balances.

Table 4.13 provides a summary of all well sampling activity associated with the indicator parameter and geochemical testing programs. Indicator parameter sample was obtained from all monitoring wells and nested piezometers (as feasible) during the July 1991 (Sections 1/9 and 6/7) and January 1992 (Sections 2/8 and 3/4) sampling quarters to allow for an assessment of the spatial variability of water chemistry in support of Phase II Well Installation Program design. Geochemical parameter sample (including indicator parameters, metals, and several stable and radiogenic isotopes) was obtained from a subset of upgradient and downgradient well clusters and nested piezometers (as feasible) during the July 1991 (Section 6/7) and January 1992 (Sections 1/9, 2/8 and 3/4) sampling quarters to allow for geochemical characterization and flow path analysis. In addition, the full suite of geochemical parameters was obtained from all completed monitoring wells at Section 1/9 during the July 1992 sampling quarter.

4.7.1 Sampling Protocols

Well purging and sampling was performed in accordance with the standard operating procedure contained in Attachment 7 to Appendix A (QAPjP) of the SIP (IT Corporation, 1990a). Sampling subsequent to the January 1991 quarter (which entailed sample collection with dedicated pump equipment) followed Revision 1 to this document, dated July 26, 1991. Field data recorded during performance of the sample collection activity was documented for each well on a Well Purging and Sampling Log. Attachment 9 contains a full record of these logs for all sampling activity to date. The following discussion summarizes the referenced well purging and sampling protocol.

The static water level in each well was measured with an electric tape prior to beginning ground water sampling activities. The well was then monitored to ascertain the presence of non-aqueous phase liquids (NAPLs) using a transparent bailer. No NAPLs have been detected to date in the sampling program. Where NAPLs are detected, these liquids are to be sampled and analyzed separately for

organic parameters listed in NYCRR 373-2, Appendix 33 to the maximum extent practicable based on sample recovery volume.

Following the measurement of the static water level in the well to be sampled, the depth of the water column in the well was calculated to estimate the volume of water to be evacuated. Evacuation of water standing in the well casing was performed to ensure for the collection of samples representative of the ground water present in the surrounding formation.

Evacuation procedures implemented by the field sampling team varied according to well casing diameter, well depth, and depth to static water level. A minimum of three well volumes (including filter pack volume) was purged from all wells except those exhibiting extremely low recovery; in the latter case, a minimum of one casing and filter pack volume was purged prior to initiation of sample recovery. Well purging was performed with centrifugal or submersible pumps or bailers. A dedicated PVC discharge hose was assigned to each well location and the hose was disposed of following use. Evacuated ground water was routed away from surface waters to the maximum extent possible and discharged to the ground surface.

Bailers were used to evacuate all low yielding shallow wells where pumping was not practical due to rapid dewatering. Submersible pumps (2.75 in. and 1.75 in. diameter) were used to purge deep 4 in. diameter and intermediate depth 2 in. diameter wells, respectively. Centrifugal pumps were used to purge shallow 4 in. diameter wells. Samples for geochemical analysis requiring filtration were collected subsequent to the purging operation and prior to pump removal, using in-line 0.45 micron filters.

Groundwater samples were collected by bailer subsequent to the performance of well evacuation. Separate decontaminated and foil wrapped bailers were used to collect sample at each well location. Bailers were constructed of inert materials (stainless steel or teflon) to preclude influencing the chemical composition of the samples. Following each sampling event, the bailers were decontaminated at the IT Edison, NJ project office in accordance with an 8 step wash, rinse and air dry protocol. The 8 step protocol (which included an acetone rinse) was modified during the July 1991 sampling quarter to a 10 step protocol substituting hexane and methanol rinses for the acetone rinse, due to the detection of trace quantities of acetone in several field (equipment) blanks. Following decontamination, bailers were wrapped in autoclaved aluminum foil, and placed in storage for later re-use.

As noted subsequently, dedicated bladder pump equipment was progressively installed in all monitoring wells starting in the January 1992 sampling quarter. Use of these pumps obviated the need for separate submersible/centrifugal pump and bailer equipment and associated decontamination procedures. Well purging and sampling was then performed by simply controlling the rate of groundwater flow through the dedicated discharge tubing system, by varying the compressed air driven pump cycle.

Field program QC was maintained through the collection of daily trip (travel) blanks and field (equipment) blanks. Two trip blanks and one field blank were collected each sampling day. The trip blanks consisted of six, 40 ml vials containing laboratory-grade deionized water. The trip blank containers were filled at the laboratory, transported with the sample containers, and returned unopened to the laboratory with ground water samples for analysis. The field blank consisted of deionized water rinsate collected from the field sampling equipment. The field blank containers were filled in the field and returned to the laboratory with ground water samples for analysis.

Laboratory QA/QC was supported through the daily or biweekly (depending on sample batch size) collection of matrix spike and matrix spike duplicate sample from each sampling matrix. Two matrices were identified for the Fresh Kills Landfill Leachate Mitigation project: (1) leachate or leachate influenced groundwater obtained from wells screened in the refuse mounds and in the shallow water table aquifer along the perimeter of the landfills, and (2) groundwater obtained from perimeter wells screened in intermediate depth and deep (bedrock) aquifer units. In addition, a one in twenty sample duplicate was obtained in accordance with sampling frequency. The sample duplicate represents a split sample that was collected concurrent with primary sample collection.

Sample volumes were retrieved from the well and transferred to sample containers in the following order:

- VOC sample
- Hexavalent chromium
- Other metals parameters
- Field measured parameters (temperature, pH, Eh, specific conductance, salinity, dissolved oxygen)
- Semi-volatile organic compounds
- Cyanide
- Remaining general chemistry parameters

Following sample collection and documentation of sampling activity, samples were transported in an iced cooler to an on-site staging trailer, where sample preservation was performed, as necessary, and chain-of-custody paperwork (initiated at the ITAS laboratory in Edison, NJ) was completed. Sample coolers were then transported twice daily to the ITAS laboratory for check-in, cold box storage, and analysis.

As an additional measure to improve the quality of sample collection and address chronic low yields associated with many of the deeper wells at the project site, dedicated bladder pump systems were installed in all of the bedrock and intermediate depth wells during February and April 1992, respectively. The equipment selected for this project was the QED, Inc. Series 1200 bladder pump. Table 4.14 documents the location, date of installation, and additional details regarding the pump assembly at each location. Dedicated bladder pumps were used to collect groundwater sample from all bedrock wells starting with the January 1992 quarter, from all intermediate wells starting with the April 1992 quarter, and from all shallow wells starting with the October 1992 quarter. A revision to the standard operating procedure for well purging and sampling (Attachment 7 to Appendix A of the SIP) to accommodate dedicated bladder pump systems was prepared during October 1992 as an addendum to Revision No. 3 of the Quality Assurance Project Plan (QAPjP).

The bladder pump body and fittings are constructed of stainless steel with a PTFE (Teflon) bladder. All sample delivery lines are constructed of polyethylene with a PTFE lining. Air lines are unlined polyethylene. Pump and packer suspension cables are constructed of PTFE-coated stainless steel. To minimize purge time, specially designed high pressure and vented packers were used in many of the deep wells. All pumps supplied by QED are decontaminated certified clean (analyte free) by QED, Inc. All cables and tubing were cut to length, preassembled, and sealed in plastic at the factory prior to shipment to the project site for installation.

4.7.2 Analytical Protocols

Groundwater quality analysis performed as part of the Hydrogeologic Investigation was executed in conformance with the methods and procedures used for data collection and analysis as required in 6 NYCRR 360-2.11 and outlined in the Fresh Kills Leachate Mitigation System Project Quality Assurance Program and Analytical Project Plans (QAPP, QAPjP). The analytical protocol applied to the project was executed according to Test Methods for Evaluating Solid Waste (SW-846) and

the New York State Analytical Services Protocol (ASP) [1991], with program modifications implemented by NYCDOS and NYSDEC.

The Quality Assurance Program Plan was developed to document that project work would be performed of known and demonstrable quality to accomplish project objectives. This document defined the IT Corporation Analytical Services (ITAS) division laboratory organization and quality management responsibilities as well as general analytical program requirements. Defined also were the objectives for data measurement to provide data of known quality suitable for project decision making. The QAPP was prepared initially on September 4, 1990, and subsequently revised on September 11, 1990 (Revision 1), and September 5, 1991 (Revision 2). Additional modifications were made on July 15, 1992 and July 29, 1992 in the form of addenda to Revision 2.

In accordance with the QAPP, a laboratory analytical Quality Assurance Project Plan (QAPjP) was created to define project critical parameters, data quality objectives (DQOs) and specify what analytical methods would be applied to meet project-defined method detection limits or practical quantitation (reportable) limits (PQLs). This document was originally prepared on July 27, 1990, and subsequently revised on September 6, 1990 (Revision 1), August 9, 1991 (Revision 2), and January 17, 1992 (Revision 3). Revision 3 was updated by addenda dated July 15, 1992 and July 29, 1992, and May 3, 1993.

The Analytical QAPjP contains the QA guidelines for the following analytical areas:

- Laboratory organization and quality management responsibilities
- Sampling and sample custody procedures
- Analytical procedures
- Calibration procedures and frequency
- Preventative maintenance
- Data verification
- Data analysis and reporting
- Non-conformance and corrective action
- Performance audits.

The laboratory standard operating procedures (SOPs) are contained in the Analytical QAPjP detailing the laboratory procedures and analytical methods specific to the Fresh Kills Landfill Leachate Mitigation System Project.

Constituent specific Data Quality Objectives (DQOs) for groundwater, identified as part of QAPjP development were identified previously on Table 4.11. The DQOs are based on New York State groundwater standards, criteria, and guidelines, and the analyte specific practical quantitation limits (PQLs) of the laboratory analytical test methods. Critical parameters for groundwater analysis, also identified within the context of QAPjP development following consultation with NYSDEC and NYCDOS, were referenced previously on Table 4.12. Critical parameters represent detected analytes for which valid data must be obtained to satisfy the objectives of sampling and analysis tasks. As additional analytical results are generated from the monitoring well sampling program (and the surface water and sediment sampling programs), additional critical parameters may be added to the project list (Section 8.0).

Table 4.15 indicates the laboratory performance Data Quality Objectives (PARCC parameters) identified for the suite of analytical test methods identified for groundwater sample analysis under the Fresh Kills Landfill Leachate Mitigation System Project. The PARCC parameters represent defined analytical program quality assurance levels relative to the precision, accuracy, representativeness, completeness, and comparability of test data.

4.8 Water Level Data

Groundwater and surface water level elevations were monitored throughout the course of the hydrogeologic field investigation. Water level data were collected or recorded from the piezometers, monitoring wells, and staff gauges installed for this investigation, as well as existing NYCDOS wells and piezometers.

Water levels were collected manually, using electronic water level indicator probes, and/or automatically at selected locations,using pre-calibrated pressure transducers and data loggers. All water level measurements were recorded to an accuracy of one-hundredth (0.01) of a foot and converted to site control elevations. Table 4.16 provides a summary of all monitoring locations for the hydrogeologic investigation, and indicates the time frame of continuous data recovery and/or periods of manual synchronous measurements.

4.8.1 Groundwater

During the hydrogeologic investigation at the Fresh Kills Landfill, groundwater level elevations were obtained and monitored at each of the monitoring well locations installed at the four landfill sections. These groundwater data were used to:

- Generate water table and piezometric surface maps for each hydrostratigraphic unit
- Estimate groundwater flow direction
- Estimate groundwater horizontal and vertical gradients
- Evaluate tidal influence on the groundwater flow regimes

The water level monitoring task included continuous water level data collection at all of the Phase I monitoring locations installed in accordance with the SIP (IT Corporation, 1990a). Water level measurements were continuously recorded to obtain transient water level data. Transient water level data were used to determine the effect of tidal action on groundwater flow within the local shallow and deep flow systems, as well as assess tidal influence on local surface water flow.

At each well cluster location a Telog Inc. electronic data logger and calibrated pressure transducer(s) were installed to record changes in head over time. At many locations, a single recorder (data logger) was used to record data from multiple wells. Pressure transducers were placed below the static water levels, within the water column, at depths calculated to monitor anticipated maximum and minimum level changes in the wells. Following initial analysis of preliminary data, transducer depths were adjusted as needed. Prior to the start of the data recorder, the static water level was measured with an electric water level indicator or a weighted graduated PVC measuring tape, and recorded for calibration purposes. At all of the monitoring locations the Telog Inc. data loggers were set to record water level changes at 30 minute intervals.

The transducer cable length was measured from the top of inner casing (TIC) elevation to the pressure probe, so that a quality control program could be established to maintain the accuracy of the readings being recorded (i.e., transducer cable length = static water level + transducer water level reading [from the recorder]). The QC program identified initial inaccuracies in recorded data at several locations due to the removal and reinstallation of pressure transducers as part of the quarterly well purging and water quality sampling program. Consequently, nylon cable tie wrap was installed at all locations to secure the transducer cable to the well riser, thus preventing misplacement of the transducer during subsequent water sampling activities, and insuring for accurate water level measurements.

At all existing wells and piezometers (i.e., 1989 NYCDOS installations), selected Phase I installations (where continuous recorder installation was pending or equipment was under repair due to prior vandalism), and all Phase II wells and piezometers, manual synchronous measurements were obtained to supplement the continuous data record. The following procedure was utilized to manually obtain water levels at a single point in time:

1. Locking casing and surface seal were inspected for integrity.

2. The depth to water from the reference point was measured using an electronic water level meter.

3. All measurements were made to an accuracy of +/- .01 ft.

4. Water level data were recorded in a notebook by field personnel as collected. Information recorded in the field book included: monitoring location, date, time of measurement, depth to water surface, reference point, and any observations noted.

5. All measuring devices were decontaminated prior to and between measurements at different locations using a methanol, then a distilled water rinse.

The following procedure was used to continuously collect and record water level data in monitoring wells using data loggers and pre-calibrated pressure transducers.

1. The water level in the well was measured and recorded as described above in a notebook by field personnel. This information included: well designation, Telog unit identification number, time, date, depth to water surface, reference point, recording length, recording interval, transducer psi, cable length, transducer reading.

2. A pre-calibrated pressure transducer was placed below the static water level in the well and connected to a data logger to measure and record head changes with time for each well monitored.

3. Stored recorder data was periodically downloaded to a portable computer.

Two types of Telog Inc. data loggers were installed at Fresh Kills: Model R-2400 Series Recorder and WLS-2109, each consisting of a circuit board enclosed in a rainproof NEMA-3R enclosure. All inputs to the recorder are made via an input terminal block located on the recorder's circuit board. All signal cabling is brought through knock-outs built into the enclosure. The WLS-2109 water level

recorder is a single channel recorder and was installed primarily at surface water monitoring locations to record tidal level changes (Section 4.8.2).

The 2400 Series Recorder has up to four independent channels for data collection, and was installed at all of the well cluster locations. Each channel provides the general functions of signal conditioning, analog-to-digital conversion of the input signal, data reduction, and data storage. Both recorder models communicate with a computer via direct connection with a Telog-supplied cable connecting the computer's serial port to the recorder's serial port. This method allows for both programming of the recorder as well as collecting data. Use of a portable computer for data acquisition avoids interruption of data collection. Continuous water level data were collected and temporarily stored in the Telog recorders, then periodically transferred to a computer for further data reduction and analysis.

- ***Landfill Section 6/7***

At Landfill Section 6/7, 32 monitoring wells and piezometers were equipped with Telog data loggers to automatically record water level changes. Eleven 1989 NYCDOS wells and piezometers and 33 Phase II monitoring wells were periodically monitored using manual measurements. Installation of data logger and pressure transducer equipment was initiated in April 1991 and continued into December 1992.

- ***Landfill Section 1/9***

At Landfill Section 1/9, 48 monitoring wells and piezometers were equipped with Telog data loggers to automatically record water level changes. Nineteen 1989 NYCDOS wells and piezometers, one Phase I and thirty eight Phase II monitoring wells were periodically monitored using manual measurements. Installation of data logger and pressure transducer equipment was initiated in April 1991 and continued into December 1992.

- ***Landfill Section 2/8***

At landfill Section 2/8, 21 monitoring wells were equipped with Telog data loggers to automatically record water level changes. Water levels at one Phase I and 21 Phase II monitoring wells were periodically monitored using manual measurements. Data logger and pressure transducer installation

occurred primarily during the month of November 1991. Installation at cluster location IT307 was delayed until February of 1992 due to the location of this well array adjacent to a public roadway, and the need to locate the monitoring equipment in a secure, subsurface road box. Monitoring continued at all instrumented locations into December 1992.

- ***Landfill Section 3/4***

At landfill Section 3/4, 21 monitoring wells were equipped with Telog data loggers to automatically record water level changes. Water levels at 24 Phase II monitoring wells were periodically monitored using manual measurements. Data logger and pressure transducer installation occurred primarily during the months of October and November 1991. Vandalism of data logger recorders at well cluster locations IT401, 402, 403 and 404 resulted in data loss and downtime as data logger equipment was repaired and re-installed in secure, subsurface road boxes. Monitoring at all instrumented locations continued into December 1992.

4.8.2 Surface Water

Surface water level elevation data were obtained from stand pipe installations in the Arthur Kill, Main Creek and Richmond Creek, and staff gauges placed along an unnamed tidal tributary lying within the eastern boundary of Landfill Section 6/7.

The stand pipes were installed to provide a basis from which to evaluate the hydraulic response to tidal fluctuations in the aquifer units underlying the project area. The staff gauges were installed to assess hydraulic communication between the upper water bearing zone and surface drainage along the eastern margin of Section 6/7.

Stilling wells were installed during August 1991 at the landfill barge staging area catwalk on the Arthur Kill adjacent to the northwestern margin of Landfill Section 1/9 (tidal gauge A), at the Main Creek bridge crossing between Landfill Sections 6/7 and 3/4 (tidal gauge B), and at the Richmond Creek bridge crossing between Landfill Sections 6/7 and 2/8 (tidal gauge C). Locations of these installations are indicated on Figure 4.33. These installations were constructed as follows:

- A slotted 4-inch PVC riser pipe was lowered vertically beneath the surface of the water and secured to a fixed fence post which was driven into the bottom.
- A pre-calibrated pressure transducer was lowered inside the 4-in. PVC pipe to the bottom and connected to a single channel Telog data logger model WLS-2109.
- The total length of the PVC riser was measured and recorded in a notebook by field personnel.
- The top of the installation was later surveyed for elevation and location.

The data loggers at the stilling well locations were set to record data at 15 minute intervals to monitor the rapid change in water levels caused by diurnal tide cycles.

Two temporary staff gauges were located along an unnamed tidal tributary located inside the eastern boundary of Landfill Section 6/7. As indicated on Figure 4.33, one gauge was located to the north, at the northeast end of a ponded water area (SG-1), and a second gauge was located to the south, approximately 750 ft north of the tributary confluence with Richmond Creek (SG-2). The gauges were constructed of an iron fence post hand-driven into the stream bed, of a length suitable to permit the collection of year-round stage recordings, and were installed to extend a minimum of one foot above the anticipated peak stage levels. Manual measurements were periodically collected at these locations with synchronous level measurements obtained from monitoring wells.

4.9 Consent Order Deliverables

As described in earlier portions of the text, a number of documents have been prepared and submitted to NYCDOS in accordance with the reporting requirement of Consent Order Appendices A-6. These are summarized as follows:

Milestone 7: Hydrogeological Site Investigation Plan (IT Corporation, 1990a; Attachment 42)

Milestone 8: Groundwater Monitoring Well and Piezometer Survey Report and Addendum (IT Corporation, 1990c, 1991b; Attachment 43)

Milestone 10: Supply Well Survey Report (IT Corporation, 1991a; Attachment 45)

Milestone 11: Hydrogeological Literature Review and Addendum (IT Corporation and Wehran EnviroTech, 1991a, 1991c; Attachment 44)

Milestone 13: Interim Hydrogeological Report (IT Corporation, Wehran EnviroTech, and O'Brien & Gere, 1992a)

Milestone 14: Draft Final Hydrogeological Report (IT Corporation, Wehran EnviroTech, and O'Brien & Gere, 1993a)

Milestone 15: Final Hydrogeological Report (IT Corporation, Wehran EnviroTech, and O'Brien & Gere, 1993b)

All documents through Milestone 11 were submitted to NYSDEC on or in advance of the milestone dates stipulated in the Consent Order, and subsequently deemed acceptable by the regulatory agency. A three month extension to the Consent Order Milestone schedule was requested by NYCDOS, and granted by NYSDEC, for preparation of subsequent milestones (14: Draft Final Hydrogeological Report, 15: Final Hydrogeological Report), in order to provide substantive response to regulatory agency comments. The Draft Final Hydrogeological Report was submitted to NYSDEC on April 10, 1993, and the Final Report was submitted on July 25, 1993. This document, which represents a resubmittal of the Final Hydrogeological Report, has been prepared in response to regulatory agency comment on the July 25, 1993 submittal contained in a Notice of Minor Milestone Deficiency dated October 12, 1993.

In addition to the required submittals, four supplemental document have been prepared as interim reports on the progress of field investigations, and to allow for development of strategies to improve data collection. These are: (1) "Phase I Milestone Report - Center Boring Program - Landfill Section 6/7" (IT Corporation, Wehran EnviroTech, and IDT, Inc., 1991), (2) "Phase I Milestone Report - Center Boring Program - Landfill Sections 2/8 and 3/4" (IT Corporation and Wehran EnviroTech, 1991b), (3) "Correlation Report - Piezo Electric Cone Penetration Tests in Support of Geotechnical Investigations at Sections 6/7 and 1/9 of Fresh Kills Landfill" (Appendix C of this report), and (4) "Final Report - Piezo Electric Cone Penetration Tests - Sections 6/7 and 1/9 of Fresh Kills Landfill" (Appendix D of this report).

In accordance with Section XI (Data Acquisition) of the Consent Order, monthly compilations of field data have been submitted to NYSDEC since the initiation of the field programs. The content of these submittals are summarized in Table 4.17.

5.0 GEOLOGY

5.1 Introduction

The interpretation of the geology of the Fresh Kills Landfill site and surrounding area provides the basic framework for this Hydrogeological Investigation. This task involves the characterization of the subsurface materials and geological features as a means of defining the three-dimensional spatial relationship of the subsurface materials within the Fresh Kills Landfill site. The development of an accurate model of the site geology provides the framework for subsequent groundwater and water chemistry evaluations. Therefore, based on the geologic framework, the hydrogeologic and geochemical tasks progress toward the larger project goals of reliably monitoring and mitigating contaminant (leachate) migration from the Fresh Kills Landfill site.

The scope of work that was developed to define the geologic framework of the Fresh Kills Landfill was specified in Appendix A-6 of the New York State Department of Environmental Conservation Consent Order D2-9001-8903 (Appendix A) and the Site Investigation Plan (IT Corporation, 1990a). On a regional basis, this project benefits from 150 years of geologic study of Staten Island, New Jersey, and other neighboring areas. The relatively well established regional geologic framework can be used to predict the expected geologic conditions at the site. The kind of geological materials present, along with age, general order of succession, basic physical properties, and lateral extent of these materials is known from various studies in this region. Properly evaluated, this information can be used to advantage in developing the model of the site geology, while not compromising the need for objectivity in evaluating and integrating the data acquired during this investigation.

The availability of this information influenced the format of the original scope of work. Recognition of the value of such information led to an extensive literature review, culminating in the Hydrogeological Literature Review Report (IT Corporation and Wehran EnviroTech, 1991a) as one of the initial stages of this project. The Hydrogeological Literature Review Report was submitted as required by Appendix A-6 of the Consent Order. This information assisted in the delineation of the site-specific geologic framework, as well as suggesting what off-site areas were of possible interest from an impact assessment perspective. Sections 2.0 and 5.2 of this

report and the Hydrogeological Literature Review Report provide an overview of the available site specific and regional geologic data base.

The initial stages of this investigation have benefitted from the findings of previous studies at the Fresh Kills Landfill and surrounding region. However, a conscious decision was made to recognize and utilize, but not depend on previous data and interpretations. A major emphasis was placed on a comprehensive, detailed, unbiased examination of data collected during this investigation in determining the geology at Fresh Kills.

In addition to the review of available information on the regional and site specific geology, as previously mentioned, four separate, but integrated, analytical methods were employed to delineate the geology of the project site as part of this investigation. These analytical methods are as follows:

- Lithostratigraphic Analyses – Conventional drilling/sampling methods were utilized to collect soil and rock samples, to which conventional methods of lithologic and stratigraphic analyses were applied.

- Geophysical Analyses – A variety of borehole geophysical logs were obtained to evaluate the physical properties of subsurface materials.

- Microfossil Analyses – Selected subsurface soil samples were studied for microfossil content (primarily pollen) to assist with the age dating/correlation of various strata.

- Piezo Electric Cone Penetration Test Analysis – Test penetrations were used to evaluate the textural and hydraulic properties of subsurface materials.

The specific methods and procedures that comprise these technologies were discussed previously in Section 4.0. Utilization of multiple technologies during this project is in keeping within the context of interpreting the geology objectively, comprehensively, and reliably. A specific program of data collection and evaluation was established to assure uniformity and consistency, particularly for the soil test boring sampling program and lithostratigraphic analyses. With regard to the remaining technologies, which are less conventional, the team utilized the services of recognized specialists. Mr. W. Scott Keys, a well known geophysicists formerly with the U.S. Geological Survey served as a consultant/advisor to the project geophysicists for the collection and interpretation of geophysical data. Professor Les Sirkin of Adelphi University was

subcontracted to perform microfossil analysis. Dr. Sirkin is an established authority on the palynology of the Cretaceous, Pleistocene, and Recent stratigraphy in the northeastern United States. The piezo-electric cone penetration testing and data interpretation work was subcontracted to Applied Research Associates, Inc., a firm with extensive experience in the development and application of piezo-electric cone technology.

The locations of all test borings and well borings, for both current and previous subsurface investigations at the site, piezo-electric cone penetrations, and regional borings identified in the Hydrogeological Literature Review (including those associated with the NYCDEP Brookfield Avenue Landfill and PASNY site) are presented on Sheets 5.1 and 5.2. Final test boring and well boring logs are contained in Appendices B and E, respectively (copies of the original field logs are contained in Attachments 1 and 3). A photographic log of the rock cores is contained in Attachment 2. The final piezo-electric cone correlation test report, which presents the results of correlation testing between penetrometer test logs and soil boring logs is contained in Appendix C. The final report of the full perimeter piezo-electric cone penetration test program is contained in Appendix D. Unprocessed and processed geophysical logs are contained in Appendices F and G, respectively. Microfossil test results for samples obtained and analyzed during this investigation and for samples obtained during previous investigations and analyzed for this study are contained in Appendix H. Summary data regarding the test borings, piezo-electric cone penetration tests and well borings are provided in Tables 4.1, 4.2 and 4.3, respectively.

The organizational framework of this chapter follows the logic of the discipline of stratigraphy. The general geologic framework for the region, Staten Island, and the Fresh Kills Landfill site is reviewed in Section 5.2.2 through 5.2.6. Sections 5.2.4.3, 5.2.5.3 and 5.2.6.3 present the depositional models for the Cretaceous, Pleistocene (Glacial) and Holocene (Recent) deposits. The relationship of these deposits at the Fresh Kills Landfill site to the depositional models is discussed in Section 5.2.4.4, 5.2.5.4 and 5.2.6.4. Section 5.3.1 presents the basic stratigraphic column proposed for the project area. Section 5.3.2 summarizes the characteristics of the individual stratigraphic units within this column; this is done in terms of the four analytical techniques identified previously. Having established the basic stratigraphy, Section 5.3.3 reviews the processes and procedures used for correlation of individual stratigraphic units across individual landfill sections and the site as a whole. The results of these stratigraphic analyses are provided with separate discussions for each landfill section in Section 5.4. Section 5.5

presents an overview of the stratigraphic analyses and geology of the entire facility through the integration of the analysis of the individual landfill sections. Finally, Section 5.6 presents the summary and conclusions regarding the geology of the Fresh Kills Landfill site.

5.2 General Geologic Setting

5.2.1 Introduction

This section provides a framework for the description of the geology of the Fresh Kills Landfill through a review of the regional, Staten Island, and Fresh Kills Landfill site physiography and geology. The review of the physiography and geology is followed by a presentation of the depositional models developed for the Cretaceous, Pleistocene (glacial) and Holocene (Recent) sediments and how the geology of the landfill relates to the depositional models. A model, defined as "a proposed standard, derived from an existing database, against which deviations from the norm are to be compared and interpreted" (Walker, 1984), can be extremely useful in developing an understanding of the geology of an area. An extensive review of available data and literature was performed, with all pertinent information incorporated in the development of the depositional models for the unconsolidated sediments at the Fresh Kills site. The Hydrogeological Literature Review (IT Corporation and Wehran EnviroTech, 1991a) and Section 2 of this report provides additional descriptions of the physiography and geology of the region.

The Hydrogeological Literature Review established that the stratigraphic column at the Fresh Kills site was regionally consistent. The general succession of strata in the project area is competent bedrock, weathered bedrock, residual clay, Cretaceous unconsolidated sediment, Pleistocene (Glacial) unconsolidated sediment, Holocene (Recent) unconsolidated sediment, and refuse/fill.

5.2.2 General Physiography

5.2.2.1 Regional Physiography

The Fresh Kills Landfill region is located within two physiographic provinces, the Coastal Plain and Piedmont (Figures 2.1 and 2.2). The Coastal Plain is characterized by relatively flat, to slightly undulating topography. The Piedmont is slightly more undulatory, with higher relief and elevations. The New Jersey physiographic province map (Figure 2.2) indicates that the Coastal Plain maybe divided into an inner and outer plain. The inner plain is topographically lower than the outer plain.

The low ridges in the Piedmont Province of northern New Jersey provided a boundary for the last Pleistocene glacial ice lobe that extended to Long Island, Staten Island, and northern New Jersey. It was at this boundary that the glacier deposited a terminal moraine. The morainal deposits, remaining after glacial ice retreated, can be seen in northern New Jersey, southern Staten Island and central Long Island.

5.2.2.2 Staten Island Physiography

Staten Island, as the name implies, is surrounded by water, the Arthur Kill to the west, Kill Van Kull to the north, and the Atlantic Ocean to the south and east. The boundary between the Coastal Plain and Piedmont Province is located in the northern portion of the island. This boundary is based primarily on geologic boundaries and topographic distinctions.

A prominent topographic feature formed by resistant serpentinite bedrock is present along the central axis of Staten Island. Todt Hill, in the north central portion of the island, reaches elevations of approximately 400 ft. The rest of the island is relatively flat, with most of the land surface exceeding 10 ft in elevation. The majority of the lowlands occur in the west central part of the island, with minor occurrences on the east side of the island. Drainage of the island is provided by tidal channels associated with the lowland marshes, perennial streams and ditches, and surface runoff that drain to the ocean or kills. The largest drainage system of the island is the Fresh Kills, Main Creek, and Richmond Creek network, located within and around the Fresh Kills Landfill site.

5.2.2.3 Fresh Kills Landfill Site Physiography

Fresh Kills Landfill is located almost entirely within a former tidal marsh environment of low relief (Sheet 5.69). Two remnant glacial topographic features (kames) existed prior to the placement of fill; one in east central Section 3/4, with an elevation of approximately 8 feet (known as Prices Island), and one in the east central portion of Landfill Section 1/9, that attains an elevation of approximately 30 ft. In the southeastern part of Section 1/9 and southern most part of Section 2/8, a topographic high or upland area is formed by remnant Cretaceous sediments. These Cretaceous sediments are sometimes overlain by a thin layer of glacial till. An upland area also occurs in the extreme eastern portion of Section 6/7, due to the higher elevation of the bedrock in that area. Four distinct mounds composed of refuse/fill (Landfill Sections 1/9, 2/8, 3/4 and 6/7) are present over most of the landfill site. Elevations in portions of the landfilled areas exceed 150 ft (Landfill Sections 2/8 and 3/4).

Numerous channels drained the former tidal marsh, the majority of which where filled in with the placement of refuse/fill. Tidal channels currently drain the marsh environment in areas of the landfill unaffected by landfilling activities. Most surface drainage eventually makes its way to the Arthur Kill/Fresh Kill/Main Creek/Richmond Creek drainage network.

5.2.3 Bedrock Geology

5.2.3.1 Regional Bedrock Geology

The regional bedrock consists primarily of the Newark Supergroup, which includes the Stockton, Lockatong, and Passaic Formations (Figure 5.1). These Formations are composed of shales, siltstones and sandstones. They were deposited in a basin (Newark Basin) that was formed in association with Mesozoic fault basins that were superimposed on older Paleozoic Piedmont rocks. A portion of the eastern boundary of the Newark Basin is marked by the Stockton Formation/Serpentinite contact on Staten Island. The western boundary is defined by the low hills of the Piedmont Province and well documented Ramapo Fault in northern New Jersey.

The Palisades diabase is also included in the Triassic-Jurassic sequence. It is an intrusive sill that is most prominent along the western shore of the Hudson River. It occurs within the Newark Supergroup sediments in northwestern Staten Island, and can be traced westward into Carteret, New Jersey.

Serpentinite is limited to the northeastern portion of Staten Island and, as mentioned previously, forms a portion of the eastern boundary of the Newark Basin. East of the serpentinite, the Precambrian to Cambrian age Manhattan Schist extends to the northeast as a prong along a narrow zone on the eastern side of the Hudson River. North of Staten Island the Manhattan Schist occurs above other crystalline rocks that comprise the New York City Group (Precambrian to Cambrian Age).

5.2.3.2 Staten Island Bedrock Geology

Precambrian to Jurassic age bedrock is found on Staten Island (Figure 5.2). The most prominent type of bedrock found on Staten Island is serpentinite. As mentioned previously, the serpentinite forms the major topographic feature on the island, as it is an extremely resistent rock. It is believed to be Ordovician in age. The serpentinite was formed by a low grade metamorphic alteration of igneous rock. Depending on the temperature, pressure and composition of the fluid and gas phases, different types of serpentinite and associated minerals were formed (Okulewicz, 1990). The Triassic Newark Supergroup is found on the western side of the serpentinite ridge. The Stockton Formation marks the eastern boundary of the Newark Basin on the Island. The Stockton is overlain by the Lockatong and Passaic Formations of the Newark Supergroup in the northwest portion of the island. The Stockton, Lockatong, and Passaic Formations are comprised of shales, siltstones, and sandstones. The Jurassic Palisades diabase, also considered part of the Supergroup, was injected as a sill within the Lockatong Formation in the northwest corner of the island. On the eastern side of the serpentinite, the Manhattan Schist is interpreted to extend in a southwest to northeast direction.

5.2.3.3 Fresh Kills Landfill Site Bedrock Geology

Four types of bedrock were encountered at the Fresh Kills Landfill. The Stockton and Lockatong Formations of the Newark Supergroup (Triassic age) were present under a major portion of the landfill site. The Stockton Formation is composed of shale, siltstone and sandstone. The Lockatong Formation is composed of shale and siltstone. In the southern half of Sections 6/7 and 2/8, serpentinite and associated chlorite schist was encountered. The Manhattan Schist was encountered in one boring in the south central part of Section 2/8. The Palisades diabase was penetrated by several borings in the northwest corner of the PASNY site, which is due west of Fresh Kills Section 3/4 (Figure 1.2). The presence or occurrence of these types of bedrock are not unexpected based on the regional and local geology.

5.2.4 Cretaceous Geology

5.2.4.1 Regional Cretaceous Geology

The Cretaceous deposits that occur below the Fresh Kills Landfill site are located in the northern Atlantic Coastal Plain. The northern Atlantic Coastal Plain forms the western margin of the Baltimore Canyon Trough. The Baltimore Canyon Trough is a large sedimentary basin that underlies the continental shelf along the Middle Atlantic States. It was a major receptor of sediment eroding off the elevated Piedmont Province during Cretaceous time (Olsson and others, 1988) (Figure 5.3).

The surface of the basement rock underlying the Coastal Plain is highly irregular. Structural upwards and downwarps, superimposed on basement rock, controlled sediment distribution along the continental margin during Cretaceous time (Owens and Sohl, 1969). The Fresh Kills Landfill site occurs in a downwarped area known as the Raritan Embayment (Figure 5.3).

The Cretaceous is divided into two major epochs; Early Cretaceous and Late Cretaceous (Palmer, 1986). In general, Lower Cretaceous strata were deposited during the Early Cretaceous, and Upper Cretaceous strata were deposited during the Late Cretaceous. Sedimentation began on the Coastal Plain during Early Cretaceous or possibly late Jurassic time. The Lower Cretaceous stratigraphic sequence is composed almost entirely of sediments of continental (fluvial) origin.

The presence of marine fossils in the Lower Cretaceous section in the distal downdip portions of the Coastal Plain suggests occasional influence by marginal marine incursions (Olsson and others, 1988).

Approximately 1000 ft of Lower and Upper Cretaceous sediment is found in the area from northern New Jersey to Long Island. These deposits are essentially composed of silt/clay and sand that may occur as distinct layers, interbedded, or rapidly (laterally and vertically) changing facies.

Documentation of biostratigraphic zonation of Cretaceous sediment utilizing assemblages of spores and pollen emerged in the 1960's. Initial zonation has been refined through subsequent studies. The current zonation uses Roman numerals for designating pollen zones. Zones I and II are representative of Lower Cretaceous sediment, Zone III a transition zone between Lower and Upper Cretaceous, and Zones IV through VII, Upper Cretaceous sediments. Detailed discussions on microfossil analysis as it relates to age dating of sediments are presented in Sections 5.2.4.5 and 5.3.2.3 and Appendix H.

During Early Cretaceous time, the Piedmont–Blue Ridge Province was uplifted and sedimentation was initiated into a broad, subsiding basin (Baltimore Canyon Trough). These Cretaceous sediments were deposited above the Triassic-Jurassic bedrock as the bedrock continued to subside along the North American continental margin. This basin is defined today by the Atlantic and Gulf Coast Coastal Plains. Deposition probably began near or just beyond the present coast line (Glaser, 1969). The deltaic and related depositional environments prograded eastward during a major regression of the Atlantic Continental margin (Frazier and Schwimmer, 1987) that coincided with Piedmont - Blue Ridge Province uplifting.

A major cycle of sea level rise, which began during late-Early Cretaceous time, led to the spread of the ocean over the Coastal Plain in the early-Late Cretaceous. Subsequent to the rise in sea level and until Pleistocene time, deposition of primarily marine sediment occurred in the Coastal Plain. Late Cretaceous sediments consist of coastal deposits of beach, lagoon, marsh and related environments; inner shelf sediments of shoreface sands and related delta front facies of micaceous clay and silty, thinly-bedded fine sands; mid-and outer shelf clayey glauconite sands and glauconite clays; and slope deposits of calcareous clays and silts (Olsson and others, 1988).

The strata of the Potomac Group form the basal sequence of sediments of the Lower Cretaceous section in the Atlantic Coastal Plain. Marine fossils found in deep wells penetrating the Potomac strata indicate near shore environments of deposition (Olsson and others, 1988). Approximately half of the Cretaceous stratigraphic section in the Atlantic Coastal Plain is composed of the Lower Cretaceous Potomac Group. The Potomac Group is interpreted as a complex of fluvial-deltaic lithofacies of a major axial river system centered in Maryland. Lithofacies include braided and meandering stream sands and gravels, floodplain, and fringing swamp deposits. The Potomac Group consists of four Formations: the Waste Gate, Patuxent, Arundel, and Patapsco (Brenner, 1963; Olssen and others, 1988).

The Waste Gate Formation consists of unconsolidated to moderately lithified arkosic sandstones and laminated silty shales and clays (Olsson and others, 1988). The earliest deposited Cretaceous sediments, including the Waste Gate are difficult to distinguish in the stratigraphic record (Glaser, 1969).

The Patuxent sediments were deposited by northeastward, eastward, and southeastward flowing rivers, originating mainly in the adjacent Piedmont, approximately 10 to 100 miles to the west of the depositional areas (Glaser, 1969). The Patuxent Formation is primarily composed of cross-bedded and lenticular sands and gravels with minor amounts of light gray, brown and pink clay beds (Brenner, 1963). The predominately coarse clastics of the Patuxent were deposited on an aggrading Coastal Plain by high gradient, perhaps initially braided river systems. Rapidly shifting channels, probably in response to periodic flooding, resulted in frequent truncation of earlier deposited bar sequences, and prevented the preservation of overbank sediments (Glaser, 1969).

A decrease in the paleoslope to the east from the base-leveling of the source area and/or decelerating basin subsidence resulted in considerably reduced stream gradients at the end of Patuxent time. This apparently produced the quiet, shallow, fresh water environment in which deposition of the Arundel Formation occurred (Glaser, 1969). The Arundel Formation consists primarily of relatively pure clays, commonly dark gray, red, and various shades of brown in color (Brenner, 1963).

Following deposition of the Arundel Formation, the source region was again subjected to mild uplift. The Patapsco Formation was deposited next, consisting of interlensing sands, silts, and

clays. Thick clay units (exceeding 100 ft in thickness) predominate the formation (Brenner, 1963). The clays are commonly massive, but also include laminated silt-clay successions, and thinly interbedded fine sands and silty clays. Fine to medium sands are the most predominant coarse-grained sediments, with gravels and coarse sands being less common. Sand bodies of probable point bar origin are present throughout the section. The sands are generally separated by clay units. The thicknesses of the sand units change rapidly laterally (Glaser, 1969).

The sedimentary structures and textural character of the Patapsco Formation suggest deposition on a low deltaic plain by sluggish, low gradient, meandering streams. Broad flood basins and swampy interfluves were important features of the depositional environment. Flooding accompanied by suspended load deposition in adjacent floodbasin and backswamp areas was probably a major depositional process, and would account for the predominance of fine-grained sediments (Glaser, 1969).

The principal geologic units of the Upper Cretaceous sequence in this region are the Raritan and Magothy Formations. The Raritan Formation is believed to be continental in origin. The Magothy formation is thought to be both continental and marine in origin. The Raritan Formation is the lowermost formation in the Upper Cretaceous sequence. It consists of the following units in ascending order (Zapecza, 1989):

- Raritan Fire Clay
- Farrington Sand Member
- Woodbridge Clay Member
- Sayerville Sand Member
- South Amboy Fire Clay Member

The specific environments of deposition are likely to be similar to the depositional environments described for the Lower Cretaceous Potomac Group sediments. However, the general trend of marine transgression that was occurring during early Cretaceous time continued into Raritan time. This pushed the marginal and marine depositional environmental further westward, closer to the Fresh Kills site (Olsson and others, 1988).

The Raritan Fire Clay is a blue, brown, red, gray, white or spotted red clay. It grades downward to a reddish brown color at the base. In New Jersey, west of the Fresh Kills Landfill site,

thickness ranges from 0 to 35 feet, however, thicknesses of over 80 ft have been reported. It occurs mostly in depressions in the bedrock. The top of the unit is undulatory and is overlain by the Farrington Sand Member or by glacial deposits (Barksdale and others, 1943; Anderson, 1968).

West of the landfill site, the Farrington Sand Member is described as an angular coarse to fine sand with lignite, pyrite and locally thin beds of gravel, and seams of clay (Anderson, 1968; Farlekas, 1979). The upper part is generally medium to fine grained. The lower portion is a coarse, arkosic, light gray or yellow sand usually containing abundant small quartz or dark chert pebbles (Barksdale and others, 1943; Anderson 1968). In Middlesex County, thickness of the Farrington Sand ranges from 0 to 129 ft. Information on distribution of the Farrington Sand beneath the Arthur Kill is generally not known or available (Farlekas, 1979). Farlekas (1979) shows the Farrington Sand outcropping on Staten Island, south of the Fresh Kills Landfill site, directly across the Arthur Kill from the Woodbridge Township-Perth Amboy city line. He also believes the Farrington Sand underlies the glacial deposits in this region of Staten Island.

The Woodbridge Clay Member consists largely of a thin to thick-bedded sequence of micaceous silts and clays containing a large amount of woody fragments and siderite concretions (Owens and Sohl, 1969). The upper portion consists of well stratified, dark gray clays containing fine-grained sand. The middle portion commonly consists of gray clay, though sandy clays or clayey sands may occur. The basal portion of the Woodbridge contains beds of compact, tough, and highly refractory fire-clay, which are white, light gray, or brick red in color (Barksdale and others, 1943). Sand content typically ranges from 5 to 50 percent. The base is undulatory. Its upper surface is irregular where glacial ice has removed sediment (Anderson, 1968).

The Sayerville Sand and South Amboy Fire Clay Members and the Magothy Formation likely occur well south of the Fresh Kills Landfill area.

5.2.4.2 Staten Island Cretaceous Geology

Research conducted by the USGS, along with the work of Owens, Minard, and others, e.g., Richards (1961); Owens and others (1968); Owens and Sohl (1969); Isphordiny (1970); and Carter (1978) showed that much of the Coastal Plain deposition, especially in embayments,

occurred in conjunction with broad individual or coalescing deltas. Staten Island is located in the northernmost embayment (Raritan Embayment) of the Atlantic Coast depositional basin that existed during Cretaceous and Tertiary time. Lateral facies changes in very short distances within the deltas were recognized. The nature of the deltaic environment, combined with relatively minor, but nevertheless significant, changes in sea level (resulting in lateral transgressions-regressions of coastal sedimentary environments), produced a succession of sedimentary strata that exhibit general lithologic tendencies (i.e., the tendency of a particular formation to consist generally of coarse grained (sand) or fine grained (clay and silt) material), with significant vertical and lateral variations. These lateral and vertical variations introduce complexity in the stratigraphic analysis and correlation of discrete lithologic units.

Cretaceous sediments occur in the southern half and extreme eastern portions of Staten Island, within the Coastal Plain (Figure 5.2). They consist of alternating sand and clay/silt units. Some stratigraphic studies (Cadwell, 1989; Olkulewitz, 1990) divided the Cretaceous sediments on Staten Island into the Raritan and Magothy Formations (Upper Cretaceous Age). Work by Kureshy (1975), Soren (1988) and Roberts-Dolgin (1991) indicates that only the Raritan Formation may be present on Staten Island. The Cretaceous sediments of Staten Island are generally buried beneath younger Pleistocene deposits, although they do outcrop locally, especially south of the terminal moraine in the southern portion of the island.

5.2.4.3 Cretaceous Depositional Model

The Cretaceous sediments in Staten Island and New Jersey are primarily the result of deltaic sedimentation (Owens and others, 1968; Kureshy, 1975; Okulewicz, 1990). A delta is a partially subaerial, partially subaqueous, contiguous mass of sediment deposited around the point where a river enters a standing body of water. A deltaic system is a three-dimensional stratigraphic unit composed of many adjacent delta lobes deposited as part of a major cycle of terrigenous sediment influx. The delta morphology and internal stratigraphy are primarily the product of an interaction between fluvial sediment input and reworking of sediment by marine or lacustrine processes (Galloway, 1975). The Cretaceous sediments below Fresh Kills Landfill site were deposited primarily in the subaerial plain (fluvial) environment of a marine delta.

Subaerial plains are characterized primarily by fluvial deposition (Owens and Sohl, 1969; Reineck and Singh, 1973). The two major types of river systems that occur within a subaerial plain are braided and meandering (Figure 5.4). Braided systems usually have higher slopes and heavier, coarser sediment loads than meandering systems. In the braided system, sand is deposited in channels and as braid bars. Very little fine-grained sediment (silt and clay) is deposited in the braided system due to the high energy and constantly shifting channels. In a meandering system, sands are usually deposited in channels and on meander loops (channel deposits), and silts and clays on levees and in flood basins (overbank deposits) (Walker, 1984).

The sand bodies deposited by both braided and meandering systems have distinct sedimentary structures, such as cross-bedding, that aid in determining the environment of deposition. Unfortunately, these structures are rarely distinguishable in two-inch diameter split-spoon samples, the principal type of sample analyzed during this investigation.

The channel floor deposits in the braided system usually consist of a lag deposit and fining upward, cross-stratified sand. Sand bars develop between the channels. The bars often coalesce due to the constant shifting of the channels, forming laterally continuous and extensive sand sheets. Silts and clays that have been deposited are usually quickly eroded by the constant lateral migration of the channels. Any silt and clay units preserved in the braided system will be isolated and laterally discontinuous (Walker, 1984).

In a meandering system, the two principle types of channel deposits are channel fill and point bar. Channel fill deposits occur largely as cross-stratified sands on the channel floor (Owens and Sohl, 1969). They are usually coarser and more poorly sorted than adjoining point bar deposits. Point bar deposits form as the outer banks of meander loops are eroded and the sediment is deposited on the inner parts of the meander loops. It is through this process that the point bar builds laterally and downstream across the flood plain. (See "channel" and "point bars", Figure 5.5), (Reineck and Singh, 1973). Oxbow lake deposits are also associated with channel deposits (Figure 5.5). The type of sediments within an oxbow lake depends on whether a meander loop was abandoned gradually or suddenly. A fining upward sequence, usually consisting of sand overlain by flood basin silts and clays is deposited if gradual abandonment occurs. Sediments in the oxbow will consist entirely of flood deposited silts and clays if abandonment is sudden (Walker, 1984).

Overbank deposits are typically much finer grained and more poorly stratified than the sandy channel fill deposits (Owens and Sohl, 1969). There are four major types of overbank deposits: natural levee deposits, floodbasin deposits (marsh/swamp), crevasse splay deposits, and swale fill deposits (Allen, 1965). They occur during flood stage when a river overflows its banks. Overbank deposits represent vertical accretion deposits, whereas, channel deposits represent lateral accretion deposits.

Natural levees are wedge-shaped ridges of sediment bordering stream channels (Figure 5.5). The maximum elevation (and thickness) of a levee is at or near the edge of the channel (Allen, 1965; Reineck and Singh, 1973). Deposition on levees occurs when a stream overflows its banks. As water velocity decreases, the sediment load cannot be transported, and is deposited adjacent to the banks. In natural levee deposits, coarser sediment and higher rates of deposition occur close to the channel, whereas, finer sediment and lower rates of deposition occur further down the levee, farther from the channel (Allen, 1965).

The flood basin (marsh/swamp) is the lowest lying part of the floodplain (Figure 5.5). It is a poorly drained, relatively featureless area with little or no relief (Allen, 1965). During river flood stages, the flood basin may be covered with variable depths of water from which clays and silts settle and become part of the marsh sequence. Marine inorganic sediments may be transported to the flood basin by normal tidal fluctuations of the various channels that drain the flood basin. Lacustrine environments form in the floodbasin during deterioration or partial burial of the marsh or swamp.

Crevasse splay deposits form when flood water overflows the levee and cuts a channel across the levee to the floodbasin (Figure 5.5). The crevasse splay deposits are narrow to broad accumulations of sediment tapering in the direction of the floodbasin. They are tens of centimeters to a few meters thick. These deposits are typically coarser-grained than the natural levee deposits with which they are associated (Reineck and Singh, 1973).

Swale fill deposits represent deposition of sediment in depressions on channel deposits. In a meandering system, these sediments are deposited in depressions on point bars. The sediment is predominately fine-grained (silt, clay, fine sand).

The model developed for a meandering system consists of a fining upward sequence comprised of coarse-grained channel deposits (lateral accretion) overlain by finer-grained overbank deposits (vertical accretion). The cut-off of meander loops is an essential component of a meandering system model. The oxbow lakes formed from the cut-off of meander loops, as mentioned previously, are filled with silt and clay. Since the silt and clay is difficult to erode, the meander belt may become confined between the oxbows, and through vertical accretion, become raised above the general level of the floodbasin. The sand unit deposited within a highly sinuous meandering river will demonstrate an elongate shape and be bounded on the sides and bottom by the floodbasin fine-grained sediments (Walker, 1984).

When the river switches to a different location within the floodbasin due to a catastrophic levee break (avulsion), the previously deposited sand unit has the possibility of being covered by the overbank deposits of the newly located river. The sand bodies of meandering systems can be totally enclosed or confined in low permeability silt and clay layers. Through the process of avulsion, sand units can be interconnected vertically, occurring as stacked channel deposits (Figure 5.4). The model for a meandering river system also predicts that if sediment supply and basin subsidence is constant, a series of point bar sand layers interbedded in floodbasin silts and clays should be developed with an overall elongate geometry (Walker, 1984).

5.2.4.4 *Relationship of Cretaceous Sediments at the Fresh Kills Landfill Site to the Cretaceous Depositional Model and Regional Depositional History*

The basal unit of the Cretaceous sequence present below the Fresh Kills Landfill site is a laterally extensive sand layer. Based on the comparison of the microfossil data to the regional geology and depositional model, this sand would be correlated as being Patapsco Formation (Upper Potomac Group) equivalent. The Patapsco Formation is composed primarily of a sand and gravel unit occurring below an upper unit consisting of predominately clay and silt. The lower sand unit was probably deposited by a braided river system. Zone I pollen (Lower Potomac Group equivalent), which would date the basal sand as Pataxent equivalent, was found in only one sample analyzed from the basal sand unit (1W91:IT006). Due to sparse microfossil assemblages in this sample, the Zone I age classification is considered unreliable and unconfirmed.

The majority of the samples analyzed from the basal sand member below the landfill site indicated a Zone IIB age (Patapsco Formation equivalent, Upper Potomac Group). At the onset of Patapsco deposition, the Atlantic coastal region was undergoing uplift. This episode of uplift may have produced a high enough gradient, at least locally, to allow a braided river system to form. The laterally extensive nature of the basal sand unit, along with the absence of any thick, continuous clay and silt layers, would be indicative of braided river system deposits, as described in the Cretaceous depositional model.

The upper portion of the Cretaceous sequence at the site is principally comprised of clays and silts, which is also the predominant composition of the Patapsco Formation. The overall predominance of fine-grained sediments versus coarse-grained sediments in the upper portion of the Cretaceous sequence indicates deposition by a meandering river system (based on the model presented). Microfossil analysis indicates that most of the upper portion of the Cretaceous sequence at the site is also Zone II, or Patapsco equivalent. Several pollen Zone III and IV samples, however, were present in the upper portion of the Cretaceous sequence, indicating the presence of some Upper Cretaceous sediments at the landfill site. If the Cretaceous sediments below the site are all Upper Cretaceous in age (see discussion Section 5.2.4.5), the Cretaceous sands may be equivalent to the Farrington Sand Member and the clay and silt equivalent to the Woodbridge Clay Member of the Raritan Formation.

Sands are deposited within the channel as channel fill or point bar deposits in a meandering system. The lateral extent of sand bodies deposited in a meandering system are dependent on channel depth and width, and the size of the meander loops. In cross-section and plan view, the sand bodies that occur in the upper portion of the Cretaceous sequence may appear to be isolated lenses because of the rapid facies changes that occur in this depositional system. As presented in the model, the overall pattern of deposition will be elongate along the river axis, with horizontal migration of the sand bodies appearing time-transgressive in nature (Figure 5.4). The sand may be interconnected laterally along its depositional trend.

Vertical interconnection between sand units would occur where stacked channel deposits are found (a time-transgressive sequence). An example of possible stacked channel deposits at the Fresh Kills Landfill occurs in Section 1/9; where thick sand sequences are seen in borings in the eastern portion of the section (primarily 1W91:IT005 and 1B91:IT512 and 513). The fining upward nature of the sands in these borings is also indicative of channel deposits.

The clays and silts of the Cretaceous sequence are variable in color across the site. The color variations of the clay and silt units may be indicative of the depositional environment (e.g., dark clays from marshes or swamps). Sedimentary structures of the clays and silts which can also aid in the interpretation of the environment of deposition are sometimes preserved in split spoon samples. The Cretaceous clays and silts were probably deposited mostly as overbank deposits in two major depositional environments.

The most common fine-grained Cretaceous sediment observed at the site is a gray to black, sometimes laminated, occasionally lignitic, clay and silt. This sediment would most likely have been deposited on a broad, poorly drained, expansive floodplain consisting of a swamp or marsh environment (Figure 5.5). As described in the previous section, most of the inorganic sediment would be supplied to the floodplain by overbank flooding of the various streams and by drift from coastal areas. Organics would come mainly from the plants growing in the swamp or marsh. The lighter colored gray clays may represent deposits within a lacustrine environment, which sometimes form in the floodplains (also described in the previous section).

The other major type of Cretaceous fine-grained sediment observed at the site is a variegated red brown and gray clay and silt. The depositional environment for these sediments is interpreted to be a near channel, levee environment (Figure 5.5). The red brown and gray mottling occurs as the clays and silts are alternately saturated and dewatered as the water in the channel and adjacent groundwater regime rises and falls in response to changes in climate and/or precipitation.

Several samples were specifically analyzed for the presence of marine microfossils (Appendix H). This was done in an effort to provide additional support for the depositional environment interpretations. In most of the samples examined, no marine microfossils were found. However, in two of the samples analyzed, microfossils indicative of brackish conditions were found in addition to pollen (Appendix H). The presence of brackish water microfossils indicates that the Fresh Kills Landfill site was relatively close to the ocean shoreline when the Cretaceous sediments were deposited, and may have occasionally experienced brackish conditions. This observation is consistent with other microfossil data from both the Lower and Upper Cretaceous strata in this region (Olsson and others, 1988; Owens and Sohl, 1969).

In summary, the Cretaceous sediments beneath the Fresh Kills site were deposited in a terrestrial environment dominated by fluvial processes. The basal sand layer was probably deposited in a

somewhat high energy fluvial depositional system (braided river system) and represents the initiation of Cretaceous deposition at the site. A floodplain consisting of meandering streams and fringing swamp/marsh area (meandering river system) formed as the paleo-slope gradient decreased. Based on the sediment distribution at the site (primarily fine grained), a meandering river system was probably the source for most of the Cretaceous sediment beneath the Fresh Kills Landfill site.

5.2.4.5 *Age of Cretaceous Sediments and Regional Implications*

Microfossil analysis of soil samples produced unexpected results regarding the age of the Cretaceous sediment below the Fresh Kills Landfill site. Most of the sediment that contained microfossils has been identified as pollen Zone II, which is indicative of Lower Cretaceous time (Figure 5.6). Lower Cretaceous sediment had not been previously identified in this area of the coastal plain; only Upper Cretaceous sediment had been previously identified. The Hydrogeological Literature Review Report (IT Corporation and Wehran EnviroTech, 1991c) contains a detailed review of the literature concerning the Cretaceous deposits in this region. The existence of Lower Cretaceous deposits in an area thought to consist of entirely Upper Cretaceous deposits proved problematic. The definitive age of the Cretaceous sediments is significant not only for stratigraphic correlation, but also for the potential hydraulic connection between the Cretaceous sediments below the Fresh Kills Landfill site and adjacent areas.

To test and verify the results of the microfossil analysis, two additional tasks were undertaken. The first task was to identify additional locations in the region where Lower Cretaceous sediments had been identified and to determine their potential correlation to the sediments below the Fresh Kills Landfill. The information that was used to evaluate the regional extent of the Lower Cretaceous strata in the vicinity of the Fresh Kills Landfill was obtained from the reports and papers discussed below, and from open file data from the New Jersey Geological Survey. The second task was to have another palynologist review a subset of the pollen samples previously analyzed in an attempt to obtain corroborating data. The findings of these tasks follow.

Palynological studies of Cretaceous strata in Long Island show that on the Long Island Platform, the oldest Cretaceous sediments present are equivalent to the Woodbridge Clay Member of the Raritan Formation (Sirkin, 1974, 1986), Zone IV in the pollen zonation scheme (Figure 5.6). In

early studies of the Long Island Cretaceous strata, Zone IV was recorded in the basal clays of the Fire Island State Park well S21091, and in thrusted Cretaceous sediments in glacial deposits in northern Nassau County, Long Island. Wells drilled to bedrock in Long Island also identified Raritan Formation strata above weathered bedrock (basal Lloyd Sand Member and the overlying Raritan Clay Member). In a west to east transect of 10 wells across Long Island, constructed as part of a latter study, Zone IV was identified in the basal sediments of three wells; Zone V in 5 wells, and Zone VII in one well, although some of the wells were not completed to bedrock.

Early studies of the southwest to northeast striking Cretaceous outcrop belt in New Jersey show that Lower Cretaceous and lower Upper Cretaceous beds trend directly toward Staten Island (Richards and others, 1962). In southwestern Staten Island, surficial and shallow subsurface deposits exhibit similarities to Raritan and Magothy strata (current zonation Zones IV through VII) based on pollen content (Baskerville, 1965). Detailed examination of Plates 5 and 6 of the Baskerville (1965) study indicated the presence of Lower Cretaceous deposits based on the inclusion of illustrations of index pollen generally associated with Zones II-B and II-C (Patapsco Formation equivalent). The Baskerville Study (1965) also indicated that advanced Zone V forms were present in these deposits (Sirkin, Appendix H). These observations are similar to the data analyzed in the current Fresh Kills study. Baskerville also found fossil foraminifera (marine protozoans) near the top of the Cretaceous beds, supporting the interpretation of a marine origin for these units in the southern part of Staten Island. Across Raritan Bay in Woodbridge and Sayreville, New Jersey, south of Staten Island, pollen assemblages in Cretaceous sediments associated with the Raritan Formation were documented (Kimyai, 1966). These microflora were subsequently shown to be representative of Zone IV, and the strata identified as the Woodbridge Clay Member of the Raritan Formation (Doyle, 1969).

In the New Jersey coastal plain area of the Atlantic continental margin, the Lower Cretaceous Patapsco Formation of the Potomac Group is found as a wedge that thins from the southwest to northeast. The Upper Cretaceous Raritan Formation is shown as extending from northeastern New Jersey to southern Long Island based on lithology and pollen studies (Weed and others, 1974; Perry and others, 1975; Doyle and Robbins, 1977). The Potomac Group is demonstrated to extend at least to Monmouth County based on correlations from deep wells in Ocean County; the Toms River Chemical Well, Co. 84 and the Island Beach well contain more than 1,400 feet of Potomac Group sediments (Zones II and III). The Raritan Formation is demonstrated to

extend from the south through the Fort Hancock well in Sandy Hook, New Jersey to the Fire Island well on Long Island.

Cretaceous pollen zones substantiating the Lower Cretaceous and Upper Cretaceous biostratigraphy in the project area have been identified in several wells in New Jersey (Figure 5.7). Patapsco equivalent strata are well documented in New Jersey, south of Staten Island, based on pollen data from reports filed with the New Jersey Geological Survey (Sirkin, 1969 to 1991; by permission of Peter Sugarman, personal communication, 1992). Zone III was observed in the Strathmore well in Matawan, Monmouth County, New Jersey, located south of Staten Island, just across Raritan Bay. To the east of the Strathmore well, Zone II-B was identified at a depth of 900 feet in a Fort Hancock well. In Marlboro, New Jersey, south of these two locations, Zone III was found at a depth of 694 feet. Farther to the south, in Ocean County, Zones II-B and II-C occur in a well in Manchester, and Zones II-A and II-B in a well in Mantoloking at depths of 1,580 feet and 1,780 feet, respectively. Zone II-A was also found in the Toms River, Island Beach and Beach Haven wells in central to southeastern Ocean County. Lower Cretaceous sediments were also encountered in central New Jersey (Burlington County); Zone II-B in the Fort Dix well at 935 feet, Zone II in the Medord well below 900 feet, and Zones II-B and II-A below 1,900 feet in Butler Place.

The depth at which Zone II is encountered in the New Jersey wells can be attributed to the downwarping of the Raritan Embayment, a structural low, while the higher elevations of the Patapsco equivalent strata in Staten Island appear to define the northern, up-dip limit of these strata along the western margin of the Long Island Platform (Sirkin, Appendix H). This interpretation would provide a rational and logical explanation for the Lower Cretaceous sediment found below the Fresh Kills Landfill site. In addition, it incorporates regional Cretaceous data that is supportive of this interpretation.

As part of the second task, Professor Gilbert Brenner was retained to perform an independent analysis of selected samples to corroborate the analysis that indicated the presence of Lower Cretaceous sediment beneath the site. Professor Brenner performs microfossil analysis for the Maryland Geological Survey. He was responsible for originating the I and II pollen zonations for the Cretaceous stratigraphic sequence (Brenner, 1963). He was given twelve samples, identified as either Lower or Upper Cretaceous pollen zonations, to examine. He was not provided with the pollen zone designation as determined by Dr. Les Sirkin. The results of the

independent analyses are summarized in Table 5.1. The major difference in the analyses is that Dr. Brenner did not conclusively identify any pollen zone older than Zone III. Pollen Zone III is diagnostic of the transition period between the Lower and Upper Cretaceous. Both Dr. Brenner and Dr. Sirkin confirmed the existence of the transition and Upper Cretaceous pollen (Zones III and IV) in the samples. In general, the better the pollen sample (number of pollen grains, variety of pollen grains, etc.), the better the agreement between the palynologists.

It is difficult to determine a definitive age of samples when pollen assemblages are sparse, as was the case in many of the samples analyzed from the Fresh Kills Landfill site. Based on the twelve samples analyzed by both palynologists, there is disagreement between the palynologists as to whether Lower Cretaceous sediments exist beneath the site. Dr. Sirkin's review of Dr. Brenner's report (Appendix H) indicates that greater similarity between the two analyses may exist based on the zonation criteria applied by Dr. Sirkin. Regardless, while Dr. Brenner's analysis did not conclusively confirm the presence of Lower Cretaceous sediment below the site (Zone I or II), it did confirm the presence of sediment deposited during the transition period between the Lower and Upper Cretaceous (Zone III), and sediment deposited during the Upper Cretaceous (Zone IV). Given the data available, it is interpreted that at least a portion of the Cretaceous sand and clay/silt underlying the landfill are potentially correlative with similar Raritan Formation sand and clay/silt in adjacent areas.

5.2.5 Pleistocene (Glacial) Geology

5.2.5.1 Regional Pleistocene (Glacial) Geology

During the last glacial episode, glacial ice advanced from Canada southward through the Champlain Lowland, into the Hudson Valley Lowland, and through the Hudson Valley (Connally and Sirkin, 1973). Ice lobes were channeled along the bedrock strike and scoured troughs into less resistant bedrock. The more resistant rocks remained as ridges and uplands between the troughs. Gneiss and schist of the Manhattan Prong (New York Group) and the serpentinite ridge in the northeastern portion of Staten Island maintained the upland to the east. The Palisades diabase formed a prominent ridge immediately northwest and west of the Fresh Kills Landfill site. The diabase ridge separates the Hackensack Lowland to the west from the Hudson Lowland to the east (Sanford and Harper, 1991).

The lobe of glacial ice advancing down the Hudson Valley coalesced with other glacial ice lobes to the west and east, forming a large ice sheet (Connally and Sirkin, 1973). The ice sheet continued to flow south and southeast, until it stopped several miles south and east of the present Fresh Kills Landfill site. A terminal moraine marks the maximum extent of glacial ice in Staten Island and adjacent areas of New Jersey and Long Island (Stanford and Harper, 1991) (Figure 5.8).

The Hudson ice lobe advanced as far south as the southern half of Long Island, the southern part of Staten Island and northern New Jersey. As the glacier advanced, it deposited glacial lodgement till (Soren, 1988; Stanford and Harper, 1991). This glacial advance accounts for the occurrence of lodgement till at the site. Glacial lodgement till is dominantly unsorted and unstratified sediment, deposited directly by a glacier without subsequent reworking by meltwater. It consists of a heterogeneous mixture of clay, silt, sand, gravel, and boulders varying widely in size and shape (Bates and Jackson, 1980). The glacial lodgement till was deposited as a fairly continuous layer over the glacially-eroded surface. Thickness generally ranges from a few ft to 30 ft (Barksdale and others, 1943; Stanford and Harper, 1991). The deposits are mainly reddish brown clayey till derived primarily from the Triassic and Jurassic shale and sandstone bedrock in the region. Local bodies of stratified sand and gravel commonly occur within the till (Soren, 1988).

A terminal moraine was deposited at the location where the ice sheet stopped (Harbor Hill Terminal Moraine) (Soren, 1988) (Figure 5.8). The terminal moraine is composed of till (mostly unsorted sand, gravel, cobbles, boulders within a silty and clayey matrix), sandy diamict, and minor sand and gravel (Soren, 1988; Stanford and others, 1990). The glacier began to retreat from the terminal moraine position approximately 20,000 years ago. As the ice retreated, a proglacial lake formed between the glacier and the moraine (Stanford and Harper, 1991). The extent of this early proglacial lake was controlled by the glacier ice to the north, the terminal moraine to the south, and various ridges or uplands to the west and east. The proglacial lake that initially existed in the area where the Fresh Kills Landfill site is now located was known as glacial Lake Bayonne (Figure 5.9). Subsequent erosion of the terminal moraine, and deglaciation of lower elevation outlets, created spillways that allowed Lake Bayonne to drain, essentially ending this phase of glacial deposition in the area of the area of the Fresh Kills Landfill. The creation of a spillway at Tremley Point served as an outlet for glacial Lake Hackensack, which was the major glacial lake stage following Lake Bayonne. Glacial Lake Hackensack occurred

north of the Fresh Kills Landfill site. The lake waters from Lake Hackensack cascaded over the spillway at Tremley Point and flowed down the Arthur Kill toward the terminal moraine at Perth Amboy, and eventually to the Atlantic Ocean.

The deposition of coarser grained sediment, primarily as outwash or ice contact stratified drift, was also associated with deglaciation (Soren, 1988; Cadwell, 1987; Okulewicz, 1990; Roberts-Dolgin, 1991).

5.2.5.2 Staten Island Pleistocene (Glacial) Geology

The glacial deposits that now exist on Staten Island were principally deposited in the last 10,000 to 20,000 years, during Wisconsin age glaciation. As the glacier advanced, it removed an unknown amount of previously deposited sediment and bedrock. It deposited lodgement till as a nearly continuous layer above the pre-Pleistocene sediments. The glacier advanced as far as the southern portion of Staten Island. A terminal moraine was deposited at this location (Figure 5.8). An outwash plain was also deposited south and east of the terminal moraine. The outwash plain now slopes into the ocean.

As the glacier melted and receded from the terminal moraine position, a succession of glacial lakes were formed between the terminal moraine, the glacier ice, and ridges to the west and east of the Arthur Kill (Figure 5.9). These glacial lakes occupied the low lying areas that are now the Arthur Kill, Kill Van Kull and Fresh Kill valley segments. Silt and clay was the most common sediment deposited in the lakes, however, streams flowing from the recently deglaciated uplands and off the glacier ice contributed coarser grained sediment to the glaciolacustrine sediment sequence. Other coarse grained glacial sediment, such as outwash and ice contact stratified drift, were deposited in scattered areas. As the glacier continued to recede it deglaciated lower elevation outlets for the glacial lakes, eventually causing the lakes to drain. The drainage of the glacial lakes essentially marked the end of glacial sedimentation on Staten Island (Kaarsberg, 1975; Soren, 1988; Okulewicz, 1990; Roberts-Dolgin, 1991; Stanford and Harper, 1991).

5.2.5.3 Glacial Depositional Model

Within the last two million years, continental ice sheets advanced southward from Canada and covered much of the North American continent (Isachsen, 1980). This resulted in specific erosional and depositional processes that have affected the surface and subsurface configuration of the sediments and bedrock in this region.

When a glacier advances, it is capable of mobilizing and redepositing large volumes of rock and sediments. The amount of sediment and bedrock removed is usually dependent on the type of sediment and degree of weathering of bedrock. Sediments and easily weathered bedrock, (e.g., shale) are usually more severely affected by glacial erosion. In cases where the glacial ice directly overlies bedrock, the upper layer of the rock that remains may be deformed and brecciated (Eyles and Menzies, 1983). The sediment and/or bedrock that has been mobilized is crushed below the glacier, with most of it being redeposited as a lodgement till a relatively short distance from where it was removed. Glacial lodgement till is the main component of the subglacial depositional system (sediments deposited below the base of a glacier).

Lodgement till is a dense, compact, unsorted, unstratified sediment (Boulton, 1972; Bates and Jackson, 1980). Sediment grain size ranges from coarse to fine, however, lodgement till is most commonly composed of a fine-grained matrix. The composition of the till is closely related to the composition of the parent material. Lodgement tills and other glacial deposits may contain sediments transported from great distances, although the majority of the sediments that comprise glacial lodgement till are local in origin.

Lodgement till is usually deposited to the maximum extent of the glacial advance. The location of maximum advance is typically marked by a terminal moraine. Moraines are formed when a glacier stops for a specific period of time. Sediment that has been incorporated in the glacier accumulates in hummocky mounds at the edge of the glacier, deposited primarily by meltwater. Recessional moraines are deposited when a glacier stops as it is receding.

Deposition of additional glacial sediment occurs as the glacier begins to melt away or recede from a glaciated area. As the glacier melts, it releases large amounts of sediment that was incorporated within the glacial ice. If meltwater is allowed to drain freely away from the glacier,

predominately coarse-grained, stratified drift is deposited. The two major types of stratified drift are ice contact stratified drift and outwash deposits.

Ice contact stratified drift is deposited near the ice margin and occurs when glacial sediment is reworked by meltwater during, or after deposition. Stratification and sorting is common in ice contact stratified drift. The large range of grain sizes, chaotic sedimentary structures, slump structures, faults, surface topography, and inclusions of glacial till/diamict suggest that this type of sediment is deposited in contact with, or in close proximity to melting ice, even though the deposits have been reworked by water. The two major types of ice contact stratified drift are kames and eskers. A kame is a low mound, hummock, or short irregular ridge, composed of stratified sand and gravel. It may be deposited by a subglacial stream as a fan or delta at the margin of a melting glacier or by a superglacial stream flowing into a low area or hole on the surface, or at the margin, of a glacier (Bates and Jackson, 1980). Kame deposits are sometimes poorly sorted, and at times, contain unstratified material and fine grained sediment (Embleton and King, 1975). An esker is a long, narrow, sinuous, steep sided ridge composed mostly of irregularly stratified sand and gravel. It is deposited by subglacial or englacial streams flowing between ice walls or in ice tunnels of a stagnant or retreating glacier (Bates and Jackson, 1980). It usually remains after glacial ice has melted. It may be branching, sinuous, straight, or consist of a number of separated elongated hills of bedded sand and gravel, which together form an elongated, but discontinuous feature (Embleton and King, 1975; Bates and Jackson, 1980).

Outwash is deposited by meltwater that is not in close proximity to melting ice. Sorting and stratification is more regular than in ice contact stratified drift. Outwash is similar to other types of coarse alluvium, however, it is influenced by the extreme variability of discharge from glacial sources. Outwash valley trains or outwash plains are formed by high gradient, braided meltwater streams flowing from a glacier, or from the confluence of alluvial fans forming at the end of the glacier (Bloom, 1978).

Proglacial lakes form when meltwater is not able to freely drain away from a melting glacier. The barrier prohibiting drainage is usually formed by a moraine deposited by the glacier. The proglacial lake is bounded by the moraine, glacial ice, and surrounding ridges. The water level in the lake rises until it begins to overflow at the lowest area on the moraine or surrounding ridges (glacial lake outlet). Meltwaters erode the sediment at the glacial lake outlet until a resistive strata, usually bedrock, is encountered, slowly lowering the level of the lake. The outlet

and lake level stabilizes at that elevation. However, as the glacier continues to melt back it may expose a glacial lake outlet that occurs at a lower elevation. When this occurs, the outlet for the lake switches to the lower elevation location and is followed by a rapid decrease in the lake level to the elevation of the new outlet.

In a proglacial depositional environment, the lake is in contact with the glacial ice and receives a substantial volume of sediment direct from meltwater conduits and subaqueous fans (Eyles and Miall, 1989). Glaciolacustrine sediments composed of silty clay to clayey silt are deposited in a proglacial lake environment. They often form silt and clay plains (Bloom, 1978), though coarser-grained deposits may also be present (Bates and Jackson, 1980; Eyles and Miall, 1989). The silt and clay may be varved. The varves represent changes of grain size between successive layers. The finer layer is composed mostly of clay and is thinner and darker. The coarser layer is composed mostly of silt and is thicker and lighter. The thin dark layers represents a phase of slow deposition under very quiet water conditions, such as would be expected in winter when the lake is frozen and little or no meltwater is entering. The lighter, thicker, coarser layer represents more rapid accumulation of lake floor sediment under more disturbed conditions, such as during the summer when meltwater is entering the lake (Embleton and King, 1975).

Analysis of glaciolacustrine sediments suggests that the stratification often observed can be described as laminated instead of varved. There has been increasing recognition that many sequences previously described as varved are simply multiple turbidite sequences of graded silt to clay units without any obvious seasonal control on sedimentation (Quigley, 1983; Eyles and Miall, 1989). The formation of varved silts and clays requires the cessation of meltwater flow into the lake during the winter to create a closed lake system where precipitation of clay particles can take place. When year-round distribution of sediments and turbidite activity occurs, the usual result is graded laminae that are not true varves. Turbidity currents deposit single or multiple graded laminae. Clay laminae may be thin or non-existent in these sediments as a result of infrequent quiet water conditions in the lake environment (Quigley, 1983). Consistent clay layer thickness and sharp textural division between silt and clay components are additional principal diagnostic criteria for varve recognition (Ashley, 1975).

Glaciolacustrine silts and clays often contain moderate to frequent distributions of coarser-grained sediment. Referred to as ice-rafted debris or water-laid till, these coarser-grained glaciolacustrine sediments are deposited at, or directly below, a floating ice margin or icebergs (Figure 5.10).

As the ice margin and/or iceberg melts, the sediment entrained in the ice is released. The sediment undergoes minimal grain-size sorting and may show crude stratification. The sediment will exhibit a till-like appearance, but still have characteristics of and be glaciolacustrine in origin (Quigley, 1983).

Turbidity flows or slumps also form glaciolacustrine sediments. These units have a till-like texture. Slumps could occur in post-glacial times as oversaturated sediment flows or slumps from the surrounding uplands into the glacial lake. Slumping would likely occur shortly after deglaciation, before vegetation was established on the sideslopes. Additional sources for this type of sediment would be sediment sliding off the melting and down-wasting glacier surface or subaqueous debris flows beneath the glacier when the ice margin was still in contact with the glacial lake. As an ice margin retreats, streams continue to move sediment into the glacial lake basin. Sediment would collect where the streams empty into the lake. Periodic slumps or flows would continue to supply coarser-grained sediment to the glaciolacustrine depositional environment (Figure 5.11).

During glacial recession, melt-out till and flow till may be deposited. Melt-out till is released either superaglacially or subglacially, and has some of the original englacial features preserved. Flow till is released supraglacially and undergoes deformation as a result of subaerial flow (Boulton, 1972). The mechanisms that produce these tills may result in less dense, sometimes coarser-grained, and often partly stratified till-like sequences.

Meltwater flowing from glacial ice or water from streams flowing from deglaciated uplands deposits sand sized sediment in the glacial lakes. These sediments are deposited as deltas or fans. These deltas or fans are produced by a sudden decrease in velocity of the water as it enters the glacial lake, resulting in deposition of the coarser grained sediment.

5.2.5.4 *Relationship of Glacial Sediments at the Fresh Kills Landfill Site to Glacial Depositional Model and Regional Depositional History*

Many of the depositional processes presented in the regional historical geology review and in the glacial depositional model have occurred at the Fresh Kills Landfill site. Several glacial erosional features are evident, or can be inferred, at the site. As the glacier advanced over the northern

portion of the site, it apparently removed any Cretaceous and earlier Pleistocene sediment that was present, plus an indeterminate amount of residual clay and weathered bedrock. When the glacier reached the Cretaceous escarpment just south of the Fresh Kills it did not have sufficient erosive capability (energy) to remove the entire Cretaceous sequence. However, it probably did remove earlier Pleistocene sediments (if present) and some Tertiary (if present) and Cretaceous sediment. This is evidenced by the very isolated occurrence of Columbia Group sediments and the occasional incorporation of Cretaceous sediments in glacial deposits (usually glacial till). As the glacier advanced past the Fresh Kills Landfill site, the thickness of the ice at the landfill site continued to increase, until the time the glacier stopped at the location of the terminal moraine (Harbor Hill Terminal Moraine)(Figure 5.8).

Lodgement till was most likely deposited as a continuous unit across the entire site as the basal unit of the glacial sequence. The lodgement till was deposited over residual clay or bedrock in the northern portion of the site, and over the Cretaceous sediments in the southern portion of the site (Figure 5.12). Due to various subsequent geologic and human processes, which will be discussed below, there are areas below the site where the lodgement till is not found (Sheet 5.56).

The parent material for the lodgement till found on Staten Island is primarily local in origin (Soren, 1988). The shales and siltstones of the Stockton, Lockatong, and Passaic Formations, would supply the type of parent material that would promote the formation of tills with a fine-grained matrix. The presence of angular serpentinite rock fragments within the lodgement till found beneath the landfill, also indicates a local source for the parent material.

Some of the lodgement till encountered below the site is composed of a sandy matrix. The till may also contain sand interbeds. Two possible sources for the material that composes the coarse-grained matrix lodgement till have been identified; the pre-Wisconsin Arthur Kill and/or Fresh Kills valley fill sediments, and the sandy facies of the Stockton Formation. Stanford and Harper (1991) indicate that ice flow through the Fresh Kills Landfill site was from the north-northwest (Figure 5.8). As the glacier moved toward the site from the north-northwest, it came across the Arthur Kill/Fresh Kills and the Stockton Formation outcrop belt. The coarser valley fill from the Arthur Kill/Fresh Kills and the sandy facies of the Stockton Formation (Sheet 5.82) could have been eroded by the glacier and deposited at the site as a sandy matrix till.

The presence of a sandy facies of the Stockton Formation beneath the site is of particular note. With ice flow having occurred in a northwest to southeast direction, and given the location of the bedrock sandy facies (Sheet 5.82), the bedrock from that area could have been removed and redeposited as lodgement till on the bedrock in the eastern portion of Landfill Section 6/7. This is a possible explanation for the origin of the higher permeability tills observed in the eastern portion of the Landfill.

Most of the glacial till below the Fresh Kills Landfill is composed of a dense, predominantly fine-grained lodgement till. Variability in the grain-size distribution of the lodgement till can be attributed to the sediments and bedrock that the glacier removed and redeposited at the site. As the glacier advanced over the Fresh Kills site, lodgement till was probably deposited as a continuous layer. No glacial deposition took place at the Fresh Kills Landfill site, other than the possibility of minor subglacial deposition, until deglaciation began. It should be noted that certain units described as glacial sand in this report (sand being the major component of the sample(s)) may be more correctly classified as "sandy" glacial till or glacial till with a sandy matrix.

Other types of glacial till found at the Fresh Kills Landfill site contain numerous sand beds and are coarser grained and less dense than the lodgement till. These glacial till sediments may have been deposited as flow till or melt-out till. The existence of the melting glacial ice margin at the site during glacial ice recession provided a favorable environment for the deposition of these types of tills. The processes that lead to the deposition of these types of units at the site are numerous and can result in complex stratigraphic sequences. An example that occurs at the site is the glacial till/diamict sediments that comprise a portion of the kame features in Landfill Sections 1/9 and 3/4 (Figure 5.13, "A" and "B"). Test boring soil samples indicate that the kames are composed of alternating layers of sand and till. The till in these kames are probably not lodgement in nature, but flow tills formed by slumping of sediment from the melting glacier. The kame features are discussed in more detail later in this section.

During the recession of the glacier (deglaciation), glaciolacustrine sediment deposited in a proglacial lake environment produced one of the predominant geologic units at the site. As the Fresh Kills Landfill site was deglaciated, much of the site was submerged below glacial Lake Bayonne. The area of the Fresh Kills Landfill site to first be deglaciated was the southern portion of Landfill Sections 1/9 and 2/8. When the glacial margin was at the Fresh Kill, most

of Landfill Sections 1/9 and 2/8 were covered by the proglacial lake. As the glacier continued to retreat, most of Landfill Section 6/7, all of Landfill Section 3/4 (except for the kame feature), and the PASNY site were covered by glacial lake waters.

The elevation of glacial lake Bayonne was controlled by an eroding spillway at the terminal moraine at Perth Amboy. The water level of the proglacial lake dropped slowly as the moraine was eroded during glacial retreat. This implies that, instead of having one, or several distinct lake elevations, as is usually the case, the elevation of glacial Lake Bayonne slowly and gradually decreased in response to erosion at the terminal moraine (Figure 5-14). Utilizing the uplift curves Stanford and Harper (1991) constructed for various glacial lakes (Figure 5-14), it can be inferred that the glacial lake level at the Fresh Kills Landfill site could have ranged from what is the present day elevation of 30 feet above sea level to almost -60 feet below sea level. Therefore, the elevation of the glacial lake could have been as high as what is now 30 feet above sea level when the glacier margin was in the southern portion of the Fresh Kills Landfill site and may have dropped over 20 feet in elevation as the glacier receded to the northern portion of the site. The gradual lowering of the lake level would have allowed for continuous and laterally extensive deposition of glaciolacustrine silts and clays.

The glaciolacustrine sediments deposited in the proglacial lakes at the Fresh Kills Landfill site are predominantly fine-grained silty clays to clayey silts. The glaciolacustrine sediments primarily overlie glacial till. Where glacial till is absent, they overlie glacial sand, Cretaceous deposits, residual clay, or bedrock. Sheet 5.41 shows the lateral extent of the fine-grained glaciolacustrine deposits across the site.

Geophysical data indicates that the glaciolacustrine sediments become siltier with depth in most locations. This could be due to the fact that when the glacier was close by, it provided a source for coarser grained sediment, but as it retreated from the area of the site, the coarser grained sediment was deposited further and further away, resulting in a gradual decrease of the sediment grain size deposited in the glacial lake. However, other explanations are possible. For example, it is possible that given the relatively small size of the Fresh Kills site glacial lake basin, sediment influx from the newly emerged Main and Richmond Creeks, plus drainage from other smaller upland streams, was sufficient to prevent the settling of fine grained sediment until the flow of those streams decreased.

Using the guidelines discussed in the glacial depositional model, the fine-grained silt and clay sediment has been described as laminated instead of varved. The thin, repeating, alternating light and dark colored silt and clay layers distinctive of varved sediment was not observed. Variations in layering and size distribution of the fine-grained glaciolacustrine sediment was observed. However, it did not exhibit the sedimentologic and depositional characteristics of varved sediments explained in the glacial depositional model.

Examination of the glaciolacustrine sediments indicates various types of sediment influx into the glacial lakes at the Fresh Kills Landfill site. In several areas, glaciolacustrine silts and clays contained moderate to frequent distributions of coarser-grained sediment, giving the samples a till-like appearance. The samples' principal component is silt and clay, however, a significant amount of coarse material (coarse to fine sand and/or coarse to fine gravel) is present. Since these types of glaciolacustrine deposits appear till-like in grain-size distribution, it is often difficult to determine if the deposit is glaciolacustrine or till. It is possible that the ice margin was floating in the lake at the Fresh Kills Landfill site. Icebergs that were calving off the margin may also have been floating in the lake. The sediment contained in the floating ice margin and/or icebergs would have been deposited as the ice melted. These types of deposits (ice-rafted debris or water-laid till) show crude stratification and minimal grain-size sorting, giving them an appearance similar to glacial till.

Other isolated till-like units were encountered in the glaciolacustrine sediments. Deposits that may represent turbidity flows or sediment slumps occur frequently near the upland portions of the site, primarily in the central portions of Section 2/8 and eastern portions of Section 6/7. Meltwater currents that redeposited sediment released from below the glacial ice may have also produced glaciolacustrine sediments that are till-like in appearance. These till-like glaciolacustrine deposits are usually limited in lateral extent.

For classification purposes, the till-like deposits described above should not be classified as glacial till, but as diamict. The term till usually applies to dominantly unsorted and unstratified drift that was deposited directly by, and underneath a glacier, without subsequent reworking (lodgement till). Diamict is a more general and generic term (which includes glacial lodgement till) used to describe an unsorted or poorly sorted sediment that contains a wide range of particle sizes (Bates and Jackson, 1980). Given these definitions, sediments such as flow till, melt-out till, water-laid till, ice rafted debris, and turbidities warrant classification as diamict. However,

due to the similarity in texture and appearance, it is often difficult to distinguish between glacial lodgement till and other diamict. For mapping purposes lodgement till was distinguished from non-lodgement till by its position in the stratigraphic sequence. If a till unit was located at the base of the glacial sequence it was considered lodgement till. If the till unit was not at the base of the glacial sequence (i.e, above glacial sand or glaciolacustrine silt and clay), it was identified as non-lodgement till. It should be realized that this is a simplified classification scheme. It is possible for isolated sand lenses to occur within the lodgement till. This is a common occurrence in this region (Soren, 1988). Therefore, it is possible that some till-sand-till sequences may actually be lodgement till-glacial sand-lodgement till, instead of non-lodgement till-glacial sand-lodgement till.

As the glacier retreated north of the Fresh Kills landfill site, the meltwater traveling down the Arthur Kill channel eroded deeper and deeper until it eventually reached the diabase. Once this occurred, erosion of the Arthur Kill channel over the diabase essentially stopped due to the hardness of the diabase unit. However, downstream of the diabase, erosion continued to occur in softer sediment and/or bedrock. The glacial lake outlet at the terminal moraine continued to erode in conjunction with the Arthur Kill channel south of the diabase. This created a spillway at the edge of the diabase, approximately in the area where the Fresh Kills flows into the Arthur Kill (Stanford and Harper, 1991). The creation of the spillway provides a possible mechanism for removal of the glacial till and glaciolacustrine silt and clay from the western portion of Landfill Section 1/9. As shown on Sheets 5.41 and 5.56, no glaciolacustrine silt and clay and only isolated areas of glacial till is present below the western portion of Landfill Section 1/9. It is postulated that the turbulence and erosive ability of the spillway north of Landfill Section 1/9 could have been a factor in removing the glacial till and glaciolacustrine silt and clay from most of the western portion of Landfill Section 1/9.

Uplift curves produced by Stanford and Harper (1991) for glacial Lake Bayonne and other glacial lakes that existed in the area of the Fresh Kills Landfill are presented on Figure 5.14. The uplift curves are useful because they allow for the correlation of glacial lake features such as spillways, deltas, and shorelines that have been adjusted for the increasing amount of isostatic rebound that occurred northward of the glacier terminal position. The spillway created by the erosion of the Arthur Kill channel down to the diabase beneath the Arthur Kill existed during Lake Hackensack time, after glacial Lake Bayonne drained. This is shown on the uplift curve for glacial Lake Hackensack (Figure 5-14), labeled as the Tremley Point spillway. The spillway elevation is

approximately at the present elevation of -30 feet below sea level. The Fresh Kills Landfill site is approximately 4.5 miles from the terminal moraine at Perth Amboy. Therefore, according to the glacial Lake Hackensack uplift curve, the spillway would have been capable of eroding the previously deposited glacial sediments (lodgement till and Lake Bayonne silts and clays) at the Fresh Kills Landfill site along the Arthur Kill to a depth that corresponds to the present elevation of -40 feet below sea level. The dashed portion of the uplift curve that extends from the terminal moraine at Perth Amboy to the Tremley Point spillway indicates uncertainly as to what the meltwater channel elevations were south of the Tremley Point spillway. The straight line implies a gradual decrease in elevation down to the outlet at the terminal moraine at Perth Amboy. However, the presence of a spillway probably created a very large decrease in the channel elevation over a very short distance below the spillway (a waterfall), with associated turbulent and erosional flow downstream of the spillway. The outlet elevation is given as approximately -60 feet below sea level based on analysis of sediments at the Outerbridge Crossing (Figure 5-14), allowing for the erosion of previously deposited sediment along the Arthur Kill to that elevation (-60 ft).

The western portion of Landfill Section 1/9 occurs along the Arthur Kill below the Tremley Point spillway. Therefore, it is possible that the previously deposited glacial sediments in the western part of Landfill Section 1/9 could have been eroded to an elevation close to the outlet elevation of the terminal moraine at Perth Amboy (-60 feet). The lowest elevations at which Recent (Holocene) sediment is observed along the western side of Section 1/9 is at approximately -60 feet (Sheet 5.7, Geologic Cross Section GA-GA). It can be interpreted that Recent sediment was subsequently deposited to this depth along this portion of the site because the glacial sediment was removed by the erosive power of the glacial meltwater as it cascaded down the Arthur Kill from the Tremley Point spillway.

Another possible mechanism for removal of the glacial till and glaciolacustrine sediments in western Landfill Section 1/9 might have been the presence of higher than present flow rates in the Fresh Kill or Arthur Kill channels in the post-glacial period. If for some period of time following glaciolacustrine sedimentation, flow rates in the channels adjacent to Landfill Section 1/9 were greater than present, erosion of much wider channels might have occurred. An additional possibility is that prior to the transgression of the sea into this area, the Rahway River continued down the Arthur Kill channel eroding most of the glacial deposits. As sea level rose, the area was slowly flooded and deposition of Recent sediment occurred.

It is believed that the absence of glacial till and glaciolacustrine silt and clay in the western portion of Section 1/9 is best attributed to erosional processes. Glacial till and glaciolacustrine sediments are deposited by separate glacial processes over a long period of time. It is more likely, therefore, that they were eroded after both had been deposited. The possibility of having two separate mechanisms preventing deposition and/or causing erosion of each glacial unit individually is very unlikely. The presence of very thick sand sequences (interpreted as Recent sand) along the western edge of Section 1/9 provides additional supporting evidence for erosion, reworking, and redeposition of the eroded glacial material by channels.

Glaciolacustrine silt and clay is present south of the kame feature (Figure 5.13, "A") in Section 1/9, making it difficult to explain the absence of glaciolacustrine silt and clay in the southeast portion of the Section (Sheet 5.41). Glaciolacustrine silt and clay is also absent in the area of the kame feature in Landfill Section 1/9 (Sheet 5.41), indicating that the kame was formed prior to, or concurrent with, the glacial lake episode. Glacial till is present in the area below the kame feature, however, glacial sand is the basal unit of the glacial sequence in much of this area. The lodgement till may have been removed by the meltwaters associated with deposition of the kame, followed by the deposition of an alternating sequence of sand and flow tills. It is also possible that meltwater eroded the base of the lodgement till and glacial sand filled in the erosional voids. The deposition of an alternating sequence of sand and flow till followed. The absence of glacial lodgement till in the northern portion of Landfill Section 1/9 (Sheet 5.56) may also be due to ice marginal erosion by meltwater.

The absence of glaciolacustrine silt and clay in the northwestern portion of Landfill Section 1/9 is attributed to non-deposition. Glacial till deposited on Cretaceous sediment that existed at higher elevations in that portion of the site created a feature that was probably above the level of the glacial lake, precluding the deposition of lake sediments. In the southern portion of Landfill Section 2/8, where refuse/fill overlies Cretaceous sediment, it is believed that the glacial sediments were removed during landfilling activities. Erosion by meltwater is the most likely explanation for the absence of the basal lodgement till in areas where either glacial sand or glaciolacustrine silt and clay overlie Cretaceous sediment. The occurrence of glacial sand as the basal glacial unit in these areas may, in some cases, be a sandy matrix lodgement till.

Two kame features (Figure 5.13, "A" and "B"), now buried beneath refuse/fill, are important with respect to glacial deposition at the Fresh Kills Landfill site. Test borings indicate that these

features are composed of a relatively thick sequence (up to 80 ft) of interbedded glacial sand and till. Two ideas have been formulated for the depositional origin of these features. The first explanation is that the features formed as a result of movement of glacial ice over a topographic "obstacle." As established earlier, glacial ice moved into the Fresh Kill Landfill site from the north-northwest. A topographic high is present immediately south-southeast of each feature; a bedrock high in the case of Feature "B", and a topographic high created by the Cretaceous deposits in the case of Feature "A". As the advancing glacier overrode these obstacles, the lower portion of the ice moved more slowly than the upper portion creating an environment favorable for deposition of till and sand. The deposition of these sediments would have continued during glacial advancement.

The second explanation is that these features formed during glacial retreat, occurring as kame-type deposits. The deposition of the kames may also be related to and dependent on changes in topography. A change in elevation could have caused the glacier to pause for a brief period of time to adjust to the new topography. These features are formed primarily at locations where meltwater streams flow off, out of, or from beneath the glacier or in depressions on the ice near the glacier margin. Figures 5.15 and 5.16 show the hypothetical locations of the glacial ice and glacial lake elevations at the Fresh Kills Landfill site and surrounding area when the kame features were deposited. These features are in alignment with the recessional ice margin in New Jersey delineated by Stanford and Harper (1991) (Figure 5.8).

The morphology of these features (Features "A" and "B" discussed above) strongly suggests that they are kames. The features are composed of glacial sand and till. Kames and ice contact stratified drift, in general, are composed mostly of sand and gravel with inclusions of non-lodgement type till (Embleton and King, 1975; Bloom, 1978). It is likely that these kames were formed at or near the glacier margin as a delta or fan built into the glacial lake or as a supraglacial or englacial stream deposited sediment in a depression on the top of or within the glacier. Flow till would occur interlayered with the sands as relatively unsorted, unstratified, sediment occasionally slumped onto the delta or into the depression as the glacier melted. The kame deposits are sometimes found interbedded with glaciolacustrine deposits (Geologic Cross Section GK-GK). If these mounds of interlayered till and sand were deposited during glacial advance, as proposed in the first explanation, they would exist as a totally separate unit beneath the glaciolacustrine silt and clay unit, which was deposited during glacial retreat. However, if the interbedded sand and till mounds are kames, they would have been deposited during glacial

retreat. The occasional interlayering of glacial sand and tills with glaciolacustrine deposits supports the interpretation that the sand/till units that form these mounds are kames deposited during glacial retreat.

If these features are representative of kames deposits, and if they were deposited at or near the glacier ice/glacial lake margin, their morphology can be used to make inferences on the glacial lake elevation at the time they were deposited. In kame delta sediments, the contact between the topset and forset beds marks the former lake level. At the Fresh Kills Landfill site it is not possible to examine the kame sediments directly to determine the topset/forset contact due to their burial beneath refuse. Split spoon samples, the primary tool used for stratigraphic analysis during this investigation, do not provide the degree of detail necessary to make such determinations. However, if it is assumed that the kames are deltas based on morphology alone, the topset/forset contact can be inferred by the location on the kame where the top surface contacts the steeper side slope of the feature. Historical topographic maps (Sheets 2 and 4, IT Corporation and Wehran Envirotech, 1991a) show the elevation of the topset/forset contact on the Landfill Section 1/9 kame to be approximately 30 feet and the elevation of the topset/forset contact on the Landfill Section 3/4 kame to be approximately 10 feet. These elevations were used to illustrate the lake elevation on Figures 5.15 and 5.16 at the time of deposition of the kames. These lake levels correspond with glacial Lake Bayonne water level elevations reported by Stanford and Harper(1991). It should be noted that the determinations of lake levels were made primarily by morphologic and topographic inference, and therefore should be considered approximate.

There is evidence that sediments were deposited in this region during the period(s) after the Cretaceous and before the last glaciation (Wisconsin). Remnants of these deposits may be present in the southern portions of Landfill Sections 1/9 and 2/8 (Sheet 5.59). For example, in test boring 2W91:IT307, in the southern portion of Landfill Section 2/8, a grayish yellow to moderate yellow sequence of sands, silt, and clay was encountered at the top of the Cretaceous stratigraphic sequence. These sediments are characteristic of certain formations of the Columbia Group. The Columbia Group is made up of three formations: the Bridgeton Formation, the Pensauken Formation, and the Cape May Formation. Although presumably listed in order from older to younger, the stratigraphic relationships between the units have not been confirmed. Disagreement still exists as to whether they are fluvial, interglacial, or glacial in origin (Bowman and Lodding, 1969; Bowman and others, 1976). There is also disagreement on the age of the

Columbia Group sediments as either being Tertiary or Pleistocene in age (Barksdale and others, 1943; Bowman and Lodding, 1969; Owens and Minard, 1979).

The general description of the Columbia Group sediments found at the Fresh Kills Landfill site, namely a yellowish to orange brown sandy, clayey unit, fits the description of both the Bridgetown and Pensauken Formations. Regionally, it is believed that both units were deposited by a drainage system that flowed northeast to southwest. Figure 5.17 shows the paleodrainage direction of the Pensauken Formation in Staten Island and New Jersey. Given the unresolved age and origin of the Columbia Group, for this report they are classified as glacial (Pleistocene) deposits. The boring number and top and bottom elevations of sediments that are believed to belong to the Columbia Group are presented in Table 5.2. It is possible that at least the southern portions of Landfill Sections 1/9 and 2/8 were part of the drainage networks that existed during the various pre-Pleistocene or Pleistocene interglacial periods. It is believed that subsequent glacial and non-glacial erosional processes removed most of the Columbia Group sediments deposited at the Fresh Kills site, as they were encountered in only eight borings. It should also be noted that, because of the characteristics of these sediments and the locations they are found, these deposits may be clean fill or possibly oxidized Cretaceous sand.

5.2.6 Holocene (Recent) Geology

5.2.6.1 Regional Holocene (Recent) Geology

The beginning of the Holocene Epoch has been placed at 10,000 years before present (Bloom, 1982; Palmer, 1983). By this time, the region surrounding the Fresh Kills Landfill site was experiencing isostatic rebound and sea level rise as the result of the retreat and melting of the Wisconsin ice sheet. At 10,000 years before present, sea level was still approximately 75 to 100 ft lower than present. At the present time, overall sea level rise has exceeded isostatic rebound, resulting in a marine transgression along the eastern coast of the United States. Sea level rise was relatively rapid until about 7,000 to 4,000 years ago and continues at a slow rate today (Bloom, 1983).

After the breaching of the moraine at the Narrows, and the draining of the glacial lakes, the area was subjected to varying geologic conditions, (i.e. erosion). In low lying areas, Recent sediments

consisting of silts, clays and sands were deposited in marsh-like environments in close association with localized fluvial deposition and marine inundation.

The patterns of distribution of Holocene coastal sediments are complex. This complexity results from lateral and vertical migration of successive tidal environments of deposition such as marshes and beaches (Kraft and Allen, 1975). Additionally, minor changes in the rate of sea level fall, in rate of tectonic subsidence, or tectonic reversal lead to stillstands, strandline fluctuations, or regressions. Examples of shorelines migrating for long distances in one direction, with minor reversals or fluctuations, is common in the stratigraphic record. It is also common for transgressive sequences to have minor regressive fluctuations (Kraft, 1978).

The details of the depositional history of a transgressive sequence should be reflected in the vertical sequence of the strata that result from the transgression. However, coastal erosion prevents preservation of the complete sequence. In the present Atlantic coastal transgression, approximately one-half of the sedimentary depositional sequence is preserved, the rest having been eroded (Kraft, 1978).

5.2.6.2 Staten Island Holocene (Recent) Geology

After the ultimate drainage of the glacial lakes, which probably occurred 10,000 years before present, Recent silts, clays and sands were deposited, primarily in the lowland areas of the island (i.e., marshes around the periphery of Staten Island). Changes in sea level during Pleistocene and Holocene time resulted in transgressive -regressive marine depositional sequences. On Staten Island, these deposits occur as interbedded to layered units of Recent silt and clay, peat, and sand, primarily in tidal marsh environments (Soren, 1988; Roberts-Dolgin, 1989). Upland swamps exist in many areas on Staten Island where drainage is poor due to shallow bedrock or low permeability layers (Roberts-Dolgin, 1989). Sand covers the beaches along Staten Island's shore line. The sand type is dependent on the parent rocks from which they were derived. The source of most of the beach sands are rocks of the New York City Group, the serpentinite, Palisades diabase, Cretaceous deposits, glacial deposits, and outcrops of other formations further up the Hudson Estuary (Okulewicz, 1990).

5.2.6.3 Recent Depositional Model

Most of the Holocene sedimentation at the Fresh Kills Landfill has occurred in a salt marsh environment (Figure 5.18, Tide Marsh). Salt marshes or coastal (saline) wetlands are vegetated saline intertidal areas that occur along the coasts of most land masses (Frey and Basan, 1978; Davis, 1983). Sedimentologically, they occur as a wedge of sediment deposited intertidally. The salt marsh is a tide-stressed environment (Frey and Basan, 1978) which grades from nearly terrestrial to nearly marine in character. Relief is typically low. Subtle variations in elevation and additional factors cause distinct zonation in the salt marsh environment. Factors that control zonation within the marsh include nutrient influx, physicochemical conditions, waves, currents, and sediment patterns, as well as tidal regime (Davis, 1983).

The marsh is typically divided into two major components: the high marsh and the low marsh (Frey and Basan, 1978). Classification is based on tidal regime, plant types, and substrate (Figure 5.19) (Davis, 1983). Tidal regime is usually the main controlling factor in marsh zonation (Frey and Basan, 1978). The low marsh is characterized by a continuous growth of cord grass. It is generally floored by a mud substrate. The low marsh vegetation extends from about mean high water neap to new mean higher high water. This part of the marsh is flooded fairly regularly (Davis, 1983); on average, more than 360 tidal submersions per annum. Low marsh zones may repeat in a rather complex pattern, created by the repetition of individual sets of physical or ecological conditions. Tidal creeks serve as general reference boundaries. Marshes that are intricately traversed by tidal creeks repeat marsh divisions behind each creek bank (Figure 5.19) (Frey and Basan, 1978).

The high marsh consists of short forms of cord grass, glasswort, salt grass, and needle rush. Needle rush is the most common type of vegetation on the high marsh. Sand or muddy sand is likely to be the substrate (Davis, 1983). High marshes undergo substantially fewer submersions and may remain subaerially exposed for long periods between tidal inundations (Frey and Basan, 1978).

A marsh is classified as youthful when low marsh environments constitute the majority of the total marsh area (Frey and Basan, 1978). Active channels within a youthful marsh, which may be numerous, exhibit minimal migration and/or accretion. At the onset of channel development, accretion is both lateral and vertical, but as development proceeds, vertical accretion dominates (Davis, 1983). The ground surface of a youthful marsh is somewhat varied, displaying a pronounced microtopography (Figure 5.19).

In a mature marsh, the area consisting of high and low marsh is approximately equal (Figure 5.20). In an old marsh, the high marsh environment comprises most of the total area. Most channels in an old marsh are sediment filled. The marsh surface has become increasingly planar (Figure 5.20). The terminology describing marshes is based on physiographic stage, not finite age of the marsh. In general, high rates of tidal deposition and subsequent marsh expansion tends to favor low marsh development. Conditions approaching an equilibrium stage, tend to favor high marsh development (Frey and Basan, 1978).

Sediment accumulation in a marsh is derived from runoff of land, from washover of barriers, landward transportation by tidal currents, wind-blown sediments, and organic aggregates (Frey and Basan, 1978; Davis, 1983). Salt marsh sediment is commonly a subequal mixture of fine mud and plant debris, with small amounts of shell material, sand-size terrigenous particles, and large plant fragments (Davis, 1983). The primary mechanism for providing sediment to the marsh is overbank flooding of channels, similar to a fluvial system. Sediments are carried largely in suspension and consist of fine organic detritus and mineral particles. During high spring tides, and especially during storm tide conditions, the marsh is flooded by sediment-laden water. There are many phenomena related to the marsh grasses that permit the suspended sediment to accumulate in the marsh. The marsh vegetation acts as a baffle, causing attenuation of waves and currents, permitting suspended sediment to settle (Davis, 1983). It is believed that settlement from suspension alone is inadequate to produce the thick accumulations of muds in salt marshes. Other mechanisms suggested include physicochemical flocculation of clays, formation of organoclays, and biogenic sediment trapping (Frey and Basan, 1978).

Formation of channels is an important process on salt marshes. Channels incised into vegetated substrates tend to be more sinuous and have more pronounced meander curvatures than channels cut in unvegetated flats, because rooted substrates offer more resistance to current or turbulent flow. Levees form along the sides of the channels due to periodic flooding. As scour deepens the channel, levees heighten the sides of the creek (Frey and Basan, 1978). Marsh channels, similar to channels in other fluvial systems, may be subject to avulsion and neck cutoff. Breeching of levees and development of crevasse splays is a means of providing large quantities of sediment to a marsh, although it is usually local in nature. Washover of sediment provides large pulses of sediment in a shape similar to crevasse splays (Davis, 1983).

In most marshes, channel processes continue to deposit and erode sediments throughout the channel's existence, although much of this activity may be on a comparatively minor scale (Frey and Basan, 1978). Small channel fill accumulations may occur in the marsh facies representing the tidal creek environment (Davis, 1983). Mussel and oyster banks established along the stream banks act as stabilizers to reduce erosion (Frey and Basan, 1978; Davis, 1983). Channel deposits are typically coarser than the fine-grained marsh deposits, and cross-stratification is common (Davis, 1983).

5.2.6.4 *Relationship of Holocene Sediments at the Fresh Kills Landfill Site to the Recent Depositional Model and Regional Depositional History*

The former salt marsh environment of the Fresh Kills Landfill is represented by a fairly complex combination of silt, clay, sand, and peat. The depositional processes are very similar to what was described for the Cretaceous sediments deposited by meandering systems, but on a smaller scale. Coarse sediment occurs mostly in the tidal marsh stream channels. The streams are very low gradient and meander through the marsh. Sediment is supplied to the marsh during flood stages of the tidal channels and by tidal mechanisms. The marsh is a zone of accumulation of predominately fine-grained sediment (silt and clay). Marsh grass grows in the marsh and as it dies and accumulates, leads to the formation of peat.

The distribution of sediment in time-transgressive depositional environments is complex. The type of sediment deposited at a given location in the sequence is dependent upon its elevation, transgressive or regressive trend of the sea, location of tidal stream channels, sediment influx and nature of vegetation. The vertical and lateral accretion of sediment, in conjunction with erosion is dependent on short term (daily-tidal) and long term (transgressive-regressive) processes.

Recent sand occurs primarily as channel fill sediment. The vertical and horizontal extent is dependent on various geologic conditions, such as sediment source and supply, and drainage patterns. In Landfill Section 3/4 and northern Landfill Section 6/7, the Recent Sand appears to have been deposited in a higher energy environment, creating a more laterally continuous layer that appear to be correlative across portions of the site. In the western portion of Landfill Section 1/9, late-glacial and post-glacial erosion and deposition along the Arthur Kill has resulted in a relatively thick correlative Recent sand sequence.

In a high energy environment, sand may form a continuous, sinuous unit within and along the channel. In lower energy portions of the channels, sand may occur as isolated lenses. Cross-Sections FK-FK, MC-MC, and RC-RC (Figures 5.21A, 5.21B and 5.21C) show the stratigraphy across Fresh Kills, Main Creek and Richmond Creek at the locations where test borings were performed to analyze subsurface conditions for the possible construction of bridges over these waterways (see Sheet 5.4). Even though Main and Richmond Creeks are large, higher energy tidal channels, they appears to carry a rather small load of Recent sand (Figures 5.21A and 5.21B). Recent sand occurs on both sides of Fresh Kills (Figure 5.21C). However, deposition does not appear to be recent in nature. The sand is now covered by Recent silt and clay and has been dissected by the stream, indicating very little to no current coarse sediment deposition. Due to the close proximity of these streams to sea level, most coarse sediment is probably deposited soon after the stream flows into the tidal marsh. It is also possible that the current sediment load is different than the load that existed during deposition of early Recent sediments. In summary, it is believed that the tidal marsh stream channels do contain sand, however it is difficult to determine the thickness, horizontal extent, and continuity of the sand. The thickness, lateral extent and continuity of the sand would also be dependent on sediment source and bed load.

Recent silt and clay is deposited in the low lying tidal marsh areas during flood stages. The Recent silt and clay exists throughout the salt marsh environment except in areas where the tidal channels are entrenched and/or have eroded through the silt and clay and into the glacial sediments. Peat accumulated in areas where conditions were suitable for sustained marsh grass growth.

Review of data associated with the Recent deposits illustrates the problem in limiting analysis to conventional plans and profiles in the development of a geologic model. The examination of contour maps and cross-sections can give the impression of a succession of relatively continuous layers of silt and clay and isolated lenses of sand, as mentioned previously (i.e. "layer cake" geology). However, this interpretation is probably oversimplified, as it ignores lateral and vertical variations that occur in a transgressive depositional environment (as presented in the geologic model).

As discussed in the Hydrogeological Literature Review, (IT Corporation and Wehran EnviroTech, 1991a) and this report, prior to placement of refuse/fill, the Fresh Kills Landfill area consisted

of a tidal marsh flanked by upland areas. Aerial photographs and historic topographic maps show channels traversing the tidal marsh. Based on the geologic model for a tidal marsh environment, the marshy areas would consist of fine-grained organic materials with coarser-grained, fluvial sediments present in the channels. Projecting the depositional process over time (in the context of marine transgression in the post-glacial period), a more complex three-dimensional distribution of materials would be expected than what is predicted by "layer-cake" geology.

The difference in the two perspectives, "layer cake" versus time-transgressive facies models, have implications important to groundwater flow. The "layer cake" perspective, which is the impression given by plan view maps and cross-sections, suggests that the Recent silt and clay is a relatively continuous layer, and as such would be expected to serve as a major restrictive, impeding layer for groundwater flow. The Recent sand appears as isolated, discontinuous lenses, with no apparent pathways for groundwater migration. The alternative time-transgressive model shows that the sand may extend vertically and laterally across the site (Figure 5.22) and, therefore provide continuous pathways for groundwater migration.

Based on the evaluation of subsurface samples and data, it is believed that the geologic conditions at Fresh Kills represent a combination of these perspectives. Sheet 5.78 shows which units occur at the surface of the Recent sequence. Silt and clay and peat primarily occur at the top of the Recent sequence, with sand occurring at the top in only isolated locations. The time-transgressive depositional model indicates that sand is predominately deposited in tidal marsh channels. Historic topographic maps and aerial photographs show several tidal marsh streams flowing into Richmond and Main Creeks. Many smaller tributary streams flowed into the main tidal marsh streams. Channel widths ranged from a few feet to a few tens of feet. Depths of the channels vary, but are usually about half of the width in vertical section, as indicated from test boring and channel depth data. Therefore, the occurrence of sand at the top of the Recent sequence in only a limited number of test borings is not unexpected.

The bottom elevation profile of several tidal marsh channels (the locations of tidal marsh channels are shown on Sheet 5.83), were projected on the appropriate cross-sections to determine what stratigraphic units the base of the channels contact. In most cases, the bottom of the tidal stream channels extend into, but not through, the Recent silt and clay. However, there are several locations in northern and western Landfill Section 1/9, and western Section 6/7 where

channels have fully eroded through the Recent silt and clay. In some of these areas, the channels are in contact with lower sand units.

There are areas of the Landfill where Recent sand is regularly encountered (Sheet 5.35), indicating it may be more laterally continuous in these areas. These apparent laterally continuous deposits may have formed in a littoral environment (near shore) through shoreline, eolian, and/or tidal channel depositional processes. It is very difficult to see the sedimentary features (stratification and structure) in split spoon samples, which would allow for a more specific determination of the environment of deposition. Sheets 5.36 and 5.37 show the specific areas across the site where lateral connection between Recent sand is possible.

5.3 Stratigraphic Analysis

Stratigraphic analyses are inherently integrative and iterative. In the case of this study, the data from multiple analytical techniques were organized and reviewed as they were collected. Tables 5.3 to 5.6 summarize the type of stratigraphic analyses performed utilizing multiple analytical techniques. This analysis led to the development of a preliminary stratigraphic column based on initial stratigraphic units. These initial units were then correlated across the site, in plan view and profile, to develop an initial interpretation of the stratigraphy for the site. This correlative process led to the appropriate revisions of the stratigraphic column. Near the end of the analytical process, the stratigraphic interpretation was compared to the depositional models developed for the site (discussed in Section 5.2) to see if they were in agreement. These analytical and correlative processes continued successively until a complete stratigraphic column, capable of site-wide application was developed. The stratigraphic unit top and bottom elevations and thicknesses for all borings utilized in this study are presented in Tables 5.7 through 5.17.

5.3.1 Stratigraphic Column

As noted in Section 2.2, previous investigations at the Fresh Kills Landfill identified a variety of stratigraphic units. The latest and most complete Hydrogeologic Investigation conducted prior to this investigation was by Wehran Engineering (1983c). The general stratigraphic units identified in that investigation were (in descending stratigraphic sequence):

- Refuse/Fill
- Recent silt and clay
- Recent sand
- Glacial sand
- Glaciolacustrine clay and silt
- Glacial till
- Cretaceous clay
- Cretaceous sand
- Residual clay
- Weathered bedrock

For this study, it was determined that an unbiased evaluation of site geology, including redefinition of stratigraphic units, when appropriate, was in order. With this in mind, the first step in data analysis was directed at identifying the basic geologic units and their associated stratigraphy. This analysis involved an iterative approach through the utilization of the four analytical techniques outlined earlier.

Field geologists classified soil and rock materials during the drilling program using standard soil and rock classification systems. This was followed by independent soil and rock sample examination of all samples collected by two experienced senior geologists under controlled laboratory-type conditions. In addition to providing for the development of consistent site-wide lithologic unit descriptions, this oversight analysis allowed for incorporation of the regional test boring and literature review data base into the development of a stratigraphic column. At various stages in this process, samples and data that were collected from the geophysical analysis, microfossil analysis and piezo-electric cone penetration testing were evaluated and correlated with the lithologic data from the soil sample descriptions. Development of the stratigraphic column also required correlation of stratigraphic units across the site. This was necessary because the complete stratigraphic sequence was not present at any single location. Through this continuous analytical process, the basic stratigraphic column was developed, tested, revised and ultimately established.

The presently established stratigraphic column for the Fresh Kills site is as follows (letters in parenthesis are abbreviations for lithostratigraphic units):

Lithostratigraphic Units	Time Stratigraphic Units
Refuse/Fill (F) Peat (Qp) Silt and Clay (Qrc) Sand (Qrs)	Holocene (Recent)
Glaciolacustrine Silt and Clay (Qgl) Glacial Sand (Qgs) Glacial Till/Diamict (Qgt)	Pleistocene (includes Columbia Group)
Silt and Clay (Kc) Sand (Ks)	Cretaceous
Residual Clay (Tlc, Tsc, Osc, Shc) Weathered Bedrock (Tlw, Tsw, Jdw, Osw, Shw) Bedrock (Tl, Ts, Jd, Os, Sh)	Triassic/Jurassic; Ordovician

The different lithostratigraphic units are representative of the evolution of different geologic environments through time. Time stratigraphic units corresponding to the groups of lithostratigraphic units are also presented. The lithostratigraphic units do not always occur in the order listed above within the time stratigraphic unit (for example, peat may occur below Recent silt and clay). The time stratigraphic units, by definition, must always occur in sequence, although units may be absent due to nondeposition or erosion. However, occasionally "blocks" of older sediment are eroded and incorporated in younger sediment. For example, Cretaceous sediment is sometimes found within glacial till (see test boring ZW91:IT301D on Sheet 5.8C). Ages of the unconsolidated materials are defined by microfossil analysis, by geological perspective (i.e., till is distinctly glacial and therefore Pleistocene in age), and by correlation with previous investigations. The age of the residual clay and weathered bedrock is not known. These units were formed after lithification of bedrock, however, the weathering process may have

continued over a long period of time (even after deposition of overlying units). Each of the stratigraphic units have distinctive characteristics, which, along with their stratigraphic position, allows for the identification of subsurface samples. These distinctive characteristics in conjunction with general techniques of geologic correlation, provide the basis for delineation of subsurface geology.

The present stratigraphic column is very similar to the stratigraphic column previously developed by Wehran Engineering (1983c). It is also generally comparable to the regional stratigraphic column presented in literature. The similarity between the local and regional stratigraphy indicates that the general succession of strata in the region is fairly consistent: bedrock → weathered bedrock → residual clay → Cretaceous strata → Pleistocene (glacial) strata → Holocene (Recent) strata. In turn, it can be inferred that the local depositional sequence: a Cretaceous marine-terrestrial deltaic sequence deposited on partially to severely weathered bedrock that overlies a consolidated bedrock platform, followed by a Pleistocene glacial sequence, and finally, a Recent marine transgression sequence deposited in a low-lying coastal area was regionally consistent.

The basic stratigraphy in the region is generally well established. However, stratigraphic study in the region included controversy and disagreement, not over the general stratigraphy but with regard to details. The uniformity of individual stratigraphic units, the local or regional aspect of vertical lithologic variations, and lateral continuity and extent of the units were some of the major questions debated. The tendency of the early stratigraphers was to deal with these questions under the operative paradigm of a geological model often likened to "layer-cake" stratigraphy. After 150 years of protracted study and debate by their successors, a different model has emerged, based on an understanding that the geologic environments of deposition were time-transgressive, laterally shifting, and laterally variable (i.e., characterized by different sedimentary facies).

The present stratigraphic column is comprised of lithostratigraphic units which, within individual time units, may vary in terms of local characteristics, thicknesses, successional order, and lateral extent. For example, the Cretaceous sediments do not always occur as sand overlain by silt and clay, as implied by the stratigraphic column. The Cretaceous stratigraphic sequence may occur as complexly interbedded lithostratigraphic units. The dominant lithologic units within the complexly interbedded sequence can usually be delineated and mapped. Similar stratigraphic

occurrences are seen in the Pleistocene and Recent depositional sequences. Certain lithostratigraphic units can be correlated across large areas of the site as grossly similar lithologies, with the general vertical sequence of these strata defined. This general sequence is reflected in the stratigraphic column provided earlier.

At the Fresh Kills Landfill site, the Cretaceous stratigraphic sequence generally consists of a basal sand overlain by a silt and clay unit, both of which generally have some lateral continuity. Interlayered beds of Cretaceous sand and silt and clay do occur within the upper silt and clay sequence. In the Pleistocene sequence, the tendency is to find a basal glacial till layer overlain by a glaciolacustrine silt and clay layer. The Recent sequence, when present, is usually comprised of a basal sand layer (not site-wide extensive) overlain by a silt/clay layer.

The tendency for certain stratigraphic units to occur site-wide and in a specific order has implications from a groundwater or hydrogeological standpoint. On a simplified, site-wide perspective, the Fresh Kills Landfill Site can be interpreted as being comprised of "layer-cake" strata, the majority of which is low permeability and fairly continuous. Individual units within the complete stratigraphic section are coarser grained and more permeable, and vary in continuity from strictly local, isolated lenses, to sub-regionally correlative units. This geologic framework represents a significant aspect of the site stratigraphy, which can be expected to influence the overall behavior of groundwater and associated contaminant migration. The geologic evaluation completed for this study concentrates on defining the occurrence, variations, and spatial relationships of individual lithologic units to assist the hydrogeological evaluation.

5.3.2 Stratigraphic Unit Characterization

5.3.2.1 Lithostratigraphic Analysis

Based on lithostratigraphic analysis (e.g., color, texture, position), the following criteria were used to identify the specific geologic units:

- ***Recent Deposits***

Refuse/fill is comprised of man-made deposits. Refuse/fill consists of discarded man-made objects and plant/food materials. It is found at the ground surface or below clean fill, and above natural geologic strata or clean fill. Clean fill is found above natural geologic strata and above, within, or below refuse/fill. It is composed primarily of varied amounts of silt, clay, sand, gravel, boulders, and cobbles.

Peat is composed of fibrous plant material or meadow mat. It is located below refuse/fill, and above or interbedded with other Recent Deposits.

Recent silt and clay is light gray to black in color, with a textural predominance of silt and clay. It is located above glacial deposits and below refuse/fill.

Recent sand is light gray to black in color with a textural predominance of sand. It is found at the ground surface, or below refuse/fill, Recent silt and clay, peat and above the glacial deposits. Due to the absence of glacial deposits in some portions of the western area of Landfill Section 1/9, other methods, such as microfossil analysis, grain size distribution, and color, were necessary to identify the Recent sand in that area.

- ***Pleistocene Deposits***

Glaciolacustrine silt and clay is red brown in color, with a textural predominance of silt and clay. It is found below the Recent deposits or refuse/fill, and above, or interbedded with glacial till/diamict.

Glacial sand is red brown in color, with a textural predominance of sand. It is found below the Recent deposits and above, below, or within the glaciolacustrine silt and clay or glacial till/diamict.

Glacial till/diamict is red brown in color with a textural predominance of silt and clay, and a greater sand and gravel size fraction than glaciolacustrine silt and clay. Occasionally a textural predominance of gravel size fraction with a high sand, silt, and clay content is seen. The glacial

till/diamict is found below refuse/fill or Recent deposits, and/or above Cretaceous deposits, residual clay, or bedrock.

Columbia group sediments are yellow to orange brown sands and silts/clays found above the Cretaceous sediments and below the glacial deposits.

- ***Cretaceous Deposits***

The Cretaceous silt and clay is light gray to black and/or variegated red brown and gray in color, with a textural predominance of silt and clay. It is found below refuse/fill, Recent, or glacial deposits and above residual clay or bedrock. In the southern portion of Section 2/8, additional methods (discussed subsequently) are necessary to identify whether a sample is a Cretaceous silt and clay or a Recent silt and clay. In areas of the landfill site where it is predominantly red brown in color and occurs below glacial deposits, it is differentiated from glaciolacustrine silt and clay by its firm, stiff, shiny nature and/or red brown and light gray mottled character.

Cretaceous sand is white to dark gray in color, with a textural predominance of sand. It occurs below Recent or glacial deposits and above residual clay or bedrock. Due to the absence of glacial deposits in the western portion of Section 1/9, other methods (discussed subsequently) were necessary to distinguish the Cretaceous sand from the Recent sand.

- ***Residual Clay***

Residual clay is red brown, light gray, yellow green, blue green, red purple, or blue gray in color with a textural predominance of silt and clay. It is found below the glacial deposits or Cretaceous deposits and above bedrock. It is differentiated from Cretaceous silt and clay by its often waxy lustre, or color association with the underlying bedrock.

- ***Bedrock***

Weathered bedrock is consolidated rock that is freshly to severely weathered and demonstrates

RQDs[1] from 50 to 70 percent or lower. Bedrock is consolidated, competent rock that is usually freshly to moderately weathered and demonstrates RQDs from 50 to 70 percent or higher.

5.3.2.2 *Geophysical Analysis*

The plots of downhole geophysical log data obtained during this investigation are contained in Appendix F. The plots include interpreted stratigraphic analysis logs as well as sample descriptions, stratigraphic unit designations and contact intervals defined by lithostratigraphic analysis. The vertical scale is plotted as elevation rather than depth. Each log display in Appendix F is labeled with the multi-parameter of logging tool used, the geophysical parameter recorded, and the logging run number (if multiple runs with a particular tool were conducted in the borehole). Depth corrections were applied to the geophysical logs as indicated in each figure in order to correlate actual casing bottom elevations with associated log response.

The geophysical logs that displayed the most consistent response and offered the highest potential for stratigraphic correlation were selected for further analysis. These logs are displayed in Appendix G. The selected logs were smoothed with moving average filters and prepared with refined log sample descriptions. Logs acquired in boreholes that were sampled at 0.5 foot increments were not smoothed and were prepared with refined sample descriptions in their unprocessed form. In order to maximize the potential for stratigraphic correlation between boreholes, log scales of processed logs were adjusted to account for scalar differences between identical logs run in different boreholes. These differences relate to the use of several different logging tools, variations of borehole diameter, and changes in the salinity of borehole fluids. For reference purposes, a graphic portrayal of characteristic log response curves associated with the range of lithostratigraphic units identified at the project site is provided as a frontispiece in Appendices F and G.

In an effort to quantify the geophysical response of identified stratigraphic units, a statistical analysis of selected quantitative logs (i.e., NG, 16NR, EMIR) was performed following

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[1]Rock-Quality Designation (RQD) is a classification index that describes the physical characteristics of the rock material recovered in a core. RQD equals the cumulative length of naturally separated core pieces, 4 in. or more in length, expressed as a percentage of the total length of the core run.

completion of geophysical log processing and stratigraphic correlation. For each landfill section, thickness-weighted mean NG, 16NR, EMIR values were calculated over depth intervals within stratigraphic units displaying relatively consistent log response. Gradational changes within stratigraphic units, intervals of erratic log response, and adjacent bed effects near stratigraphic contacts were excluded from the analyses. Thickness-weighted mean log responses for stratigraphic units within each landfill section were calculated by dividing the sum of products of average log response throughout the unit, and the thickness of the elevation interval over which the average was calculated, by the total sum of interval thicknesses throughout the landfill section.

In general, the results of the geophysical testing show good agreement with the lithostratigraphic analyses, and strongly support the lithostratigraphic interpretation. The geophysical logs are useful for stratigraphic purposes in two ways. First, when viewed together for a given borehole, general geophysical responses are evident. These responses are caused by changes in geophysical signatures at similar locations corresponding with actual geological or stratigraphic unit boundaries and consistency within intervening intervals. In other words, even without detailed study of individual logs, geophysical responses that are related to geologic variations are evident.

Second, the logs are useful when studied individually. If one studies, for example, the natural gamma (NG) logs for all test sites, a general response for NG variations emerges. In utilizing geophysical information for stratigraphic subdivision at the site, both approaches were utilized. Conveying the geophysical results in view of the massive geophysical data base is difficult. The simplest way is to refer to selected examples. The geophysical logs in Appendix G were reviewed in order to identify profiles that represent as much of the full stratigraphy as possible across all landfill sections. This led to the selection of the following typical profiles:

Landfill Section	Appendix Page	Well Name
6/7	G4	IT157D
1/9	G21	IT004D
1/9	G22	IT005D
1/9	G36	IT507
2/8	G51	IT809
3/4	G52	IT405D

The reason for selection of multiple examples for Section 1/9 is to illustrate some of the stratigraphic variations identified in the Cretaceous sediments, the good correlation between geophysical log response and lithology, and the level of detail made possible by geophysical testing.

A general review of these typical profiles shows the overall visual patterns evident through side by side comparisons of the multiple log records for any given borehole. A definite geophysical response suggestive of the various stratigraphic units is evident. This is confirmed by examination of the lithologic logs also shown on these profiles.

The same profiles can be studied to identify general tendencies through examination of the vertical variations of individual log response curves. The natural gamma (NG), spontaneous potential (SP), single point resistance (SPR), and electromagnetic induction (EMI) logs are the most useful logs for determining geologic unit boundaries, with the NG and SPR being the most useful.

Natural gamma is very useful for stratigraphic subdivision. The characteristic response curve (frontispiece to Appendix G) shows an uppermost layer, usually on the order of 50 CPS. This layer generally corresponds with cased materials commonly including refuse/fill and/or the Recent materials. If clayey materials are included in the cased section, then the transition to the underlying non-cased material (usually glaciolacustrine silt-clay) tends to show a slight downward increase in NG levels.

The natural gamma logs for the uppermost refuse were examined to determine if vertical variations in refuse properties could be identified. Other than the fact that refuse NG values tend to be low, on the order of 50 CPS, no obvious signatures, especially any indicative of vertical variations within the refuse, were obvious. However, an inconsistent, subtle tendency of a slight downward decrease in NG values within the refuse is seen. The natural gamma properties of refuse/fill are not established in the literature, therefore, it is not possible to determine the significance of the NG responses recorded within the refuse at the Fresh Kills site.

Most NG profiles show a significant increase to a level of about 150 CPS below cased-hole sections. This corresponds to Recent and Pleistocene (glaciolacustrine) silt/clay. The downward increase of the NG response from the cased refuse/fill and Recent sediment to the uncased silt/clay allows for reliable identification of the glaciolacustrine unit without having to refer to the lithologic logs, in most cases.

Generally, the NG log does not distinguish the glaciolacustrine unit from glacial till. Although the CPS values in the till may be slightly lower than for the silt/clay, which can lend support to stratigraphic interpretation on a multiple log, side-by-side study of stratigraphy in a single borehole. In general, the presence of glacial till would not be readily distinguishable without first examining the lithologic log. In other words, differences in the NG logs for the till versus the glaciolacustrine unit are too subtle to be useful by themselves. Where the glacial till is underlain by Cretaceous silt/clay, the same responses are evident (i.e., no significant NG differences between the two fine grained units).

The NG log is very reliable at identifying sand or sand and gravel strata and in distinguishing between coarser and finer grained materials. The characteristic NG curve exhibits a decrease in CPS values in coarse grained units. The distinction between two similarly textured and contiguous time stratigraphic sand units (e.g., a Pleistocene sand overlying a Cretaceous sand) would not be possible in most cases. The NG log is capable of detecting the presence of relatively thin sand bodies within the finer grained materials. The NG log is capable of distinguishing layers as thin as one to two ft. It cannot be determined if the NG logs detected all the thin sand layers at the Fresh Kills site.

The spontaneous potential (SP), single point resistance (SPR), and electromagnetic induction (EMI) logs all relate to the ability of soils to transmit electrical currents, although each has different sensitivity ranges. The first two logs (SP and SPR) measure electrical resistance. The third log (EMI) measures the inverse property of conductance. As can be seen on the characteristic response curves (Appendix G frontispiece), all show an ability to distinguish between coarse and fine grained materials. However, unlike natural gamma, for which absolute values appear to be useful, the variations of electrical resistance or conductance are only useful in a relative sense. Furthermore, the electrical conductance is also dependent on the electrical properties of contained pore fluids. For example, the Cretaceous sand is generally less conductive (EMI) than silt/clay units, but as can be seen on IT007D, the reverse can occur; this is believed to be due to differences in the salinity of pore fluid in the sand.

To summarize, geophysical log analysis is very helpful both as an independent and as a supplemental screening device. NG and SPR logs provide the most consistent response to lithology. SPR is generally useful for thin strata. However, all profiles are useful from an overview visual interpretive perspective. It should be noted that geophysical testing is not a stand-alone analytical technique, and exhibits certain definite limitations. For example, geophysical log response is not necessarily uniform over the thickness of the unit being tested, even where the unit appears uniform from visual soil sample inspection. Also, some known zones of variations in soil texture show no apparent corresponding geophysical response. Despite such limitations and the need for concern in interpretation, the geophysical data provide a significant means of support for the stratigraphic analyses.

5.3.2.3 Microfossil Analysis

A total of 182 samples were selected for microfossil analysis following examination of archived soil samples and consultation with project oversight and field geologists. Test results of these analyses are contained in Appendix H. This appendix also contains the results of analyses performed on 50 samples obtained during drilling in previous site investigations. Twelve prepared and previously analyzed microfossil samples were submitted for independent review.

Samples were processed by standardized treatment schedules at a clean (uncontaminated) laboratory work station. The potential for contamination within the laboratory environment was routinely monitored by the sampling and analysis of ambient air and water. Laboratory glass and plastic tubes and beakers, as well as utensils, were washed before use. Sample processing involved the use of a centrifuge, hot plate, scale, stirrers, and centrifuge tube racks. In a typical analytical setup, an eight-place, 15 ml centrifuge was used, with samples prepared in multiples of four or eight.

In the laboratory, samples were cleaned to remove surface contamination, wall cake and handling contamination. The orientation of the samples was noted. The size of the sample to be processed was dependent on the apparent organic content, as determined from soil type, texture, grain size, color, and available sample. Generally, one to two grams of peat, two to five grams of organic silt and clay, and up to 50 grams of coarser sediment were required for pollen analysis. A sample was initially split in order to provide enough sample for concentrating the different types of microfossils, such as foraminifera and diatoms, and to retain a portion as a

reference sample. Visual inspection was used to choose the portion of the samples for analysis that contained the most apparent pollen.

Treatment schedules for pollen analysis included deflocculating the sample in a water softener with water, concentrating the sample in a tube by centrifugation, washing the sample to remove the water softener, and drying the concentrated sample. Organic-rich samples were treated with a weak potassium hydroxide solution to remove soluble organics, and then concentrated and washed. Mineral-rich samples were centrifuged, dried, and then treated with a heavy liquid flotation process using zinc chloride solution to separate pollen and spores from the sediment. The float containing the pollen and spores was decanted, diluted, concentrated in tubes, and washed with weak hydrochloric acid and water. It was then dried, suspended in mounting medium, and mixed thoroughly. The suspension was then used to prepare microscope slides for analysis, which were sealed and stored in slide boxes in a cool, dry area.

The slides were analyzed on a high-powered, binocular optical microscope. The count data were entered on an appropriate counting sheet. Generally, a significant number of pollen and spores were identified in order to provide a statistical basis for the determination of pollen assemblage zones. Identification of taxa, as well as index microfossils and zonal assemblages was performed with the use of illustrated descriptions in texts and journals, as well as reference collections. Stratigraphic zonations were based on pollen assemblages (assemblage zones) and individual species of known range. Standardized pollen zones from the literature were utilized for evaluating and age dating Cretaceous and Quaternary (Holocene and Pleistocene) biozones. The results of these analyses are incorporated in the geologic analyses.

The examination of samples for pollen and spores is the most useful method for determining the age of sediment in the Fresh Kills Landfill Site since most of the sediments are continental (terrestrial) in nature. Pollen and spores from different genus/species of plants are distinctive and by identifying the pollen/spore assemblages present in sediment samples, the palynologist is able to determine the type and relative abundance of specific plants that existed in a specific region. This is done by identifying the plant genus or genus/species, and number of pollen/spores of each genus/species that is present. The time period(s) that each genus/species existed has (have) been determined. If a specific plant genus/species existed during a relatively short period of time, its observance in the sediment can be used to date the sediment. In most cases, plants existed over several time periods. When pollen/spores from plants that existed during multiple time periods are observed, the age of the soil sample is determined by observing where the overlap of the various pollen/spores zonations occur.

The relative abundance of certain pollen/spores can be used to delineate more specific time periods. This is possible, because, while certain plants existed during long time periods, they may have been prolific for only a short period of time. Therefore, if an abundance of a pollen/spore is identified in a sample, it is indicative only of the period of time that the plant was prolific and not the entire time zone it existed.

Specific pollen zonations are available for the Quaternary period (Pleistocene and Holocene/Recent). In the late 1950's, E.S. Deevey published a paper that established the pollen zonation for the late Pleistocene and Holocene in northeastern North America (Deevey, 1958). These pollen zonations have provided a means of identifying and dating late glacial and post-glacial sediments, and reconstructing vegetation and climate, throughout the northeastern United States. Significant additions to this zonation have been made for Long Island, Staten Island, and the New Jersey area. Detailed pollen assemblage data pertaining to this area has been incorporated particularly for the late glacial, the interglacial and interstadial intervals, and for the pre-Wisconsin (Sirkin, 1977). The basic zonation for the interval following the recession of the late Wisconsin glacier includes the late-glacial Herb (W, T, or H) and Spruce (A-1 through A-4) zones, and the post-glacial Pine (B1, B2) and Oak (C1 through C3) zones. Similar intervals, particularly oak and spruce zones, have been interpreted for earlier interstadial and interglacial pollen sequences.

Cretaceous deposits in the mid-Atlantic coastal plain have been studied by palynologists for several decades. Biostratigraphic zonation utilizing assemblages of spores and pollen first appeared in the literature in the 1960's. Brenner (1963) first noted a distinct difference in pollen and spore assemblages between the Lower Cretaceous Potomac Group in Delaware and the lower part of the Upper Cretaceous Raritan Formation in Maryland. Brenner development his biostratigraphic zonation based on the observation of evolutionary changes, mainly in the increased complexity of angiosperm pollen. Brenner (1963) used Roman numerals to designate specific pollen zones, with Zone I representing the early Potomac Group beds, and Zone II the late Potomac or Patapsco Formation. Doyle (1969) and Doyle and Robbins (1977) documented the angiosperms representative of Zones I, II-A, B, and C, and the previously informal "transition zone", Zone III. Zonation was extended into the Late Cretaceous by Doyle (1969), Wolfe and Pakiser (1971), Sirkin (1974), and Wolfe (1976) who provided the palynological data for subdividing the Raritan and Magothy formations, and the overlying units of the Campanian and Maestrichtian stages. Sirkin (1974) and Doyle and Robbins (1977) used the designation Zone IV for the Lower Raritan, Woodbridge Clay equivalents, Zone V for the Upper Raritan, and Zone VII for the Magothy.

Wolfe (1976) developed the CA-1 through CA-6, and MA-1 zonation for the Matawan and Monmouth groups, with Zone CA 1 succeeding Zone VII. Working with more polleniferous and lignitic surface deposits in Maryland, Christopher (1977, 1979) was able to recognize assemblage zones that provided details for refining the numerical zonation. The assemblage zones were valuable where significant microfloras, and particularly the nominative genera were present. In the less fossiliferous marine units, the numerical zones may be more appropriate and are based on the first appearance of significant taxa, as in the work of Wolfe and Pakiser (1971), and Sirkin (1974).

A list of the specific pollen types that are diagnostic of the zonations discussed above was not made for this investigation. The references given above provide a detailed description of the pollen/spores that define the various biostratigraphic zones.

5.3.2.4 Piezo-Electric Cone Penetration Test Analysis

The interpretation of 191 piezo-electric cone penetration tests (P-ECPTs) was completed utilizing corrected and scaled profiles generated at the office of Applied Research Associates, Inc. (ARA) in Royalton, Vermont. The Final P-ECPT profiles include sleeve friction, tip stress, friction ratio, pore pressure, and soil classification. The combined evaluation of these five profiles allows for the determination of soil type and therefore, stratigraphic contacts. The principle objective of the P-ECPT program was to identify the uppermost confining layer with respect to containment wall design.

The cone penetration profiles were divided as follows to provide a general guide for analysis of the data:

Sleeve Friction (PSI)	**Tip Stress (PSI)**	**Ratio (%)**	**Pore Pressure (PSI)**
Low = <10	Low = <750	Low = <1	Low = <20
Medium = 10 -20	Medium = 750 -1500	Medium = 1 -5	Medium = 20 -30
High = 20+	High = >1500	High = 5+	High = 30+

The general P-ECPT responses for the specific stratigraphic units follow:

- Recent silt and clay (Qrc); low sleeve friction, low tip stress, low to high friction ratio, medium to high pore pressure.

- Recent peat (Qp); low sleeve friction (slightly higher than Qrc), low tip stress (slightly higher than Qrc), high friction ratio, high pore pressure.

- Recent sand (Qrs); low to medium sleeve friction depending on silt and clay content, medium to high tip stress, low friction ratio, low pore pressure.

- Glaciolacustrine silt and clay (Qgl); low to medium sleeve friction, low to medium tip stress depending on course fraction present, medium friction ratio, low to high pore pressure depending on silt content (silt tends to dilate, resulting in an apparent decrease in pore pressure).

- Glacial Till/Diamict (Qgt); medium to high sleeve friction, medium to high tip stress due to coarse fraction, low to medium friction ratio depending on amount of coarse fraction, low pore pressure.

- Glacial Sand (Qgs); low to medium sleeve friction depending on silt and clay content, high tip stress, low friction ratio, low pore pressure.

- Cretaceous silt and clay (Kc); medium to high sleeve friction, low to high tip stress due to density, medium to high friction ratio, low to high pore pressure depending on silt content (dilation as explained previously).

- Cretaceous sand (Ks); medium to high sleeve friction depending on silt and clay content, high tip stress, low to medium friction ratio, low pore pressure.

- Residual clay (Shc, Tsc, Tlc, Osc); medium to high sleeve friction, medium to high tip stress, low to medium friction ratio, low to high pore pressure (dilation as explained previously).

A classification that presented difficulty at times was the differentiation of glaciolacustrine silt and clay and glacial till/diamict due to the varying amounts of coarse fractions that may occur in either type of deposit. During visual examination of soil samples, it was sometimes difficult to determine if the soil was glaciolacustrine silt and clay or glacial till/diamict due to the gradational textural changes which sometimes occur due to the processes of deposition of the two units. Difficulty also occurred in distinguishing between clean fill and glacial till, seen mainly on the southeastern side of Section 1/9, because clean fill often consists of glacial material.

5.3.2.5 Geostatistical Analysis

Geostatistics is a term that is applied to a special branch of statistics that was developed originally to address problems in application of conventional statistical theory to spatial changes in the grade of ore in a mine. However, because geostatistics is an abstract theory of statistical behavior, it is applicable to many circumstances in different areas of geology and other natural sciences (Davis, 1986). A key concept of geostatistics is that of the regionalized variable, which has properties intermediate between a truly random and a completely deterministic variable. Unlike random variables, regionalized variables have continuity from point to point, but the changes in the variable are too complex to be described by any specific deterministic variable. The procedure through which the regionalized variable and its characteristics (e.g. spatial uncertainty) are defined is termed kriging.

Within the context of this report, application of geostatistical analysis (point kriging) has been limited to an independent estimation of the glaciolacustrine silt and clay unit thickness distribution at Landfill Section 6/7. Additional discussion relative to this specific investigation is contained within report Section 5.4.1.5.

5.3.3 Stratigraphic Correlation

Classic "layer cake" geology is useful for a basic stratigraphic analysis where: (1) a stratigraphic column is established, (2) individual stratigraphic units are correlated across an area of interest, and (3) results are presented on geologic maps and profiles. Analysis of time-transgressive, laterally variable and shifting depositional environments requires a more sophisticated three-dimensional analysis, but utilizes many of the same basic principles of "layer cake" geological interpretation.

The principles of stratigraphy present the basic methods for correlating lithologic units. A stratigraphic unit may contain certain distinctive characteristics that allow for extrapolation and interpolation, and thereby the definition of a specific layer. In addition, an iterative, trial and error process helps identify other specific lithologic characteristics of specific units; for example, a distinctive color of a certain sand unit. Color is often an extremely useful lithologic

characteristic. Other stratigraphic principles that have been applied in the stratigraphic analysis at Fresh Kills are:

- Stratigraphic sequence or order of units
- Thicknesses of units
- Reference to expected environments of deposition
- Microfossils

Stratigraphic analysis has resulted in an understanding of the characteristics, occurrence and correlatability of individual lithologic units. The following is a summary of the correlatability of the lithostratigraphic units, presented as a general overview and to assist with the understanding of the detailed stratigraphic analysis provided in subsequent sections.

Peat does not occur as an easily correlatable unit. It is found above, within, and below the other Recent units. This is indicative of the depositional complexity of the Recent marine transgression. Pinch-outs are frequent, and lateral correlation as a continuous stratum is difficult to establish, even with the amount of data available.

Recent sand is potentially significant as a transmissive pathway for contaminant transport. Recent sand often occurs in plan and profile view as apparent isolated lenses, but occasionally occurs as a laterally continuous layer. Recent sand bodies that occur as apparent lenses are found within finer-grained materials, specifically Recent silt and clay. The examination of multiple cross-sections indicates that the sand bodies within the silt and clay tend to be localized, discontinuous lenses. Based on the depositional model for the Recent deposits, the sands are probably fluvial deposits deposited within channels in tidal marshes, similar to the channels in the present day tidal marshes in the area. In a transgressive depositional system, channels migrate laterally over time. Aggradation results in an upward accumulation of sediment, mostly tidal marsh silt/clay and peat, and occasionally sand.

The symmetry of channel deposit sands is likely to be sinuous in plan view, and laterally variable in profile. Due to the sinuous pattern of deposition of channel sands, it is likely that plan view maps or profiles would give the appearance that the sand occurs as isolated lenses, when in fact they may occur as interconnected channel deposits that may be laterally continuous along the axis of the channels. One approach in attempting to evaluate the potential significance of interconnected Recent sands in terms of groundwater flow and contaminant transport is to assume the sands are interconnected and to characterize the size, frequency, and volume of the sand.

The Recent silt/clay and glaciolacustrine silt/clay units are as equally significant relative to hydrogeology as the Recent sand. The top and bottom surfaces or stratigraphic boundaries of the Recent silt/clay and glaciolacustrine units can be readily identified and correlated because these units are usually laterally extensive. This leads to the concept, which is common in stratigraphy, of undifferentiated complexes and/or formations. A formation is most simply defined as a mappable or a correlatable unit. In cases where lithologic variability is significant, discrete lithologic materials may be defined as complexes or groups, not formations. For example, the Recent and Pleistocene silt and clay units are mappable, but not as a single, uniform lithologic unit. Both units contain other strata (e.g., sand lenses) of limited areal extent that make accurate depiction of the thickness of the silt and clay difficult. Nevertheless, the overall tendency or character of the unit is defined by the aggregate character of the whole. In this context, the Recent and Pleistocene sequences should generally be regarded as complexes dominated by fine-grained materials. This concept is also important from a hydrogeologic perspective. It establishes that the geologic units directly below the landfill are not comprised entirely of vertically and laterally extensive transmissive (sand) units, but are instead comprised of a predominately fine grained matrix within which occur generally discrete, and volumetricly smaller, transmissive units. This concept affects subsequent interpretations regarding the potential movement of contamination through these units, as well as the planning for potential remedial strategies.

Glacial till/diamict has a distinctive lithologic character. Most of the glacial till unit was deposited as a continuous lodgement till at the base of the glacial sequence. Glacial diamict/non-lodgement till was deposited as turbidities, ice rafted debris, and other subglacial, englacial, or supraglacial till "types", such as flow till and melt out till. The other glacial diamict deposits texturally resemble lodgement till, but are much more limited in lateral extent. Glacial sand bodies are also found within the glacial till. The glacial lodgement till is regarded as a mappable unit containing localized bodies of sandy material.

Due to textural and other similarities, the lodgement till could be combined with the overlying glaciolacustrine unit, and in turn with the Recent silt/clay. This composite unit would be an appropriate generalized representation of the overall character of the post-Cretaceous section, even though these individual units can be identified and correlated individually.

Glacial sand occurs in areas primarily associated with kame features identified at the site. Thick sand units occur within the kames. Glacial sand units that extend away from or are not

associated with the kame features are usually thinner and are less likely to be correlatable for any significant distance.

Correlation of glacial deposits was based on the depositional model developed for the Pleistocene sequence as well as the glacial depositional history of the region. As described previously, the glaciolacustrine silt and clay and glacial lodgement till occur as regionally or subregionally extensive units. At its maximum extent, glacial Lake Bayonne extended in a north/south direction from the terminal moraine at Perth Amboy to Newark Bay and in an east/west direction from eastern New Jersey to Long Island sound, which would allow for the regionally extensive deposition of the glaciolacustrine silt and clay. The gradual, versus sudden lowering of the glacial lake level, as described in Section 5.2.5.4, would have promoted the large scale correlative nature of the glaciolacustrine silt and clay.

Ice contact glacial sands and non-lodgement type tills tend to be more localized deposits due to the depositional processes that produce these units. Based on the depositional model and processes, the occurrence of ice contact glacial sand and/or non-lodgement glacial till as isolated bodies in the glaciolacustrine silt and clay is more likely than glaciolacustrine silt and clay occurring as an isolated unit within non-lodgement glacial till or glacial sand. It is also quite common for glacial sand to occur as isolated lenses in glacial lodgement till , but extremely uncommon for lodgement till to occur as an isolated feature within glacial sand. These concepts are based on sound, well established "rules" regarding the correlation of glacial sediments.

Therefore, during the correlation process, the glaciolacustrine silt and clay unit and glacial lodgement till unit were correlated as being continuous and laterally extensive, with the other glacial units as pinching out, unless other information was available to suggest an alternate interpretation. It should be noted, that this method of correlation was used only if no other information (i.e., nearby features and/or environment of deposition) was available to guide the correlation. An example of an exception to the above rule, based on the probable environment of deposition, is the classification of glacial till/diamict in this report that was not the basal glacial unit. As a general rule, all glacial till/diamict strata not located at the base of the glacial sequence was classified as a non-lodgement till. Therefore, a glacial till/diamict, glacial sand, glacial till/diamict, residual clay sequence would be interpreted as non-lodgement till, glacial sand, lodgement till, residual clay. However, an alternate interpretation would be to define all the glacial till as lodgement till and the glacial sand as an isolated lense within the till.

Determining correlatability of individual units in the Cretaceous is difficult. This is principally due to the complexity of a deltaic sedimentary environment. In general, the upper portion of the Cretaceous sequence tends to contain more fine-grained sediment (silt and clay), and the lower portion of the sequence tends to contain more coarse-grained sediment (sand). This correlation suggests a simple, site-wide, two-layer model. However, multiple interlayered units of silt/clay and sand occur throughout the Cretaceous sequence across the Landfill site. The interconnection of laterally and vertically variable sand layers is difficult to determine. Correlatable sand units do occur within the Cretaceous sequence.

Surface contour and isopach (thickness) maps were constructed for every major geologic unit present at the site. These units are:

- Refuse/Fill
- Peat
- Recent sand
- Recent silt and clay
- Glaciolacustrine silt and clay
- Glacial sand
- Glacial till (lodgement)
- Cretaceous clay and silt
- Cretaceous sand
- Residual clay
- Weathered Bedrock
- Bedrock (surface contour only)

Surface contour and thickness maps were constructed for Recent sand to evaluate areas where correlative deposits may exist, though the Recent depositional model predicts most of the sand occurs as channel deposits. All the sands present at the site (Recent, glacial, Cretaceous) were delineated as units (Sheets 5.36, 5.37, 5.49, 5.50, 5.63, 5.64). A unit is defined as a correlative sand body. Structural contour maps showing major stratigraphic contacts, including pre-Holocene (Recent), pre-Pleistocene, and pre-Cretaceous surfaces, are presented on Sheets 5.28 through 5.77. Horizontal depth slices, constructed to show stratigraphic unit distribution at specific elevations, are contained on Sheets 5.85 through 5.92. The locations of geologic cross-sections and perimeter cross-sections are indicated on Sheets 5.3 through 5.5. Geologic cross-sections GA through GR are contained on Sheets 5.6 through 5.23. Perimeter cross-sections are contained on

Sheets 5.24 through 5.27. Other sheets that are included in this report are: Top of Time Stratigraphic Units Geology (Sheets 5.78 through 5.81), Geologic Map of Consolidated Bedrock (Sheet 5.82), Historic Topographic Map (Sheet 5.83) and the Test Borings in the Area of the Bulls Head Well Field (Sheet 5.84).

5.4 Geology of the Individual Landfill Sections

This section presents a detailed discussion of the geology of each landfill section. A general review of the data obtained from the lithostratigraphic, geophysical, microfossil, and piezo-electric cone penetration tests analyses is presented first. A detailed description of the structure, thickness, and/or occurrence of each geologic unit follows. These discussions are based primarily on maps, figures, and cross-sections produced for this report. A summary of the most important geologic findings is given for the individual sections.

5.4.1 Landfill Section 6/7

5.4.1.1 Lithostratigraphic Data Base

A total of 120 conventional test borings were used for the lithostratigraphic analysis of Landfill Section 6/7 (Sheet 5.1). These included 21 deep perimeter well borings completed to bedrock, 13 deep center test borings completed to bedrock, 21 shallow perimeter well borings, and 10 shallow perimeter test borings drilled as part of this investigation (Table 5.3) and 56 borings completed as part of earlier investigations. Copies of the field test boring and well boring logs are contained in Attachments 1 and 3, respectively. Final test boring and well boring logs are contained in Appendices B and E, respectively. Test boring logs from previous investigations are contained in the Hydrogeological Literature Review (IT Corporation and Wehran EnviroTech, 1991a). Appendix I contains the logs of regional borings obtained subsequent to submittal of the Literature Review Report. Photographs of recovered bedrock core are contained in Attachment 2. Tables 5.8 and 5.15 summarize the stratigraphic unit top and bottom elevations and unit thicknesses for all borings utilized in the analysis of Landfill Section 6/7.

The geologic units identified by lithostratigraphic analysis in Landfill Section 6/7 are as follows:

- Recent Deposits
  - Refuse/Fill
  - Peat
  - Silt and Clay
  - Sand
- Pleistocene Deposits
  - Glaciolacustrine Silt and Clay
  - Glacial Sand
  - Glacial Till/diamict
- Cretaceous Deposits
  - Silt and Clay
  - Sand
- Residual Clay
- Bedrock
  - Weathered Bedrock
  - Competent Bedrock

5.4.1.2 Geophysical Data Base

The data base for geophysical testing at Section 6/7 is summarized as follows:

- 18 boreholes tested
- Table 5.3: overview tabulation identifying borings in which geophysical data was obtained (locations indicated on Sheet 5.1)
- Table 4.9: Summary table of geophysical logs obtained in each borehole
- Appendices F and G: Unprocessed and processed geophysical logs, respectively, including geologic soil/rock sample descriptions for comparison
- Table G.1, Appendix G: Tabulation of elevations of stratigraphic unit boundaries determined by analysis of geophysical logs
- Table G.2, Appendix G: Comparison of soil/rock sample descriptions versus geophysical log interpretations

- Tables G.3 and G.4, Appendix G: Statistical analyses of geophysical log data by boring, and as collective thickness weighted mean response by stratigraphic unit, respectively

As noted in the discussion in Section 5.3.2.2, the results of geophysical analysis generally provide strong support for the lithostratigraphic interpretations. One of the most notable results of geophysical analysis suggests that the glaciolacustrine silt/clay unit becomes siltier (more resistive) with depth.

5.4.1.3 Microfossil Data Base and Results

Soil samples from 10 borings were selected for microfossil analysis in Section 6/7 (Table 5.3). The results from the analyses are contained in Appendix H. A final written report on the microfossil analyses prepared by Dr. Les Sirkin is also included in Appendix H. Samples from test borings performed in previous investigations (6P81:C24D, C25D) were also analyzed for microfossils, with the results provided in Appendix H.

The only Cretaceous sample submitted from Landfill Section 6/7 (6W91:IT157) yielded a Zone IIB age. A possible B zonation was obtained from a sample of glaciolacustrine silt and clay from deep center boring 6B91:IT657. Recent sediment samples submitted from Landfill Section 6/7 yielded pollen of the Recent C3 pollen zone (i.e., 6W91:IT160, 161; 6B91:IT657, 666; 6P81:C24D).

5.4.1.4 Piezo-Electric Cone Penetration Test/Perimeter Boring Database

The database for the piezo-electric cone penetration test (P-ECPT)/perimeter boring program is summarized below:

- 101 P-ECPT borings were performed as part of this investigation and six as part of a previous investigation (loctions indicated on Figure 4.12 and Sheet 5.2).
- 11 conventional soil borings were performed to verify P-ECPT data, replace P-ECPT borings that did not meet Consent Order requirements, or as additional correlation borings (locations indicated on Sheet 5.1).

- Table 4.2: Summary of P-ECPT/perimeter boring data, including completion date, survey control, depth of penetration, dissipation tests depths and time intervals, and correlation well borings.

- Table 5.16: Tabulation of elevations of stratigraphic unit boundaries determined by interpretation of P-ECPT borings, including P-ECPT borings from a previous investigation, and conventation soil borings.

- Appendix C: Correlation Report - Piezo-Electric Cone Penetration Tests in Support of Geotechnical Investigation at Sections 6/7 and 1/9 of Fresh Kills Landfill; comparing P-ECPT results with correlation conventation soil borings.

- Appendix D: Final Report - PEizo-Electric Cone Penetration Tests - Sections 6/7 and 1/9 of Fresh Kills Landfill; includes the P-ECPT profiles and discussions on methodology and results.

5.4.1.5 Geologic Units – Extent and Structure

- ***Recent Deposits***

Refuse/fill covers almost the entire extent of Landfill Section 6/7. The top of the unit is the present ground surface within the landfill section, and is shown on Sheet 5.28. The highest ground surface elevations are in the northeast portion of the landfill. The bottom elevation of the refuse/fill (Sheet 5.29) ranges from above sea level in the east to approximately -15 ft in the north and center of the section. Thickness ranges from 70 to 80 ft in the center of the section, to as little as 3 ft near the edge.

Peat was encountered in 32 conventional test borings and 63 piezo-electric cone penetration test (P-ECPT) borings in Landfill Section 6/7 (Sheet 5.31). There appears to be no specific pattern to its occurrence, beyond its occurrence in former tidal marsh areas. The majority of the P-ECPT borings in the former tidal marsh areas encountered peat. The examination of Perimeter Cross-Section GP 6/7 (Sheet 5.27) indicates that correlative areas occur in the northern and southwestern portions of the section even though peat was not encountered in every boring. The high frequency of occurrence of peat in the P-ECPT borings suggests that it may also occur with similar frequency in the internal portions of the landfill that were formerly tidal marsh. The low frequency of occurrence in conventional test borings may be attributed to sample recovery (i.e., overdrilling, soft sediment recovery problems).

Recent silt and clay is found throughout Landfill Section 6/7 with the exception of areas in the eastern portion of the site. The top of the unit is fairly flat, with a slight slope to the west/northwest (Sheet 5.33). The bottom of the unit slopes to the west. The thickness of the unit is variable, though it appears to thicken to the west. Conventional test borings show it to be a mostly homogeneous and correlative unit; whereas, P-ECPT borings show it to be more complexly interbedded with other Recent units (peat and sand). Microfossil analysis of Recent silt and clay samples from borings 6W91:IT160, 161, and 6B91:IT666 yielded an age of C3b, which is classified as Holocene (Post Glacial – Colonial).

Recent sand occurs predominantly in the western portion of the section (Sheet 5.34). It generally occurs at the base of the Recent sequence, though P-ECPT borings show it to be interbedded with other Recent sediments at some locations. The Recent sand in the northern portion of Landfill Section 6/7 is part of Recent sand Unit 1, which is correlated over much of the site (Sheet 5.36). The top surface is of moderate relief, ranging between -8 ft and -23 ft in elevation. The top surface elevation of units 6 and 7 in the southern portion of Landfill Section 6/7 range from -6 ft to -17 ft. The unit generally slopes from east to west. Thickness is usually a few feet, however, in certain areas in the northwest portion of the site thickness approaches 10 ft (6Z91:IT707S, 6P81:C39D).

Correlation of the Recent sand between Landfill Sections 6/7 and 3/4 is likely, but may not occur across the entire length of Main Creek. Geologic Cross-Section GO shows the sands being interconnected between the landfill sections. Other cross-sections across Main Creek (Cross-Sections MC, GN, GP) suggests that if an interconnection exists, it is partial. If the sands are interconnected, the slope of the unit across Main Creek would be from east to west. The Recent sand may also exhibit some interconnection with the glacial sand in the northeastern corner of the section.

- ***Pleistocene Deposits***

Glaciolacustrine silt and clay extends beneath almost the entire extent of Landfill Section 6/7. The only area where it does not occur is in the upland portion along the northeast boundary of the Section (Sheet 5.41). The top surface generally occurs at an elevation between 10 and -20 ft, although at several areas the top is found at elevations below -20 ft. In the east, the top surface of the unit dips in a direction similar to the present day ground surface. The glaciolacustrine silt and clay pinches out against the uplands in the eastern portion of the section. The bottom surface

shows more relief, sloping to the west from an elevation of about -5 ft to greater than -60 ft near Richmond and Main Creeks (Sheet 5.43). In general, the unit thickens from east to west from a few feet to in excess of 30 ft. Interbeds of glacial till and/or glacial sand are present (6W91:IT156, 157, 160, 162, 163, 6P91:654).

Pollen analysis indicates Pleistocene (undifferentiated) zonations from center borings 6B91:IT660 and 656, a possible zone B from center boring 6B91:IT657, and C3 Recent (post-glacial) zonations from 6W91:IT160. In the geophysical EML, 16NR, and 16 NC logs, the glaciolacustrine silt and clay was observed to grade from a conductive, possibly clavier material to a more resistive, possibly siltier material with increasing depth. The test borings where it grades to more resistive glacial till are 6W91:IT151D, 157D, 158D, 160D, 161D, 6B91:IT651, 655, 657, 666; and 6P91:IT664.

As presented in the Phase I Milestone Report for the Landfill Section 6/7 Center Boring Program (IT Corporation, Wehran Envirotech, IDT, Inc., 1991), and included in this report as Appendix K, geostatistical analysis was applied to provide confidence estimates for the thickness and continuity of the primary confining unit stratum (glaciolacustrine silt and clay) within this landfill section. Point kriging of the silt and clay unit thickness was performed in order to develop an independent estimate of the continuity and variability in the thickness of the confining unit. These analyses allow for the spatial interpolation of the thickness data, and provide an estimate of the variability (standard deviation of the estimate) at a series of grid nodes established across the entire Section 6/7 land area. The thickness and variability estimates are developed by fitting a curve through a series of data points that define the relationship between distance and variance (semi variogram) for every possible combination of data points within the defined area. These analyses resulted in the development of a kriged (interpolated) contour map of glaciolacustrine silt and clay unit thickness across Section 6/7, a contour map of the standard deviation of the kriged thickness estimates, and several "confidence" interval maps of the thickness estimates. The confidence interval maps, derived by mathematically combining the estimated thickness and standard deviation map data, indicate the probability that the confining unit thickness is greater than some threshold.

For this investigation, thresholds of 0 and 5 ft were utilized; 5 ft was selected as a minimum reasonable estimate to define a competent confining unit. The results of the confidence interval mapping analysis (Figure 5.23) indicate a 90 percent or greater probability of confining unit thickness in excess of 5 ft across the entire area of Section 6/7, with the exception of the eastern section margin. These results provide quantitative and rigorous statistical support for the

lithologic interpretations and relationships derived through the conventional stratigraphic analyses described previously. Following completion of the Phase II Drilling Program, a larger data set was available for the analysis of stratigraphy at Landfill Section 6/7. In order to evaluate the efficacy of the initial geostatistical investigation, supplemental analysis was performed with the additional data (Appendix K), with results presented on Figure 5.23A. As indicated, the distribution of the confidence estimate is very similar to the result of the earlier analysis, highlighting the value of this investigation technique. Namely, even with the limited database available during the initial phases of this project, geostatistical analysis provided valuable insight into those areas where supplemental field investigation should be prioritized relative to evaluation of the continuity of the Qgl confining unit. The supplemental analysis improves on the accuracy of the estimate, but does not substantively alter the initial findings.

Glacial sand occurs scattered throughout Section 6/7 (Sheets 5.49 and 5.50). Since it occurs as individual units and as interbeds in the other glacial deposits, it is difficult to demonstrate its extent in plan view. The glacial sand deposits of the kame feature (Sheet 5.49, Unit 1; Figure 5.13, "B") in Landfill Section 3/4 and the glacial sand in Landfill Section 6/7 along Main Creek appear to be interconnected (Sheet 5.49). The surface of the Unit 1 sands generally slopes to the east from about -20 ft to about -70 ft in Landfill Section 6/7. The top surface elevations of the glacial sand units in the northeastern portion of the Landfill Section (Sheets 5.49 and 5.50; Units 2, 3, 4, and 19) generally occur from 5 ft to -20 ft, except for Unit 19, which occur from approximately -30 ft to -50 ft. Unit 5 extends in a southeast to northwest direction beneath Main Creek and into Landfill Section 3/4. The top surface slopes from about -20 ft to about -60 ft at Main Creek (Sheet 5.49). Six smaller glacial sand units (Units 21 and 22) occur in the western and southern portions of Landfill Section 6/7 (Sheets 5.49 and 5.50). These units were generally limited in areal extent with top surface elevations ranging from 0 to -5 ft.

Thickness of the glacial sand units throughout the section ranges from 1 to 21 ft, though it usually does not exceed 10 ft. Based on the geophysical EMIR thickness-weighted mean-log response, the glacial sand found in Landfill Section 6/7 appears to be coarser grained or sandier than the glacial sand found in the other landfill sections.

It is believed that the glacial sand in the northwestern portion of the landfill section and the glacial sand in the northeastern portion of the landfill section are not interconnected, or that the interconnection is limited. The glacial sand in the southern portion of the landfill section may be interconnected with the glacial sand across Richmond Creek in Landfill Section 2/8 (Sheet 5.46).

Glacial till occurs as the basal glacial unit throughout Landfill Section 6/7 except for isolated locations in the north-central portion of the site; specifically, in the area of test borings 6W91:IT162D, and 6B91:IT652 and 655 (Sheet 5.56). The unit dips from east to west. The top surface elevations range from above 10 ft in the east to less than -60 ft in western portions of Landfill Section 6/7. The relief of the top surface is much greater in the eastern portion than the western portion of the site. The bottom surface also dips from east to west. It slopes from about 0 ft in the east to approximately -70 ft in the west. As with the top surface, most of the bottom surface relief is present in the eastern portion of the section. In the southernmost portion of the section, the unit dips to the southeast in conjunction with the bedrock surface. Very little relief is noted in a north-south direction in the unit. Thickness ranges from 2.5 to 50 ft, but on average is less than 20 ft. Interbeds of glacial sand appear to be most common in the southern portion of the site.

- ***Cretaceous Deposits***

Cretaceous sediments were encountered in only two borings in Landfill Section 6/7 (6W91:IT157, and 6W92:IT166) (Sheet 5.60). Borings 6W91:IT157 and 6W92:IT166 are in the southernmost portion of the site. They are located south of where the bedrock surface slopes steeply to the south. This demarcation is interpreted to represent the "Fall Line". Alternating layers of Cretaceous silt and clay and sand were encountered in both borings. The units are correlatable between the two borings. The units dip to the east and south.

- ***Residual Clay***

Residual clay is present in only certain areas under Landfill Section 6/7 (Sheet 5.68). Sheets 5.68 and 5.69 show that the unit, when present, slopes to the west, except in the vicinity of 6W91:IT157 where it dips sharply to the southeast. The bottom surface of the unit slopes in the same general direction as the top surface. Top elevations range from -1.0 ft in the northern portion to -122.7 ft in the southern portion of the Section. Bottom elevations range from -43.3 ft in the northern portion to -147.7 ft in the southern portion of the Section. The residual clay is usually less than 20 ft thick. In an area near the northeast corner of the section it is greater than 40 ft thick (Sheet 5.69). The residual clay in Section 6/7 is formed primarily from the in situ weathering of the Stockton formation, though in certain areas in the southern portion of the landfill section it is formed from serpentinite or a chlorite schist.

- ***Bedrock***

The surface of the bedrock beneath Landfill Section 6/7 trends from east to west with elevations ranging from approximately 0 ft in the east to greater than -90 ft in the west (Sheet 5.74). In the area of borings 6W91:IT155, 159 and 6P91:IT663, 664 a bedrock saddle occurs. The bedrock south of the saddle trends sharply to the southeast from an elevation of approximately -50 ft down to -140 ft.

The top of the weathered bedrock slopes from less than 0 ft in the east to over -100 ft in the west (Sheet 5.71). In the northern portion of the site, the relief is almost 90 ft. The bottom of the unit shows the same trend, with elevations approximately 10 to 30 ft lower than the top of the unit (Sheet 5.72).

Three types of bedrock were encountered below Landfill Section 6/7; the Stockton Formation, serpentinite, and chlorite schist (Sheet 5.82). The Stockton Formation is found below the northwestern half of the site. The Stockton is (with the exception of 6W91:IT163, 164 and 165) described as, arkosic with interbedded red brown shale and siltstone. A multi-colored sand described above the residual clay in 6W91:IT652 has been classified as a highly weathered arkosic Stockton strata. Grain size is variable, ranging from coarse to fine. Sheet 5.82 shows the distribution of the sandy portion of the Stockton. The bedrock cores from borings 6W91:IT163, 164 and 165 consist of siltstone and shale.

Several of the borings that encountered the Stockton Formation adjacent to the serpentinite (6P91:IT654, 6B91:IT656, 657) found the Stockton to have been altered to some extent. These rocks contain numerous vugs, many being filled with quartz crystals (Sheet 5.82). Quartz veins are also common. Slickensides were also found along many fractures. In these altered rocks, the Stockton, in addition to its predominantly red brown color, includes dusky blue green, dusky yellow green, and grayish olive green coloring.

The serpentinite occupies nearly the entire southeastern portion of Landfill Section 6/7. Samples examined range from fine grained dark green serpentinite, to the classic "snake skin" serpentinite with a porphoryritic texture (6W91:IT156), to the serpentinite group mineral lizardite in boring 6B91:IT660. Most samples were usually porphyritic to mostly porphyritic. The bedrock samples that consisted of mostly fine grained, usually dark green serpentinite were 6B91:IT663, 665, 666 and 6W92:IT167, 168. Lizardite was present along with talc in many borings (6B91:IT154, 159 and 6B91:IT663). Several borings (6W91:IT154, 159; 6B91:IT659, 664, 665

and 666) contained calcite or quartz veins that cut through the rock. Magnetite was occasionally encountered in core sample (6W91:IT158 and 6B91:IT665). Vugs were sometimes encountered in the serpentinite cores near the Stockton Formation/serpentinite contact (Sheet 5.82). The serpentinite often has a weathered surface, and if highly weathered, may exhibit a sandy texture.

In the southeastern corner of Landfill Section 6/7, a chlorite schist was encountered. It is green to yellowish green to green gray in color. The schist is fairly well fractured in the upper portion of the unit, as observed in core sample. The schist has a high talc content. It is either a product of metamorphism of the serpentinite body, as described by Okulewicz (1990) or possibly altered Manhattan schist delineated by Soren (1988). Its composition and location strongly suggest that it is associated with, and is a product of metamorphism of the serpentinite body.

5.4.1.6 Bulls Head Well Field Investigation

The Bulls Head Well Field is an abandoned well field situated to the northeast of Landfill Section 6/7 (Sheet 5.84). Borehole data acquired for the Hydrogeological Literature Review Report (IT Corporation and Wehran Envirotech, 1991c) was examined to evaluate the stratigraphy between the landfill and the well field. One hundred forty six test borings from this area were interpreted and are contained in Appendix I. Table 5.7 summarizes the stratigraphic unit top and bottom elevations and unit thicknesses for the 146 borings. Unfortunately, the majority of the borings were too shallow to determine an accurate or complete stratigraphic column between the landfill and the well field.

The majority of the test borings between the landfill and well field were shallow penetrations (less than 30 feet), usually drilled for construction purposes. They encountered a combination of glacial sand, glacial till, and sandy glacial till. No borings directly between the well field and landfill penetrated deep enough to encounter stratigraphic units below the glacial sequence, including bedrock. A few borings located to the east of the well field and/or Section 6/7 did encounter bedrock, but due to their location, did not provide information useful for determining the complete stratigraphic section in the area between the landfill and the well field. Test borings performed near Richmond Avenue encountered glaciolacustrine silt and clay and Recent silt and clay in the lower elevation areas between the landfill and well field.

5.4.1.7 Summary

Refuse/fill covers almost the entire section. Most commonly, the refuse/fill is underlain by Recent deposits consisting of silt, clay, peat, and sand. Refuse/fill overlies glacial till or glaciolacustrine deposits in the former upland area in the eastern portion of Landfill Section 6/7. The Recent silt and clay, and peat occur individually or interbedded. The sands tend to occur at the base of the Recent sequence and may be correlative over some portions of the site. Some of the Recent sand is deposited as channel sand and is interpreted to be interbedded with the silt and clay, or peat. The correlation of channel sands between borings is difficult to establish, since they probably occur as time-transgressive deposits with lateral and vertical variability. The Recent silt and clay appears to thin and pinch out as the uplands are encountered to the east.

Below the Recent deposits is a unit of glaciolacustrine silt and clay. The glaciolacustrine deposits are continuous across the section, except for a small area in the northeast portion of the section where the higher elevation uplands occur within the eastern portion of the landfill site. A deposit of glacial till is present below the glaciolacustrine silt and clay. The glacial till is variable in composition, but is mainly composed of a fine-grained matrix. Sandy to gravelly units or sand interbeds are encountered in the glacial till.

Glacial sands are found throughout the glacial sequence. The sands occur above or within the glaciolacustrine silt and clay, and above, within, and below the glacial till. The glacial sand encountered in the northwestern portion of the site is probably associated with ice marginal deposition related to the deposition of Kame shown in Figure 5.13. This sand has been correlated westward beneath the Main Creek to glacial sand in Landfill Section 3/4. Another glacial sand unit trends in a southeast to northwest direction from Landfill Section 6/7 underneath Main Creek to Landfill Section 3/4. Many smaller glacial sand units also occur, including some along the eastern portion of the landfill section that are interpreted as small alluvial fans or deltas formed by streams flowing off the uplands.

Layers of Cretaceous silt and clay and sand are found in the southernmost portion of Landfill Section 6/7 in borings 6W91:IT157 and 6W92:IT166. The Cretaceous deposits are associated with a steeply dipping bedrock surface.

The occurrence of residual clay is concentrated in the northern part of the section, but does occur in small areas in the west-central and far southeast corner of the section. It consists primarily

of clay material formed by in situ weathering of the Stockton Formation, though, in the southeastern portion of the section it is formed by weathering of serpentinite or chlorite schist.

The bedrock surface, Triassic Stockton in the northwest and Ordovician serpentinite in the southeast, dips to the west over most of the section. In the south central portion of the site a bedrock saddle occurs. South of the saddle, the bedrock surface dips steeply to the southeast. Chlorite schist was encountered in the far southern portion of the section.

5.4.2 Landfill Section 1/9

5.4.2.1 Lithostratigraphic Data Base

A total of 172 conventional test borings were used for the lithostratigraphic analysis of Landfill Section 1/9. These include 18 deep perimeter well borings completed to bedrock, 16 deep center test borings completed to bedrock, 19 shallow perimeter well borings and 8 shallow perimeter test borings drilled as part of this investigation (Table 5.4) and 111 borings completed as part of earlier investigations. Copies of the field test boring and well boring logs are contained in Attachments 1 and 3, respectively: Final test boring and well boring logs are contained in Appendices B and E, respectively. Test borings from previous investigations are contained in the Hydrogeologic Literature Review (IT Corporation and Wehran EnviroTech, 1991a). Appendix I contains the logs of regional borings obtained subsequent to submittal of the Literature Review Report. Photographs of recovered bedrock core are contained in Attachment 2. Table 5.9 is a summary of stratigraphic top and bottom elevations and thicknesses for all borings utilized in the analysis of Section 1/9.

The geologic units identified by lithostratigraphic analysis in Landfill Section 1/9 are:

- Recent Deposits
  - Refuse/Fill
  - Peat
  - Silt and Clay
  - Sand
- Pleistocene Deposits
  - Glaciolacustrine Silt and Clay
  - Glacial Sand (includes Columbia Group Sediments)
  - Glacial Till

- Cretaceous Deposits
  - Silt and Clay
  - Sand
- Residual Clay
- Bedrock
  - Weathered Bedrock
  - Competent Bedrock

5.4.2.2 Geophysical Data Base

The data base for geophysical testing at Section 1/9 is summarized below:

- 24 boreholes tested.
- Table 5.4: Tabulation identifying borings in which geophysical data were obtained (locations indicated on Sheet 5.1).
- Table 4.9: Tabulation of geophysical logs obtained at each borehole.
- Appendices F and G: Unprocessed and processed geophysical logs, respectively, including geological soil/rock sample interpretations for comparison.
- Table G.5, Appendix G: Tabulation of elevations of stratigraphic unit boundaries determined through analysis of geophysical logs.
- Table G.6, Appendix G: Comparison of soil/rock sample descriptions versus geophysical log interpretations.
- Tables G.7 and G.8, Appendix G: Statistical analyses of geophysical log data by boring, and as collective thickness weighted mean response by stratigraphic unit, respectively.

Geophysical analysis supported the results of the lithostratigraphic analysis. In general, the geophysical log responses are indicative of lithologic variations.

5.4.2.3 Microfossil Data Base and Results

Soil samples from 23 test borings were selected for microfossil analysis in Section 1/9 (Table 5.4). The results from these analyses are presented in Appendix H. A final report prepared by Dr. Les Sirkin discussing the microfossil analyses is also in Appendix H. Samples from test borings performed in previous investigations (1P81:C16D, 1W82:D1, D5, D10) were also analyzed for microfossils, with the results presented in Appendix H.

Recent sediments analyzed for microfossils were designated as Recent C3 or C3b pollen zones. In one boring, 1W91:IT004D, late glacial sediments were found to contain pollen representative of Zone A (spruce).

Zone IIB pollen was found in samples analyzed from 14 borings. Pollen Zone IIA was defined in 2 borings located in the center and in 1 boring in the southeast part of the section. Pollen Zone IIC, diagnostic of late Potomac Group, ranging to pollen Zone III, diagnostic the early Raritan Formation, was found in 6 borings.

Two borings, 1W82:D5 in northern Landfill Section 1/9, and boring 1W91:IT012D in the western part of the section, encountered younger Cretaceous sediments (Zone VII, Magothy equivalent). These isolated occurrences of the Upper Cretaceous may be attributed to Cretaceous sediments incorporated in glacial thrust slices or other methods of pollen redeposition.

5.4.2.4 Piezo-Electric Cone Penetration Test/Perimeter Boring Data Base

The database for the piezo-electric cone penetration test (P-ECPT)/perimeter boring program is summarized below:

- 90 P-ECPT borings were performed as part of this investigation and 12 as part of a previous investigation (locations indicated on Figure 4.13 and Sheet 5.2).

- 15 conventional soil borings performed to verify P-ECPT data, replace P-ECPT boring that did not meet Consent Order requirements, or substitute for P-ECPT borings not completed due to access problems (locations indicated on Sheet 5.1).

- Table 4.2: Summary of P-ECPT/perimeter boring data, including completion date, survey control, depth of penetration, dissipation tests depths and time intervals and correlation well borings.

- Table 5.15: Tabulation of elevations of stratigraphic unit boundaries determined by interpretation of P-ECPT borings, including P-ECPT borings from a previous investigation, and conventional soil borings.

- Appendix C: Correlation Report - Piezo-Electric Cone Penetration Tests in Support of Geotechnical Investigations at Sections 6/7 and 1/9 of Fresh Kills Landfill comparing P-ECPT results with correlation conventional soil borings.

- Appendix D: Final Report - Piezo-Electric Cone Penetration Tests - Sections 6/7 and 1/9 of Fresh Kills Landfill includes the P-ECPT profiles and discussions on methodology and results.

5.4.2.5 Geologic Units - Extent and Structure

- ***Recent Deposits***

Refuse/fill covers most of landfill Section 1/9. The top of the unit is the present ground surface. Elevations exceed 120 ft in the central and southeast portions of the section (Sheet 5.28). Bottom elevations range from over 20 ft in the southeast portion, to less than -20 ft in the northwest portion near Great Fresh Kills. The maximum thickness of fill encountered is 140 ft in the central portion (IB91:IT505, 506). As little as 4 ft of fill (clean fill) has been found at some locations.

Peat was encountered in 56 test borings in Landfill Section 1/9 (Sheet 5.31, Table 5.9). Most occurrences are in the west and northeast portions of the Section. In these areas, the peat can be correlated between several test borings. Top surface elevations range from almost sea level to less than -20 ft. Thickness of the peat ranges from 1 to 7.5 ft (1W92:IT017), but is usually only a few feet thick.

Recent silt and clay is encountered in the northern and western portions of Landfill Section 1/9 (Sheet 5.33) and in the eastern portion of Landfill Section 1/9 (in a former tidal marsh

environment). The top of the unit is fairly flat, ranging in elevation from 0 to in excess of -20 ft between borings 1W91:IT013 and 1B91:IT506, and near 1B91:IT514. In the northern portion of the section, the bottom of the unit slopes generally to the southwest. In the western portion of the section, the unit slopes from south to north over 25 ft. Most of the relief is in the south and north, with the center being fairly flat (Sheet 5.34). Other Recent deposits are found interbedded with the Recent silt and clay. Along the western portion of the section, the thickness of the Recent silt and clay is greater than 15 ft. Valid EMI data over the Recent silt and clay intervals in borings 1P91:IT506 and 514, indicate that the material is highly conductive, suggesting that it may have a high clay content. The high conductivity may also be related to the presence of a greater concentration of electrolytes in the pore fluids (i.e., leachate influence).

Recent sand occurs throughout the northern and western portion of Landfill Section 1/9 (Sheet 5.35). It is also found in the area of boring 1W91:IT004, in the east central portion of the section, where a former tidal marsh channel was located (Figure 5.18). Pollen data from borings 1W91:IT001, 003, 004, 010, 012, and 1B91:IT510 have yielded a C3 or C3b zonation, indicative of post-glacial time.

The top surface of Unit 1 ranges from a few feet above sea level to less than -20 ft in the northern portion of the Landfill Section. The thickness of Unit 1 in this area ranges from less than one foot to 23 ft.

Along the western portion of the section, the Recent sand occurs above, below and occasionally interbedded with the Recent silt and clay unit. The upper sand unit (Unit 2) averages 10 ft in thickness. The top of Unit 2 generally occurs from a few feet above sea level to -7.5 ft. The Recent sand unit that occurs below the Recent silt and clay in the western portion of the landfill section (Unit 1) ranges from 20 to 40 feet thick and occurs at -20 ft or less throughout most of the portion of the landfill section. The top surface of Unit 3 ranges from about 2 ft above sea level in the southern portion to -10 ft in the northern portion of the unit. The thickness of Unit 3 does not exceed 10 ft.

As discussed in section 5.2.5.4, the lower Recent sand unit is present to an elevation of approximately -60 feet. The interpretation of this sand unit as being Recent in origin is based on the varied color distribution of the sand, the site and area specific glacial depositional model (Section 5.2.5.4), and microfossil analysis for 1W91:IT-010D (Appendix H). Additional support for this interpretation is provided by the stratigraphic data presented by Stanford and Harper (1991) in Figure 5.14 concerning the base of the Recent (Holocene) sediment at the Outerbridge

Crossing. Figure 5.14 shows that the base of the Holocene (Recent) sediment at the Outerbrige Crossing is at approximately -60 ft. The dashed line portion of the Lake Hackensack uplift curve infers a gradual decrease in elevation of the Arthur Kill channel. the presentation of this portion of the uplife curve as a dashed line demonstrates the uncertainty as to the elevation of the Arthur Kill channel south of the Tremely Point spillway. It is possible that south of the Tremley Point spillway, a sudden change in the elevation of the channel occurred as the glacial meltwater cascaded over the spillway and down the Arthur Kill. This could have caused the erosion of most of the glacial deposits and the subsequent reworking and redeposition of the glacial and other deposits as Recent deposits.

- ***Pleistocene Deposits***

Glaciolacustrine silt and clay occurs in the northern and eastern portion of Landfill Section 1/9 (Sheet 5.41). It is not present in the west central, and southwestern portions, or in the northeastern portion of the landfill section that roughly corresponds to the kame feature discussed in Section 5.2.5.4. The silt and clay appears to be segmented into two separate units (Unit 1 and 2, Sheet 5.42) probably due to erosion and/or deposition of Kame "A" (Sheet 5.46). From north to south, the top surface occurs at about -30 ft, sloping upwards in elevation to the south, rising to over 10 ft between borings 1W91:IT005 and 004 (Sheet 5.42). The bottom of the unit ranges from -10 to less than -60 ft in the northern area and slopes from approximately -5 ft to -45 ft in the east and central portion (Sheet 5.43). In the north, it is fairly thick, ranging from about 10 ft to 40 ft. In the east and central portion of the site it ranges in thickness from 3.5 to over 25 ft. Interbeds of glacial till or sand are not common, but have been observed (1P92:ATW-D).

The glaciolacustrine silt and clay was observed to grade from an electrically conductive, possibly clavier material, to a more resistive, possibly siltier material, with increasing depth in the geophysical EMI and 16NC logs run in borings 1W91:IT002D, 003D, 004D, and 1P91:IT507. NG and EMIR thickness weighted log response show that this unit appears to be clavier in Section 1/9 than in Landfill Section 6/7. Pollen analysis of the glaciolacustrine silt and clay unit in boring 1W91:IT004 indicated Zone A pollen (Late Wisconsin) was present. A deeper sample from the same unit provided a Cretaceous, undefined zonation, probably from redeposited pollen.

The glacial sand in Landfill Section 1/9 occurs in three main areas: in the west central, north and east (Sheets 5.49 and 5.50). In the northern portion of the site three separate units are delineated; Units 6, 7 and 8 (Sheet 5.49). The top surface elevation of Unit 6 ranges from -1.1 in the southern portion of the unit to -35.0 in the northern portion. The top surface of Unit 7 is

fairly flat, ranging from -17.0 to -21.0 ft. Unit 8 occurs at lower elevations, with the top surface ranging from -40 ft to -60 ft. Unit 6 exceeds 10 ft in thickness, Unit 7 exceeds 20 ft in thickness; and Unit 8 is less than 5 ft in thickness.

The glacial sands in the eastern part of Section 1/9 are associated with the kame deposit present in this portion of the site. They usually occur interbedded with glacial till/diamict. The deposition of the kame feature results in a complex distribution of glacial sand that is difficult to correlate. Four separate units have been identified in this area; Units 9, 18, 23 and 25 (Sheets 5.49 and 5.50). The top surface of the units occurs from about sea level to less than -40 ft. They range in thickness from 2 to 21 feet. The numerous borings and piezo-electric cone penetration tests performed as part of the perimeter boring program demonstrate the complex stratigraphic and structural configuration of the sand bodies within the kame deposit. This interlayering is shown on Perimeter Cross-Section GP 1/9 (Sheet 5.24) between borings 1W91:IT003 and 004.

Glacial sand occurs at two locations in the western portion of the landfill section; Units 13 and 13A (Sheet 5.49). The top surface of Unit 13 ranges from approximately -35 to -60 ft. The top surface of Unit 13A occurs at approximately -50 ft. The thickness of Unit 13 ranges from a few to 30 ft. Unit 13A is less than 5 ft thick (Sheet 5.53). If glacial till is present, the sand is found above the till. Where the glacial till is not present, the glacial sand occurs above Cretaceous deposits. Recent sand deposits occur above portions of the glacial sand in this area of the landfill section.

Glacial lodgement till is absent in the extreme south and southwestern portions of the landfill section, in addition to portions of the extreme northern, eastern, and western areas (Sheet 5.56). The top of the unit slopes east to west, from elevations of about 30 ft to less than -60 ft. In the north, it slopes to the southeast from about -10 ft to -40 ft. The bottom of the unit shows dip similar to the top, sloping from -40 to -60 in the north, and from 20 to -70 throughout the rest of the site (Sheet 5.57). Thickness of the glacial lodgement till in this landfill section is usually less than 10 ft (Sheet 5.58).

Columbia group sediments were encountered in four borings along the southeast boundary of Section 1/9 (Sheet 5.59). The unit top elevation is between 25.6 ft and 8.4 ft. The unit bottom elevation is between 19 ft and 5.4 ft. Thickness ranges from 3 ft to 11 ft. The deposits consist of fine sand and silt and clay.

- ***Cretaceous Deposits***

Cretaceous clay and silt occurs beneath all of Landfill Section 1/9 except for areas in the northeastern and northwestern portions of the section (Sheet 5.60). The Cretaceous clay and silt occurs above a laterally continuous basal sand unit. In a few isolated locations, the basal sand is missing and the silt and clay overlies residual clay. In a generalized stratigraphic configuration, the Cretaceous clay and silt tends to occur above the Cretaceous sand, however, interbedding of the sand and silt and clay is common. The Cretaceous sand does occur at the top of the sequence in some locations (Sheet 5.80). The clay and silt unit thickens to the south and southeast. Interbedding with Cretaceous sand also increases to the southeast and south. The top of the unit generally increases in elevation from west to east, although "pinch-outs" and interbedding with the Cretaceous sand results in an uneven and serrated top surface. The bottom of the unit decreases in elevation to the south and southeast. Cumulative thickness ranges from 0.5 ft in the central portion to over 100 ft in the southern portion of the section (Sheet 5.61). In the southeastern portion of the section, where a thick sequence of Cretaceous sand occurs, the Cretaceous clay is relatively thin in places. South of this area the thickness of the Cretaceous clay increases rapidly, as stated above.

The EMI and 16NC geophysical logs run in test borings 1W91:IT008D, 010D; 1P91:IT013Z; and 1B91:IT503, 506, 514, indicate that the Cretaceous silt and clay grades from a conductive, possibly clavier material to a more resistive, possibly siltier material. However, the gradation was less distinct than what was observed in the glaciolacustrine silt and clay in this section. Pollen zonation ages from numerous test borings indicate a Zone II or Zone III age (Patapsco to early Raritan).

Cretaceous sand also occurs beneath most of Landfill Section 1/9 (Sheet 5.62). In general, it thickens to the south and southeast. In the south central portion of the section, the sand unit is very thick; the thickest accumulations being in the east-central portion of the landfill section. It is interbedded with Cretaceous silt and clay throughout the landfill section, complicating accurate delineation of individual unit surfaces and thicknesses.

A basal layer of Cretaceous sand occurs on top of residual clay across most of the site. Thickness of the basal unit usually ranges from several feet to over 20 ft. The basal sand occurs as a separate unit throughout most of the section, however, in some locations it may be interconnected to the Cretaceous sands that occur at higher elevations in the stratigraphic section. The basal sand and other Cretaceous sand layers that are interconnected to it have been defined

as Unit 1 (Sheet 5.63). The general trend of the top surface of this unit is from north to south to northwest to southeast. Unit 1 tends to thicken to the southeast, with a total thickness of over 80 ft observed (Sheet 5.66).

The basal sand appears to be finer-grained or clavier than the basal sand found in Landfill Section 2/8, based on NG thickness weighted log response. Results of pollen analysis for the Cretaceous sand indicate Zone I to Zone II zonations, Potomac Group equivalent.

Two other individual Cretaceous sand units have also been identified in Landfill Section 1/9; Units 2 and 3 (Sheet 5.64). The top of Unit 2 is fairly flat, occurring at about -30 ft. The thickness of Unit 2 ranges from 2 to 15 ft (Sheet 5.67). Unit 3 trends in a northwest-southeast direction from the southeastern portion of Landfill Section 1/9 into the southwestern portion of Landfill Section 2/8. Top surface elevation ranges from sea level to 25 ft above sea level. In Landfill Section 1/9 this unit thickens to the southeast from approximately one foot to about 15 ft (Sheet 5.67).

The NG and EMI log responses over the Cretaceous sand interval from -98 to -128.5 ft in borehole 1W91:IT007D (Appendix G, Figure G-24) provides an excellent example of how geophysical data was used to distinguish lithologic units. The logs indicate that this sand is probably saturated with saline water, a condition that would not be evident through standard soil sample analytical techniques. In contrast, the log responses over the Cretaceous sand unit from -47 to -61 ft in borehole 1W91:IT006D, as defined by lithostratigraphic analysis, (Appendix G, Figure G-23) are not as distinguishing, and may represent a gradual increase in grain size within the Cretaceous silt and clay stratigraphic unit and not a sand unit. Contact elevations determined for the Cretaceous sand unit based on the responses of the logs run in borehole 1W91:IT004D (Appendix G, Figure G-21) differ only slightly from contact elevations defined by lithostratigraphic analysis.

Downhole EMI logs acquired throughout the basal Cretaceous sand in Landfill Section 1/9 indicate that the material in boreholes 1W91:IT006D, 007D, 008D, 010D, 011D, 012D, 1B91:IT506, 511, 514 and 1P91:IT507 are more conductive than elsewhere in the site. Downhole EMI data were not acquired in borehole 1W91:IT510, and not acquired past a borehole elevation of -45 ft in deep borehole 1B91:IT509. It would appear from the evaluation of these logs that the groundwater in the basal Cretaceous sand beneath the southwestern portion of Landfill Section 1/9 is more saline than the overlying sands penetrated by boreholes further to the north, northeast, and east. It should be noted, however, that the conductivity of sediments

saturated with fluid is a function of the salinity of those fluids as well as the effective porosity of the sediments. Clay percentage can also cause changes in conductivity that are not related to the salinity of the interstitial fluid. Therefore, if the lithology of the Cretaceous sand changes significantly between the boreholes, the differences in conductivity observed may not be entirely related to the salinity of the interstitial water. The significance of these observations is the apparent saline (seawater) intrusion of the lower (basal) Cretaceous sand unit.

Mean EMI response observed in the lower Cretaceous sand unit and mean chloride concentration (ug/L) measured within monitoring wells screened within this unit are presented in Table G.9. A linear regression fit to the plot of mean EMI response[2] versus mean chloride ion concentration is presented in Figure 5.24. This figure clearly demonstrates that the EMI log is responding correctly to salinity changes in interstitial fluid. Figure 5.25 indicates the distribution of chloride concentration in the lower Cretaceous sand unit based on the relationship identified on Figure 5.24.

Since this figure includes empirically derived data from geophysical logs performed in the central landfill areas (where no monitoring well analytical data are available), it is especially useful in mapping the distribution of seawater intrusion within the lower Cretaceous sand. As indicated, this influence extends across the western, central, and southern regions of Landfill Section 1/9.

- ***Residual Clay***

Residual clay is found beneath all of Landfill Section 1/9 (Sheet 5.68). The top surface of the unit trends to the south from an elevation of approximately -40 ft in the northwestern corner, to approximately -130 ft in the southeastern corner. The top surface has more relief in the southern half of the section than the northern half. The base of the unit also generally trends to the south, but shows more relief and variability than the top of the unit, with depressions apparent in the northeastern corner and central areas (Sheet 5.69). The bottom surface elevation ranges from -63 ft in the northwest portion to -207 ft in the southeast corner of the landfill. The unit is quite variable in thickness, ranging from 3 to 79 ft (Sheet 5.70). The residual clay in Section 1/9 is formed from the in situ weathering of the Stockton Formation.

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[2]The inverse of mean resistivity (i.e., conductivity) was used as input to the linear regression analysis.

- ***Bedrock***

In the northern portion of Landfill Section 1/9, the top of the bedrock surface demonstrates less relief than the southern portion (Sheet 5.74). The center portion is highest in elevation, with the surface sloping to the west and east in this area and exhibiting approximately 20 ft of relief. In the center of the site, the bedrock surface slopes steeply to the south along a narrow band from 1W91:IT012, 1W92:IT016 to 1W91:IT004. The surface levels off again for about 1,000 ft laterally in a southerly direction and again dips steeply in the southernmost portion of the site from an elevation of -140 ft to about -200 ft.

The top of the weathered bedrock has a trend similar to the bedrock as a whole, sloping to the east and west in the northern portion of the Landfill Section (Sheet 5.71). It slopes steeply to the south in the center portion, flattens out, and then slopes steeply to the south in the southern portion of the section. The bottom of the unit (Sheet 5.72) shows a similar trend in the north and south but does not exhibit the steep slope in the central portion. Thickness ranges from 0 ft to greater than 50 ft, with the thickest area in the central portion of the landfill section.

The bedrock is composed of the siltstones, shales, and sandstones of the Stockton Formation. Sandstone occurs in portions of the eastern, northeastern, western and central portions of the landfill section (Sheet 5.82). Sand sizes range from fine to coarse. The sand units occur interbedded with siltstone/shale units. Thick, massive units consisting entirely of sandstone were not usually seen. Most of the bedrock unit beneath Section 1/9 consists of a red brown and light gray siltstone and shale. It is fairly well weathered and fractured at the top. It becomes more purplish and greenish in the western and southern portion of the section, possibly representing a transition zone to the Lockatong Formation. The alteration noted in cores of the Stockton Formation in other landfill sections was not noted in Landfill Section 1/9.

5.4.2.6 Summary

Refuse/fill covers virtually the entire area of Landfill Section 1/9. Recent deposits, glacial deposits, or Cretaceous deposits occur directly below the refuse/fill. Recent deposits are found in the north, in a small area in the east central part of the section, and in the western half of the landfill section. Most of the Recent deposits are associated with tidal marshes that were present prior to placement of fill. Recent silt and clay, peat, and sand often occur interbedded.

Refuse/fill overlies Recent deposits over a large part of the western and northern portions of the site.

Glacial deposits are limited primarily to the northern and eastern portions of the landfill section. The glaciolacustrine silt and clay is limited to specific areas of the north and eastern portions of the section (Sheet 5.41). In addition to most of the western portion of Landfill Section 1/9, glacial till is absent in specific areas in the north and eastern portions of the site (Sheet 5.56). Nine individual glacial sand units were identified within the glacial sequence in Landfill Section 1/9. The glacial sand in the eastern part of the section, where a former topographic high existed, occurs interbedded with glacial till and is associated with a kame feature. Refuse/fill overlies glacial sediments in portions of the northern and eastern portion of Landfill Section 1/9.

Cretaceous silts and clays and sands are present under most of Landfill Section 1/9, with the exception of the northeast corner and small areas of the western landfill section boundary. The upper portion of the sequence is predominately clay and silt, but intermittent layers or lenses of sand are found interbedded with the clay and silt. A basal sand unit that overlies residual clay occurs across the section. A thick sand unit present in the east central portion of the site may be indicative of a large stacked or aggradional channel complex. The silt and clay and sand units occur as a complexly interbedded stratigraphic sequence.

A residual clay layer of variable thickness exists under the entire section. The residual clay is formed from the in situ weathering of the Stockton Formation. The residual clay is the first laterally continuous confining unit under Landfill Section 1/9. The bedrock, comprised of the Stockton Formation, slopes primarily to the south-southwest. A weathered, fractured zone of the bedrock occurs between the residual clay and competent bedrock. Along the eastern boundary of the landfill section, the permeability of the weathered bedrock zone is markedly lower than elsewhere.

5.4.3 Landfill Section 2/8

5.4.3.1 Lithostratigraphic Data Base

A total of 54 conventional test borings were used for lithostratigraphic analysis of Landfill Section 2/8. These included 11 deep perimeter well borings completed to bedrock, 10 deep center borings completed to bedrock, and 14 shallow perimeter borings drilled as part of this

investigation (Table 5.5) and 19 borings performed for earlier investigations. Copies of the field test boring and well boring logs are contained in Attachments 1 and 3, respectively. Final test boring and well boring logs are contained in Appendices B and E, respectively. Test boring logs from previous investigations contained in the Hydrogeological Literature Review (IT Corporation and Wehran EnviroTech, 1991a) and Appendix I. Photographs of recovered bedrock core are contained in Attachment 2. Table 5.10 is a summary of the stratigraphic unit top and bottom elevations and thicknesses for all borings utilized in the analysis of Section 2/8.

The geologic units identified by lithostratigraphic analysis in Landfill Section 2/8 are:

- Recent Deposits
  - Refuse/Fill
  - Peat
  - Silt and Clay
  - Sand
- Pleistocene Deposits
  - Glaciolacustrine Silt and Clay
  - Glacial Sand (includes Columbia Group Sediments)
  - Glacial Till
- Cretaceous Deposits
  - Silt and Clay
  - Sand
- Residual Clay
- Bedrock
  - Weathered Bedrock
  - Competent Bedrock

5.4.3.2 Geophysical Data Base

The data base for geophysical testing at Section 2/8 is summarized as follows:

- Nine boreholes tested.
- Table 5.5: Overview tabulation of borings in which geophysical data were obtained (locations indicated on Sheet 5.1).

- Table 4.9: Summary tabulation of geophysical logs obtained at each borehole.

- Appendices F and G: Unprocessed and processed geophysical logs, respectively, including geological soil/rock sample interpretations for comparison.

- Table G.10, Appendix G: Tabulation of elevations of stratigraphic unit boundaries determined through analysis of geophysical logs.

- Table G.11, Appendix G: Comparison of soil/rock sample descriptions versus geophysical log interpretations.

- Tables G.12 and G.13, Appendix G: Statistical analyses of geophysical log data by boring, and as collective thickness weighted mean response by stratigraphic unit, respectively.

As with other landfill sections, the geophysical data base is too large and detailed to provide specific comments on an individual test boring basis. Instead, the results of geophysical analysis have been incorporated into the stratigraphic interpretations discussed subsequently.

5.4.3.3 Microfossil Data Base and Results

Soil samples from 10 test borings were selected for microfossil analysis in Section 2/8 (Table 5.5). The results of these analyses are presented in Appendix H. Samples from test borings performed in previous investigations (2P81:C15D; 2P82:C8D, C11D, C51; 2W82:D17) were also analyzed for microfossils, with the results presented in Appendix H. Zone C (Holocene) pollen was found in the Recent sediments analyzed. With the exception of two Zone IV (Upper Cretaceous) samples from near the top of the Cretaceous strata (2P81:C15D and 2B91:IT804), all other Cretaceous pollen was Zone II (Lower Cretaceous).

5.4.3.4 Geologic Units - Extent and Structure

- ***Recent Deposits***

Most of Landfill Section 2/8 is covered by refuse/fill, with the exception of areas in the south central and eastern portions. The top surface elevations range from less than 20 ft in the western portion to over 100 ft in the east (Sheet 5.28). The bottom of the fill (Sheet 5.29) slopes from

south to north from approximately 15 ft to -10 ft. Thickness ranges from 0 ft in the southwest and east portions, to 115 ft in the east/northeast (Sheet 5.30).

Six test borings encountered peat in Landfill Section 2/8 (Sheet 5.31, Table 5.10). All are located near Richmond Creek. The former tidal marsh area in Landfill Section 2/8 is much larger, based on the examination of historic topographic maps and aerial photographs, than the area delineated by borings encountering peat. This may be attributed to sampling problems (primarily overdrilling), removal of the peat prior to the placement of fill in some areas, or nondeposition of peat in certain areas of the tidal marsh. The peat in Landfill Section 2/8 is usually 2 to 3 ft thick.

Ten test borings encountered Recent silt and clay in Landfill Section 2/8, all located in the former tidal marsh environment in the northern portion of the site (Sheet 5.33, Table 5.10). The top of the unit is fairly flat, ranging from 2.0 to -12.7 ft in elevation. The bottom surface also shows little relief, ranging from -7 to -14.7 ft in elevation. The unit is only a few feet thick. It pinches out to the south in the area where the tidal marsh gives way to the uplands (Figure 5.18). It was also encountered in the eastern portion of the site (2P79:E7) in a tidal marsh area between the refuse/fill and Richmond Avenue.

Recent sand was encountered in five borings, all within the former tidal marsh environment (Sheet 5.35, Table 5.10). The Recent sand encountered in three borings located in the northwest corner of the section is part of the laterally extensive Recent sand Unit 1 (Sheet 5.36). The sand occurs between -9 ft to -15 ft in this area. The other two borings that found Recent sand are located in the eastern portion of the section (Sheet 5.37, Recent sand Units 4 and 5), where the sand occurs at elevations of 6 ft to -10 ft. Sand thickness ranges from 0.5 ft to over 14 ft in these units.

- ***Pleistocene Deposits***

The glaciolacustrine silt and clay occurs primarily in the northern and eastern portions of the section (Sheet 5.41). Isolated occurrences are found in the southern and western portions of the Landfill Section (Sheet 5.41, Units 2, 3, 4, and 5). The top of the unit (Sheet 5.42) slopes gradually from approximately -20 ft in the north to about 5 ft in the south. The bottom of the unit (Sheet 5.43) has a similar slope, but rises more steeply, from elevations of greater than -60 ft in the north to approximately -5 ft in the south. Thickness ranges from 2 to 37 ft (Sheet 5.44). Interbeds of glacial till and glacial sand are common in the glaciolacustrine deposits in Section

2/8 (borings 2W91:IT301, 303, and 2B91:801, 802, 805, 811). Several samples analyzed for microfossils were found to be barren of diagnostic species. As evidenced in EMI and EMIR logs, this unit was observed to grade from a conductive, possibly clavier material to a more resistive, possibly siltier material with increasing depth. It grades into the more resistive glacial till in test borings 2W91:IT301D, 302D and 2B91:801, 809. Based on NG thickness weighted log response, the glaciolacustrine silt and clay appears to be clavier in Section 2/8 than in the other landfill sections.

Glacial sand occurs in various areas across Landfill Section 2/8 (Sheet 5.48). The glacial sand in 2W91:IT301 is interpreted as an isolated lense in the glacial till, possibly correlatable with the glacial sand in 1Z91:IT554 (Glacial sand Unit 8). Units 14, 15, 17 and 24 occur in the southern portion of the site (Sheets 5.49 and 5.50). Some of the southernmost units occur above sea level. Thickness of the sand ranges from one ft to over 20 ft. The glacial sand present in the middle of Landfill Section 2/8 is interpreted to be associated with the kame feature located in the eastern portion of Landfill Section 1/9. Five individual glacial sand units associated with the kame have been delineated; Units 9, 10, 18, 23 and 25 (Sheets 5.49 and 5.50). These units extend through the central portion of the landfill section. Top surface elevations range from almost 10 ft above sea level to less than -40 ft. Unit thickness rarely exceeds 20 ft. Due to the complexity of the kame-ice contact sediment sequence, it is difficult to determine if the glacial sand is correlatable across this area of Landfill Section 2/8 as a continuous unit.

Approximately half of the sand described as glacial sand in the southwestern portion of Landfill Section 2/8 is interpreted as belonging to the Columbia Group (Sheet 5.59). The lateral extent of the Columbia Group sand is very limited, occurring in only four borings. The discontinuous nature of these sands can be primarily attributed to the erosional processes of glaciation. The remaining sand in the southwestern portion of the section is glacial in origin (2W92:044, 045, 311, 2P82:C14).

Glacial till underlies most of Landfill Section 2/8. Glacial lodgement till is absent along a northwest to southeast trending band that cuts through the section, same of it possibly removed by meltwater erosion. Cretaceous sediments occur below refuse/fill at several locations in the southern portion of the section where the lodgement till is not present (Sheet 5.56). Review of historic aerial photographs and topographic maps suggests that some of the glacial till in this area was removed during landfilling activities (Sheet 5.83). The top of the lodgement till slopes from south to north from approximately 40 ft to -50 ft in elevation (Sheet 5.56). The base of the unit has a similar trend and slopes from 30 ft to -70 ft in elevation (Sheet 5.57). Thickness ranges

from 3 ft to over 30 ft. Non-lodgement till occurs interbedded with the glacial sands and glaciolacustrine silt and clay. It is mainly associated with the deposition of the kame/ice contact deposits.

- ***Cretaceous Deposits***

Cretaceous silt and clay occurs in the southern half of Landfill Section 2/8 (Sheet 5.60). The top surface increases in elevation from north to south from -26.5 ft to 22.1 ft. The bottom surface decreases in elevation to the south from -47.5 ft to -91.9 ft. The Cretaceous silt and clay unit thickens rapidly to the south. It becomes more complexly interbedded with Cretaceous sand to the south, resulting in multiple sand and silt and clay sequences. Total thickness of the silt and clay unit in the southern portion of the section, including the sand interbeds, is in excess of 100 ft. Pollen zonations range from Zone II to IV, indicative of Patapsco to Woodbridge/Raritan equivalents.

Cretaceous sands occur in the southern two thirds of the site (Sheet 5.62). Interfingering of Cretaceous sand with Cretaceous clay is common beneath the section, however, the interfingering tends to decrease to the east. The Cretaceous sands in this section tend to be thinner than those observed in Landfill Section 1/9, rarely exceeding 20 ft in thickness. A basal sand also occurs above residual clay or bedrock in this section, although it is thinner than in the other sections. The basal sand and other Cretaceous sand layer correlated and interconnected to it forms Cretaceous sand Unit 1 in Landfill Section 2/8 (Sheet 5.63). Three other Cretaceous sand units occur above Unit 1 in Landfill Section 2/8 (Sheet 5.64). The surface Unit 3 occurs above sea level in the southwestern portion of the site. Thickness ranges from just over one foot to over 40 ft. Unit 4 occurs over more than half the site, the top surface occurring from just below sea level to less than -40 ft. Thicknesses of over 40 ft occur. Unit 5 is in the southeast corner. The top surface occurs from about 10 ft above sea level to 25 ft above sea level. The observed thickness is over 20 ft. The sand layers trend in a south/southeast direction.

In test boring 2B91:IT804, EMI and EMIR logs indicate that the Cretaceous sand grades from a conductive, possibly clavier material to a more resistive, possibly siltier material with increasing depth. However, the gradation was less distinct than what was observed in the glaciolacustrine silt and clay within the section. An example of geophysical log response that is not completely consistent with lithology, and where stratigraphic contacts are not marked by sharp log deflections, is seen in the geophysical logs of boring 2B91:IT801 (Appendix G, Figure G-45). In boring 2P91:IT806 (Appendix G, Figure G-49), the thin Cretaceous sand and Cretaceous silt

and clay beds below elevation -61 ft are mostly based on the SPR log. Contact elevations defined may not agree exactly with those defined by lithostratigraphic analysis because the beds are thin and the contacts are probably gradational. Pollen zonations within the Cretaceous deposits ranged from II to III, indicative of Patapso to earliest Raritan equivalents.

- ***Residual Clay***

Residual clay is present in the western and southeastern portions of Landfill Section 2/8. Sheet 5.68 shows the distribution of residual clay beneath the section. The top surface of the unit shows a general trend to the south-southeast. Elevations of the top surface range from approximately -55 ft to -145 ft (Sheet 5.68). The bottom surface of the residual clay is very similar to the top in trend, with elevations ranging from -70 to -190 ft (Sheet 5.69).

The residual clay is thickest in the western portion of the section, ranging from 11 to 56 ft. Thickness in the southeast ranges from 4 to 40 ft. The differences in thickness can be partially be explained by the origin of the clay. The residual clay in the western portion is formed from the more easily weathered Stockton Formation, whereas, the residual clay in the southeast is formed from the more resistant serpentinite. The residual clay formed from the Stockton in borings 2W91:IT302, and 2B91:IT809, 811 is very similar in appearance and texture to the residual clay formed from the Stockton Formation in Landfill Section 1/9. Color changes that are observed in the residual clay in borings 2W91:IT307 and 308 appears to indicate that some alteration of the Stockton Formation has occurred in this area of the landfill section.

- ***Bedrock***

The surface of the bedrock beneath the northern portion of Landfill Section 2/8 is relatively flat (Sheet 5.74). In the southern part of the section, the bedrock slopes to the southeast. The slope is fairly uniform, with elevations decreasing from about -50 ft in the center and northeastern portion of the section, to about -100 ft along the northern, western, southern, and eastern boundaries of the section.

Weathered bedrock overlies the bedrock below the site (Sheet 5.71). The top surface elevation ranges from approximately -70 ft in the north to -190 ft in the south. The trend is somewhat radial, sloping to lower elevations in the west, south and east. The bottom surface shows a southward sloping trend, ranging from approximately -67 ft in the north to over -200 ft in the

south (Sheet 5.72). Thickness of weathered bedrock ranges from 7 to 30 ft, but thicker areas occur in the northwest corner (greater than 50 ft) and south central (greater than 30 ft) portions of the section (Sheet 5.73).

Four types of bedrock have been identified in Landfill Section 2/8; the Stockton Formation, serpentinite, chlorite schist, and Manhattan Schist (Sheet 5.82). The Stockton Formation occurs in the western portion of the site. The rock core sample from borings 2W91:IT302, 2B91:IT809, 811 are described as typical Stockton shale, siltstones, and sandstone. The Stockton is very arkosic in 2B91:IT811. The cores from 2W91:IT307 and 308 indicate an altered Stockton Formation. In boring 2W91:IT307, the core is generally darker than typical Stockton strata. Quartz veins are common, and veins of chlorite are also observed. In boring 2W91:IT308, the core is also darker than typical Stockton strata, and appears to be altered to a very soft, fine grained, white material from 108 to 112 ft below the ground surface. Vugs are present in the cores of these two borings (Sheet 5.82).

Serpentinite occurs in almost the entire eastern two-thirds of the site. In boring 2B91:IT808 the serpentinite is slightly altered, with veins of quartz and calcite or aragonite. In boring 2B91:IT801 the core is a fine-grained, massive, somewhat porphyritic serpentinite/ pyroxene. In boring 2P91:IT806 the core is a fairly porphyritic serpentinite. Core samples from 2B91:IT802 and 2W91:IT304 were fairly homogeneous. 2W91:IT303 ranged from porphyritic to homogeneous in texture. Lizardite was encountered in 2B91:IT802 and 2W91:IT304 and 306. Other minerals encountered were talc (2B91:IT802, 804), magnetite (2B91:IT804, 808 and 2W91:IT306), and pyrite (2W91:IT306). Vugs were noted in 2W91:IT306. Most fracturing was horizontal in nature.

The bedrock in boring 2W91:IT305, located in the southeastern portion of the site, has been identified as a chlorite schist. It is massive, foliated, and contains large plates of talc. It is believed that the rock was formed as an alteration product of the serpentinite. In boring 2W92:IT310, the rock was identified as Manhattan Schist, based on the presence of the classic foliation, almandine garnets, and mica typical of the Manhattan Schist.

5.4.3.5 Summary

Refuse/fill was identified in most of the test borings drilled in Landfill Section 2/8. Recent silt and clay or peat, is found below the refuse/fill in the northern and far southeastern portion of the

section. Recent sand was found in the north and east portions of the section. The Recent deposits are confined to a tidal marsh area in the northern and southeastern portions of the landfill site that was present prior to placement of fill.

Glaciolacustrine silt and clay occurs in the northern, eastern, and west-central portions of the landfill section. Glacial lodgement till is present primarily in the northern and western portions of the section. Non-lodgement till is encountered in association with glacial sand or glaciolacustrine silt and clay, that was part of the ice contact deposition that occurred in this landfill section. Glacial sands occur throughout the section. The largest and thickest occurrence of glacial sand is along a east/west trending band in the center of the section. This sand is associated with the kame feature that occurs in Landfill Section 1/9.

In the central and southern portions of the section, glaciolacustrine silt and clay or glacial till predominately underlies the refuse/fill. Four IT series borings (2W91:IT306, 2W92:IT321S, 2B91:IT804 and 2P91:IT806) found Cretaceous deposits directly below the refuse/fill. The primary interpretation for the lack of glacial deposits is that they were excavated as part of landfilling activities. Analysis of historic topographic maps and aerial photographs tends to support this interpretation (Sheet 5.83). Meltwater erosion may also account for the removal of some of the glacial sediments.

Alternating layers of Cretaceous silts and clays and sands are found below the glacial deposits in the southern two-thirds of the section. The Cretaceous sequence thickens rapidly to the south. In the area where the Cretaceous deposits occur, sand is present as the basal unit, except at locations 2B91:IT801, 2W92:IT309 and 311 and 2P92:ATW-D. The basal sand can be correlated subregionally to the basal sand that occurs in Landfill Sections 1/9 and 6/7. The sands in the upper portion of the sequence are complexly interbedded with the clay and silt, however, the sand units and silts and clays between borings within the section have been correlated.

Residual clay, formed from the Stockton Formation in the west and serpentinite and schist in the southeast, trends south-southeast. The bedrock surface, Triassic Stockton in the north and west, and serpentinite and schist in the south and east, is relatively flat.

5.4.4 Landfill Section 3/4

5.4.4.1 Lithostratigraphic Data Base

A total of 66 conventional test borings were used for lithostratigraphic analysis of Landfill Section 3/4. These included 11 deep perimeter well borings completed to bedrock, 10 deep center borings completed to bedrock, and 17 shallow perimeter borings drilled as part of this investigation (Table 5.6) and 28 borings completed as part of earlier investigations. Copies of the field test boring and well boring logs are contained in Attachments 1 and 3, respectively. Final test boring and well boring logs are contained in Appendices B and E, respectively. The logs for the borings from previous investigations used on this analysis are contained in the Hydrogeological Literature Review (IT Corporation and Wehran EnviroTech, 1991a) and Appendix I. Photographs of recovered bedrock core are contained in Attachment 2. Table 5.11 is a summary of the stratigraphic unit top and bottom elevations and thicknesses for all borings utilized in the analysis of Section 3/4.

The geologic units identified by lithostratigraphic analysis in Landfill Section 3/4 are:

- Recent Deposits
  - Refuse/Fill
  - Peat
  - Silt and Clay
  - Sand
- Pleistocene Deposits
  - Glaciolacustrine Silt and Clay
  - Glacial Sand
  - Glacial Till/Diamict
- Residual Clay
- Bedrock
  - Weathered Bedrock
  - Competent Bedrock

5.4.4.2 *Geophysical Data Base*

- Eight boreholes tested.
- Table 5.6: Overview tabulation identifying borings in which geophysical data was obtained (locations indicated on Sheet 5.1).
- Table 4.9: Summary tabulation of geophysical logs obtained in each borehole.
- Appendices F and G: Unprocessed and processed geophysical logs, respectively, including geologic soil/rock sample interpretations for comparison.
- Table G.14, Appendix G: Tabulation of elevations of stratigraphic unit boundaries determined through analysis of geophysical logs.
- Table G.15, Appendix G: Comparison of soil/rock sample descriptions versus geophysical log interpretations.
- Tables G.16 and G.17, Appendix G: Statistical analysis of geophysical log data by boring, and as collective thickness weighted mean response by stratigraphic unit, respectively.

As noted in earlier discussions, geophysical log responses support and supplement the findings of the stratigraphic analyses, and is incorporated into the subsequent geologic unit descriptions.

5.4.4.3 *Microfossil Data Base and Results*

Soil samples from six borings were selected for microfossil analysis in Section 3/4 (Table 5.6). The results from these analyses are presented in Appendix H. A final report prepared by Dr. Les Sirkin discussing the microfossil analyses is also in Appendix H. In addition to pollen indicative of Recent age, a surprisingly large amount of Upper Cretaceous pollen, usually mixed with Recent pollen, was observed. Reworking and redeposition of the Cretaceous pollen with the glacial sediments is the likely explanation.

5.4.4.4 Geologic Units - Extent and Structure

- **Recent Deposits**

Refuse/fill was identified in all the IT series borings and wells drilled in this section. The top of the unit is the present ground surface and rises to over 120 ft (Sheet 5.28). The bottom of the unit ranges from slightly above 0 ft in the northwest to almost -20 ft in the southwest and southeast (Sheet 5.29). Thickness of the fill ranges from 10 ft near the perimeter to over 150 ft in the center of the section (Sheet 5.30).

Peat was encountered in many of the borings drilled in Landfill Section 3/4 (Sheet 5.31). Practically all of Landfill Section 3/4 is located in a former tidal marsh environment (Figure 5.18). The unit occurs from about sea level to -10 ft below sea level. Thickness of the peat ranges from 0.5 ft (3W91:IT401) to 8.8 ft (3W91:IT406), but, on average, is only a few feet thick.

Recent silt and clay is present under most of Landfill Section 3/4, the exception being areas in the western and central portion of the section (Sheet 5.33). The top surface of the unit is fairly flat; in the north and center portions of the landfill section it is between 0 and -10 ft in elevation and in the southeastern portion of the section it ranges from -5 to -20 ft in elevation. The relief of the bottom of the unit is similar to the top of the unit (Sheet 5.34). Lower elevation areas occur in the north and south, where elevations exceed -25 ft. In the center of the section, bottom surface elevations are about -10 ft. In general, the unit is less than 10 ft thick. The thickest part of the silt and clay unit (27.5 ft thick) was encountered in boring 3W92:IT433 along the eastern side of the section. In borings 3W91:IT406, 410, 3P79:E16 and 3B76:T5, the silt and clay is found interbedded with other Recent deposits.

Pollen analysis performed on Recent silt and clay sediment from borings 3B91:IT908 and 3W91:IT406 indicated C3 and C3b zonations, which are indicative of post-glacial periods. In boring 3B91:IT901, sediments analyzed yielded a B or C pollen zonation, indicative of late-glacial or post-glacial periods. Zone VII pollen (Upper Cretaceous) was also found in boring 3B91:IT901. The pollen in this sample is interpreted as being redeposited.

Recent sand was encountered in every boring drilled through the complete sequence of Recent sediments in Landfill Section 3/4, with the exceptions of borings 3P92:IND201 and 3P92:IND202 (south central portion of the section), 3P81:C27S, 3B91:IT904 (center of section) and 3B91:IT908

(southeast portion of section). Borings 3P81:C27S and 3B91:IT904 were drilled near a former upland or topographically high area (Figure 5.13, "B") where Recent sand probably was not deposited. Boring 3B91:IT908 was drilled where a bedrock high exists. The bedrock high may have resulted in a ground surface high, precluding the deposition of sand. The unit slopes from the north to the south and east. In general, the unit thickens to the west. Thickness of the unit is generally less than 10 ft, however, in the western portion of the site, thickness exceeds 20 ft in some locations (3W92:IT408, 3W91:IT902, 903). The unit is interbedded with layers of peat and Recent silt and clay in the southwest portion of the section. Microfossil data from borings 3W91:IT401, 406 and 3B91:901, 903, and 909 indicate C3b, C3b1, or Holocene (undifferentiated) zonations which are consistent with the Recent classification of the sediment. A pollen Zone V zonation was indicated from the bottom of a unit of gray sand sample analyzed boring 3B91:IT909. This sand sample probably represents redeposited or reworked Cretaceous pollen.

- ***Pleistocene Deposits***

Glaciolacustrine silt and clay was found in almost every boring drilled in Landfill Section 3/4. The top surface slopes from an elevation of about -15 ft in the north to -30 ft in the south (Sheet 5.42). The bottom surface slopes from about -20 ft in the north to over -60 ft in the center, then down to over -80 ft along the southwest boundary, and up to -20 ft in the southeast corner of the section (Sheet 5.43). Thickness ranges from 2 to 40 ft. The unit is interbedded with glacial sand and glacial till at many locations. Interbedding with other glacial units results in a rapid change in the top and bottom surface elevations of the unit in the east central portion of the site.

A pollen zonation of C3 (post-glacial) was obtained near the top of the unit in 3B91:IT903. A Cretaceous-undifferentiated pollen assemblage was identified at the top of the unit in 3W91:IT406, which is probably due to redeposited pollen. In the EMI logs, this unit was observed to grade from a conductive possibly clavier material to a more resistive, possibly siltier material with increasing depth. It grades to the more resistive glacial sand or glacial till in borings 3W91:IT405D, 406D, and 3B91:901, 903, 908, 909.

Most of the glacial sand that occurs in Landfill Section 3/4 is associated with the kame feature discussed earlier (Figure 5.13, "B"). The kame occurs in the central portion of the landfill section. It is composed primarily of glacial sand interbedded with non-lodgement till. The sands associated with the kame extend into the western portion of Landfill Section 3/4 and beyond

Main Creek to the east where they are correlated with glacial sands in Landfill Section 6/7 (Sheet 5.49, Glacial sand Unit 1). The thickness of Composite Unit 1 ranges from 0.5 ft to over 50 ft (Sheet 5.53). Two other glacial sand units were also identified in Landfill Section 3/4. Unit 5 occurs in the southern portion of the landfill section and extends under Main Creek into Landfill Section 6/7 (Sheet 5.53). The top of the unit occurs from approximately -50 to -70 ft. Thickness ranges from 2 ft to 14.5 ft (Sheet 5.53). Glacial sand Unit 20 occurs in the southwestern corner of Landfill Section 3/4 (Sheet 5.50). The top surface elevation of Unit 20 ranges from -12 ft to -24.5 ft. Thickness ranges from 1.0 ft to 15 ft.

Glacial lodgement till occurs below most of Landfill Section 3/4. The top surface of the unit generally occurs at -20 ft to -60 ft in the northern portion of the section, and -30 ft to -90 ft in the southern portion (Sheet 5.56). The bottom surface slopes from -40 ft in the north to less than -80 ft in the southwest, and less than -60 in the southeast. The unit shows a slight trend to the south, though the top and bottom surfaces of the unit could be described as undulating. The thickness of the lodgement till unit ranges from 3.5 to 32 ft (Sheet 5.58).

Non-lodgement till also occurs in Landfill Section 3/4. Its deposition is believed to be associated with the ice contact deposition that produced the kame in the east-central portion of the site. It is often interbedded with glacial sand and/or glaciolacustrine silt and clay.

Glacial till layers in boring 3B91:IT901 are marked by a large positive SPR and negative EMI response, which may correspond to a 2.5 ft diameter boulder. Large, positive SPR deflections observed in borings 3B91:IT901 and 903 may also correspond to subsurface boulders. The high SPR response observed in boring 3B91:IT908 is supported by low and erratic EMI responses, which suggests that the glacial till encountered in this borehole is highly resistive.

- ***Cretaceous Deposits***

No Cretaceous sediments occur within Landfill Section 3/4. Identification of Cretaceous pollen in samples analyzed for microfossils, as described in the preceding section, is interpreted to represent redeposited or reworked Cretaceous sediment during glacial or Recent depositional sequences.

- ***Residual Clay***

Residual clay underlies all of Landfill Section 3/4. Sheets 5.68 through 5.70 show the distribution and thickness of residual clay beneath the site. The surface of the unit in the central portion of Landfill Section 3/4 is fairly flat, but the surface in general trends to the southwest. Top surface elevations range from approximately -45 ft in the northern portion to -92 ft in the south central portion (Sheet 5.68). The bottom of the unit shows the same general trend, with a low occurring in the north central area near test boring 3B91:IT901. The bottom surface elevations range from -50 to -120 (Sheet 5.69). The residual clay generally thickens to the north toward IT901, then thins northward away from that area. Observed thickness for the unit across the section ranges from 4 to 58.5 ft. In the northern and western portions of the site, the residual clay is formed from the Lockatong Formation. It is commonly gray, green, or blue in color. The residual clay formed from the Stockton Formation under the remaining portion of the section is predominately red brown clay and silt, with occasional gray coloring.

NG and SPR log responses indicate that areas of the residual clay may contain inclusions of weathered bedrock up to a few feet thick. Based on NG and 16NR thickness weighted log response, the residual clay identified in Landfill Section 3/4 appears to be siltier than that found in other landfill sections.

- ***Bedrock***

The surface of the bedrock beneath Landfill Section 3/4 shows a general trend to the south, with top surface elevations ranging from approximately -40 ft in the northern portion to -100 ft near the southwest corner (Sheet 5.74). A bedrock surface low exists near 3B91:IT901, similar to what was observed in the residual clay surface. A bedrock high exists in the southeast corner of the section, which may explain, or be a factor in, the sinuous path of Main Creek near its juncture with the Fresh Kills.

Weathered bedrock occurs on the bedrock surface throughout most of the section, with the exception of isolated areas in the north and west (Sheet 5.71). The general trend of the top surface of the weathered bedrock is to the southeast; however, the surface undulates in the center down to almost -100 ft. It slopes up to about -50 ft and then slopes down again to over -100 ft in the southeast corner of the section (Sheet 5.71). The bottom surface of the weathered bedrock undulates to the southeast, ranging in elevation from approximately -45 ft to -120 ft (Sheet 5.72).

In general, the weathered bedrock unit thickens toward the center of the section, with thickness ranging from approximately 5 to over 100 ft (Sheet 5.73).

Two types of bedrock occur beneath Landfill Section 3/4; the Lockatong Formation and the Stockton Formation. The Lockatong Formation is found in the north and west portions of the section. It is commonly a very light gray to grayish black and grayish green shale. The Stockton Formation is found in the southeast area of the site. It is primarily composed of red brown shale and siltstone.

5.4.4.6 Summary

Refuse/fill was identified in all the IT series test borings and well borings drilled in this landfill section. Analysis of historic topographic maps indicates that Recent deposits should be present over almost the entire section since the area represents a former tidal marsh environment (Figure 5.18). Refuse/fill occurs above the Recent deposits except for the area below the kame feature (topographic high), where it occurs above glacial deposits. Recent silt and clay and/or peat is usually found directly below the refuse/fill. There is an area in the north and central part of the Landfill Section where Recent sand is found to be in contact with the refuse/fill. The Recent sand is laterally extensive beneath most of the landfill section. When the sand is not present at the top of the Recent sequence, it is found below the silt and clay or peat. In areas of the Landfill Section, the silt and clay, peat and sand occur as interbedded units.

The Recent deposits are underlain by glaciolacustrine silt and clay beneath the entire section with the exception of a location in the east central portion of the landfill where the kame feature existed prior to placement of refuse/fill. Glacial lodgement till, present over most of the landfill section, is found below the glaciolacustrine silt and clay. Non-lodgement glacial till is often encountered interbedded with glacial sands and glaciolacustrine silt and clay associated with the kame deposit.

Three glacial sand units were identified in Landfill Section 3/4. The sand is often interbedded with non-lodgement till or glaciolacustrine silt and clay. Most of the glacial sands are associated with ice marginal deposition that formed the kame feature in the east central portion of the section (Figure 5.13, "B"). Two of these units are correlated beneath Main Creek to glacial sand units in Landfill Section 6/7.

A relatively thick residual clay is present below the glacial deposits and underlies the entire section. The residual clay is formed from the Lockatong Formation in the northern and western portions of the section, and from the Stockton Formation in the remaining portion of the landfill section. The surface of the residual clay unit in the central portion of the section is fairly flat, however, section-wide the clay shows a general dip to the southwest. The bedrock surface in Landfill Section 3/4 trends to the southwest. The Lockatong Formation occurs in the north and west portion of the section, and the Stockton Formation occurs in the southeast portion of the section.

5.5 Fresh Kills Landfill Geology - Integrated Analysis

5.5.1 Introduction

This chapter began with an overview of the regional and local geology in the area of the Fresh Kills Landfill. It presented the established stratigraphic units present at the Fresh Kills landfill site. These units consist of discrete refuse/fill, overburden and bedrock units. The stratigraphic subdivision was based on four related, but independent analytical methods: lithologic examination of soil and rock core samples, piezo-electric cone penetration testing, downhole geophysical analysis, and microfossil analysis. A review of the characteristics of stratigraphic units determined by these analytical methods was followed by a summary of the stratigraphic correlation process.

The combination of the development of a stratigraphic column and the process of correlation leads to the development of a geologic framework that is representative of the geology of the site. This framework is the three-dimensional spatial geometry of different types of geologic deposits. Such a framework, considered with an understanding of the sedimentary environments of deposition, can be referred to as a geologic model.

The dominant characteristic of the Recent, Pleistocene, and Cretaceous strata is the predominance of fine grained (silt and clay) material. These fine grained materials can be correlated across the site as individual lithostratigraphic units, or aggregately as a composite stratum. This method of correlation is demonstrative of a layer-cake model. However, included within this fine grained framework are coarse grained, sandy materials that occur as layers, lenses, stratified drift and channel deposits. Some of these coarse-grained materials along with the fine-grained materials may be representative of time-transgressive facies. The correlation of sand units in many places

is difficult. It is possible that sand units that do not appear to be correlative in plan view and/or profile are interconnected due to the depositional patterns of the time transgressive sequences.

The following discussion is intended to serve as an integration of the geologic data. The individual landfill section data is integrated and presented at a site-wide level, focussing on stratigraphic units and textural descriptions for each unit. Figures 5.26A and 5.24B provide a summary of the generalized geologic section and textural description of sediments and bedrock at the project site. This discussion is followed by a detailed vertical perspective of the occurrence of stratigraphic units beneath the site. Finally, the three-dimensional spatial relationship of the geology of the Fresh Kills Landfill site is presented as a means for subsequent analysis of groundwater flow and solute transport.

5.5.2 Site-wide Overview

5.5.2.1 Stratigraphic Units

- ***Recent Deposits***

Peat occurs in the former tidal marsh areas throughout the landfill site (western portion of Landfill Section 1/9, northern portion of Landfill Section 2/8, most of Landfill Sections 3/4 and 6/7). Thickness of the peat is usually on the order of a few feet. It tends to occur near the top of the Recent sequence. In cross-section, it appears to be sporadically distributed, however, in plan view, it appears to be common and extensive in some former tidal marsh areas (Sheet 5.31). As discussed in Section 5.4, the peat may be more common and correlative than what is indicated by conventional borehole data. During conventional borehole advancement, samples directly below the refuse may not have been taken due to overdrilling, or recovered due to the soft nature of the soil. Piezo-electric cone penetration test (P-ECPT) borings recover soil data continuously and with little disturbance, eliminating many of the problems experienced at the site with regard to shallow sample recovery by conventional drilling methods. P-ECPT's show a more consistent delineation of the top, bottom, and thickness of the peat. The generalized textural description[3] of the peat is: Black PEAT, trace to little Silt and Clay, trace fine Sand.

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[3]Principal soil components are fully capitalized; minor components are described by a series of proportional terms representing percentage by weight of sample, as follows: trace (1-10%), little (10-20%), some (20-35%), and (35-50%).

Recent silt and clay occurs throughout most of the site with the exception of the northwestern portion of Landfill Section 3/4, eastern portions of Landfill Section 6/7, eastern portions of Landfill Section 1/9, and the southern and part of the northern portions of Landfill Section 2/8 (Sheet 5.33). When it occurs, it is usually the unit located directly below the refuse. Since peat and sand often occur interbedded with the silt and clay, it is difficult to generate representative thickness maps for the silt and clay. When associated with Recent sand, it tends to occur above the sand unit. The generalized textural description of the Recent silt and clay is: Light gray to black CLAY and SILT, trace fine Sand, or dark gray Organic SILT, trace fine Sand.

The Recent sands are limited to the former tidal marsh environments and occur as either channel or sheet-like deposits. Generally, the Recent sand tends to occur at the base of the Recent sequence. When it occurs at the top of the Recent sequence, it is in direct contact with the refuse/fill. In Landfill Section 2/8 the sand occurs primarily in the northern portion of the landfill section. In Landfill Section 3/4 the sand occurs with a consistency that suggests distribution as a layer or sheet-like deposit. Recent sand is encountered in the western and extreme southern portion of Landfill Section 6/7. However, it is absent in many former tidal marsh locations in Landfill Section 6/7, which suggest the possibility of limited horizontal correlation. In the western portion of Landfill Section 1/9, along the Arthur Kill, Recent sand occurs as two distinct layers; an upper layer that occurs near sea level and a lower layer extending to depths greater than -60 ft. These layers are separated by Recent silt and clay and peat. Eastward, toward the upland portions of Landfill Section 1/9, the sand becomes thinner and more scattered in occurrence. As mentioned previously, the apparent isolated, discontinuous occurrences of Recent sand may be related to a time transgressive channel sequence, and may in fact be more extensive than delineated by the test borings. The correlation of the Recent sand was performed with this possibility in mind and is represented on contour maps mostly as sheet-like deposits. The generalized textural description of the Recent sand is: Light gray to black SAND, trace to little Silt and Clay.

A problem that was encountered in delineating the thickness of the Recent deposits was the occasional overdrilling of a portion of the Recent deposits. This periodically occurred because samples were generally not obtained in refuse, and if sampling was not initiated at the appropriate depth, the upper portion of the Recent deposits may have been missed. In some cases, refuse sloughing into the hole resulted in little or no sample recovery in the Recent deposits. Comparison of the thickness of Recent deposits in the correlation piezo-electric cone penetration test borings to the adjacent conventional test borings provided data to confirm this situation, and

allowed for more accurate definition of Recent deposits along the perimeters of Landfill Sections 1/9 and 6/7.

The Pre-Holocene (Recent) surface map (Sheet 5.75) shows the post-glacial terrain that probably existed prior to deposition of Recent sediments. The higher elevations represent glacial till or Cretaceous uplands where little, if any, Recent sedimentation occurred. The former proglacial lake beds or glaciolacustrine deposits are found primarily below elevation 30 ft and formed the base for most Recent sediment deposition. The tidal marshes formed in areas approximately elevation 0 ft and lower.

In summary, Recent sediments, which are predominantly silt and clay, are found nearly site-wide in the areas of former tidal marsh environments. The peat deposits are somewhat laterally discontinuous and extensively interbedded with the silt and clay. One Recent sand unit is correlative across a large portion of the site. Other sand units occur as localized deposits in each landfill section. The sands were deposited in sinuous channels within the tidal marsh silt and clay stratum or as sheet deposits. The channel deposits can appear discontinuous in plan and profile view. The potential for these channel sands to be interconnected exists based on the depositional processes of a transgressive depositional system in which they were deposited. In portions of each landfill section, the Recent sand appears to occur as laterally continuous sheet deposits. The potential for interconnection and pathways for leachate migration is discussed in detail in Sections 5.5.2.3.

- ***Pleistocene Deposits***

Glaciolacustrine silt and clay occurs over much of the project area (Sheet 5.41). The primary areas where it is absent is in the southern, western, east central, and northwest portions of Landfill Section 1/9; southern portion of Landfill Section 2/8; and the extreme eastern portion of Landfill Section 6/7. The silt and clay unit is restricted to lower elevation terrain. It ranges from a few feet to several tens of feet thick, the thickest sequence being in the western portion of Landfill Section 6/7. Layered or laminated glaciolacustrine silt and clay primarily occurs in areas of the landfill where the unit is thickest. These areas are northern Landfill Sections 1/9 and 2/8, east central Landfill Section 1/9, western and southern Landfill Section 6/7, and western and north central Landfill Section 3/4. The glaciolacustrine silt and clay appears to be siltier in the eastern portion of Landfill Section 1/9 and in all of Landfill Section 6/7, based on the apparent decrease in average NG log response and increase in average EMIR log response throughout this area (Figure 5.27). Frequent interbeds of non-lodgement glacial till and glacial sand occur within

the sequence. The generalized textural description of the glaciolacustrine silt and clay is: Moderate red brown SILT and CLAY, trace to little Sand, trace to little fine Gravel.

Glacial sand is found throughout the site and throughout the glacial sequence (Sheets 5.49 and 5.50). The majority of the glacial sand found at the site is associated with kame features that occur in Landfill Sections 1/9 and 3/4 (Figure 5.13, "A" and "B"). Based on the glacial depositional model and boring data (e.g., 3B91:IT904 and 906 and 1B93:IT542 through 548), it is likely that the stratigraphic and structural configuration of the sand bodies within the kame features is complex due to interbedding with non-lodgement glacial till/diamict and occasionally glaciolacustrine silt and clay. The glacial sand units that extend away from the principal kame deposits would form continuous lateral pathways. However, the interbedding with the non-lodgement tills makes correlation of the kame sands difficult. Correlative Kame "A" sands probably extend westward into the central portion of Landfill Section 1/9, eastward into Landfill Section 2/8, and possibly beneath Richmond Creek into Landfill Section 6/7. Correlative Kame "B" sands probably extend westward to west central Landfill Section 3/4 and under Main Creek into northwestern Landfill Section 6/7, and possibly to the eastern portion of Landfill Section 6/7. Several glacial sand units have been identified throughout the site which are separate from the kame complexes. These include sand units probably deposited by streams flowing into the eastern portion of Landfill Section 6/7. The generalized textural description of the glacial sand is: Moderate red brown SAND, trace to little Silt and Clay, trace to and Gravel.

Glacial till/diamict is found below most of the site. The glacial till/diamict is composed of two separate units; lodgement till and non-lodgement till/diamict. Lodgement till occurs as a relatively continuous unit at the base of the glacial sequence (Sheet 5.56). It is absent in the southern portion of Landfill Section 2/8, the east central, northeastern, western and southwestern portions of Landfill Section 1/9, and isolated areas of Landfill Sections 3/4 and 6/7. Most of the lodgement till that is absent was probably eroded away by meltwater or removed during landfilling activity. Non-lodgement till/diamict is found within the glacial sequence as melt-out till, flow till, water-laid till and turbidities. The kame features are composed of a fairly large amount of non-lodgement till that is interbedded with glacial sand. Non-lodgement tills also occur throughout the glaciolacustrine sequence at the site as water laid till, turbidities, melt-out till and flow till. The generalized textural description of the glacial till/diamict is: Moderate red brown SILT and CLAY, little to and Sand, little to and Gravel.

The pre-Pleistocene surface (Sheet 5.76) is more complex than the pre-Holocene (Recent) surface due to the absence of Cretaceous sediments in the northern portion of the site. The residual clay

or bedrock defines the pre-Pleistocene surface in this northern area. Due to post-Cretaceous erosion, especially glacial erosion, this map may represent very little of the original pre-Pleistocene topography. The Pleistocene sequence constitutes a site-wide unit, dominated by fine-grained material. The fine-grained unit can be divided into two discrete sub-units, glaciolacustrine silt and clay and glacial till/diamict. Coarse-grained deposits (glacial sand) are present within the fine-grained unit. The sand deposits are usually localized, although there are areas in the site where the sand is laterally extensive and correlatable, specifically the sand associated with the kame deposits. The potential for interconnection and pathways for leachate migration is discussed in detail in Sections 5.5.2.3.

- ***Cretaceous Deposits***

The Cretaceous sediments occur over most of the landfill south of Fresh Kills/Richmond Creek (Sheets 5.60 and 5.62). The Cretaceous sediments were deposited primarily in a subaerial (continental) deltaic environment by braided or meandering systems. The braided system has a high gradient and is predominately composed of coarse-grained sediments. The meandering system occurs in a relatively flat, broad depositional plain, very close to sea level and is characterized by both fine and coarse-grained sediments. These depositional systems result in complexly stratified deposits that are difficult to map using conventional methods. The Cretaceous sediments represent a classic, time-transgressive depositional sequence, however, a simple layer-cake distribution of sediment can be recognized (i.e., an upper silt and clay unit and a basal sand unit). Clay and silt units do however occur within the basal sand and sand units do occur within the silt and clay unit.

Along the Cretaceous escarpment at the northern extent of the Cretaceous deposits, the sands and silt/clay units occur in a non-uniform pattern, mainly as a result of glacial erosion. In addition, the Cretaceous sediments are undulating and tilted so that the resulting exposure at the escarpment is varied and non-uniform. The exposure of Cretaceous sand to other transmissive units along the escarpment is possible. In Landfill Section 2/8, the glacial sand associated with the kame deposit appear to be in contact with Cretaceous sands along the escarpment.

The basal sand unit has been correlated across a large portion of the southern area of the Fresh Kills Landfill site. It is thickest in Landfill Section 1/9, gradually thickening to the south, and thinning to the east in Landfill Sections 2/8 and 6/7. The sand units above the basal sand are more difficult to correlate; however, correlations have been made in these upper units in portions of Landfill Sections 1/9 and 2/8. Cretaceous sands occur at the top of the Cretaceous sequence

in several locations (Sheet 5.80). In the areas where Recent or glacial sediments are absent in Landfill Sections 1/9 and 2/8, the Cretaceous sand would be in contact with refuse/fill when it occurs at the top of the Cretaceous sequence.

Silts and clays are the principal materials of the upper portion of the Cretaceous sequence. The upper silt and clay unit shows an overall thickening to the south. East to west, it is fairly uniform in thickness. The unit is thin in the east central portion of Landfill Section 1/9, due primarily to the presence of thick sand deposits. In the extreme eastern portion of the landfill site (southern portion of Landfill Section 6/7), the silt and clay decreases in thickness. Sands within the silt and clay in the upper portion of the Cretaceous sequence may provide pathways for leachate migration. The potential for these sands to be interconnected is discussed in detail in Section 5.5.2.3.

The Cretaceous silt and clay appears to become siltier throughout the west central portion of Landfill Section 2/8, as indicated by the apparent decrease in average EMIR log response (Figure G.2, Appendix G). The clay content of the clay/silt stratigraphic unit may increase toward the center of Landfill Section 1/9, based on the increased average NG log response in this area.

The generalized textural description of the Cretaceous silt and clay is: Light gray to black or moderate red brown and light gray CLAY and SILT, trace fine Sand; and for the Cretaceous sand: Very light gray to dark gray SAND, trace to little Silt and Clay.

Questions of regional importance were raised by microfossil analysis of the Cretaceous sequence at the Fresh Kills Landfill. Most of the Cretaceous sediment that yielded microfossils was identified as belonging to a Lower Cretaceous pollen zone (Pollen Zone II). A review of literature the Cretaceous geology of New Jersey, Long Island, and Staten Island, adjacent to the Fresh Kills landfill site did not indicate that Lower Cretaceous strata was present in this region. Some studies have established the presence of Lower Cretaceous sediment in southern New Jersey and other areas south of Staten Island, indicating a possible correlation of the sediments identified as Lower Cretaceous beneath the Fresh Kills Landfill site to the sediments found in these areas.

In an attempt to corroborate the microfossil analysis indicating a Lower Cretaceous age for the sediments at the Fresh Kills site, select samples were examined independently by another palynologist, Dr. Gilbert Brenner (Appendix H). Some disagreement was noted through this

analysis, especially regarding the presence of Zone II (Lower Cretaceous) age sediment (Table 5.1 and Appendix H). Although final review (Appendix H) indicates a greater similarity between the two analyses. It can be concluded that the Cretaceous sediment below the Fresh Kills Landfill is at least Zone III to IV in age (Lower Cretaceous/Upper Cretaceous transition zone to Upper Cretaceous). This age determination suggests the potential for correlation of at least a portion of the Cretaceous sediment beneath the landfill to the Cretaceous sediments in adjacent areas.

- ***Residual Clay***

Residual clay occurs throughout Landfill Sections 1/9 and 3/4. It also occurs in the northwestern and southeastern portions of Landfill Section 2/8, and the northern and extreme southern portions of Landfill Section 6/7 (Sheet 5.68). It is formed from the in situ weathering of bedrock to a clay unit. It tends to form thicker sequences over the Newark Supergroup bedrock (Stockton and Lockatong Formations), while it is usually absent or thin over the serpentinite or schist. The generalized textural description of the residual clay is: Moderate red brown, red purple, moderate gray, yellow green, or blue green CLAY and SILT, trace fine Sand, trace Gravel.

- ***Weathered and Unweathered Bedrock***

Weathered bedrock occurs across almost the entire extent of Landfill Section 1/9, across the entire extent of Landfill Section 2/8, portions of Landfill Section 6/7, and most of Landfill Section 3/4 (Sheet 5.71). It is fractured, weathered, broken rock above the "competent" bedrock surface (competent, in this context, meaning not weathered). The contact between the weathered bedrock and "competent" bedrock was delineated by calculating bedrock RQD.

Four major bedrock types occur at the Fresh Kills Landfill site (Sheet 5.82). The Lockatong Formation occurs in the western and northern portions of Landfill Section 3/4. The Stockton Formation occurs throughout Landfill Section 1/9, the western portion of Landfill Section 2/8, the southeastern portion of Landfill Section 3/4, and the northwestern half of Landfill Section 6/7. A sandy facies of the Stockton Formation occurs in specific areas beneath the site (Sheet 5.82). Serpentinite occurs in the southeastern portion of Landfill Section 2/8 and southern portion of Landfill Section 6/7. Chlorite schist (6W91:IT157) and talc schist (2W91:IT305) have been identified in the southern portions of Landfill Sections 2/8 and 6/7. They are believed to have formed as alteration products of the serpentinite body. The occurrence of what appears to be

Manhattan Schist in test boring 2W92:IT310 is consistent regarding the type of basement rock expected beneath the coastal plain in this area based on the literature review.

The bedrock surface shows a general slope to the south below the landfill site. Locally, the surface slopes to the southeast through Landfill Section 3/4, and from east to west in Landfill Section 6/7. A bedrock low or "trough" occurs between Landfill Sections 3/4 and 6/7. This low may be an extension of the buried channel that was cut into bedrock to the north of the site, as documented by Lovegreen (1974).

5.5.2.2 *Vertical Perspective of Stratigraphic Units*

The preceding discussion presented an overview of the site on a stratum-by-stratum basis, providing an understanding of the horizontal extent of the strata. An understanding of the vertical extent of the strata is equally important, given the goals of this investigation of defining potential pathways for leachate migration. The following discussion adds a vertical perspective, enabling a three-dimensional evaluation of the landfill site. Special attention is given to the distribution of the transmissive sand units.

The primary references for the vertical perspective evaluation are horizontal depth section maps (Sheets 5.85 to 5.92). The horizontal depth section maps are constructed to cover five foot intervals every 10 feet, starting at elevation zero. The geologic cross sections (Sheets 5.6 through 5.27) and the maps showing the distribution of geologic units at the top surface of the time stratigraphic units (Sheets 5.78 to 5.81) were also used.

The horizontal depth sections show the lateral distribution of, and apparent contact between stratigraphic units at specific depth intervals. It is important to note that the apparent contact between transmissive units as indicated on horizontal depth section maps may lead to misinterpretation due to several factors. For example, the presence of more than one unit within a five foot interval, the dip or inclination of individual units, and the lateral spacing of data points (borings and wells) need to be taken into consideration when evaluating horizontal depth section maps. Potential interpretation problems based solely on horizontal depth slices can be demonstrated through the evaluation of horizontal depth sections covering Landfill Section 3/4. The horizontal depth sections constructed at -60 to -65 feet and -70 to -75 feet (Sheets 5.91 and 5.92) show glacial sand in contact with weathered bedrock/bedrock in various locations in Landfill Section 3/4. Due to the factors presented above, the apparent contact between glacial

sand and weathered bedrock/bedrock based on the horizontal depth sections is misleading. The borings performed in Section 3/4 have defined a laterally continuous residual clay layer (Sheet 5.68) that is between 20 and 40 feet thick (Sheet 5.70). Having defined the stratigraphic column in Section 5.31, it is known that glacial sand occurs above residual clay, which in turn occurs above weathered bedrock/bedrock. Therefore, since residual clay occurs as a laterally continuous unit, as defined by the available database, glacial sand cannot be in contact with weathered bedrock/bedrock, as it appears to be on the horizontal depth sections for the intervals of -60 to -65 feet and -70 to -75 feet.

The following discussion of the vertical perspective of the strata present below the Fresh Kills landfill site is presented in a manner that defines the potential vertical extent and interconnectedness of stratigraphic units and vertical pathways for contaminant migration. Subsequently, the vertical extent evaluation is integrated with the horizontal extent evaluation to determine the three-dimensional distribution of transmissive units, which is presented in Section 5.5.2.3. The vertical and horizontal extent of transmissive units presented in a three-dimensional perspective allows for a comprehensive hydrogeological evaluation.

Except for the areas shown on Sheet 5.28, refuse/fill occurs over most of the upper vertical sequence of the Fresh Kills Landfill site. It is the primary unit through the vertical sequence from the present ground surface to sea level, especially in the former tidal marsh areas. Areas where strata other than refuse/fill occur above sea level are in the southern portions of Landfill Sections 1/9 and 2/8, the eastern portion of Landfill Section 6/7, and at the location of the kame feature in Landfill Section 1/9 (Figure 5.13, "A"). Below sea level, the vertical extent of the refuse/fill begins to decrease (Sheet 5.85) until it is no longer present in the vertical section below elevation of -25 ft (Sheet 5.88).

Peat occurs between elevations of 0 ft to -30 ft. It is present at the top of the Holocene sequence (directly below refuse/fill) in many small areas throughout Landfill Section 6/7, the northern, east-central, and southwestern portions of Landfill Section 3/4, the north and northeastern portions of Landfill Section 2/8, and in scattered locations in the western portion of Landfill Section 1/9. It is present in very limited areas from sea level to -5 ft (Sheet 5.85). Its occurrence increases with depth to the -10 to -15 ft interval where it comprises much of the Holocene sequence. Most occurrences within that interval are in the western portions of Landfill Sections 1/9 and 6/7 (Sheet 5.86). The unit quickly decreases in horizontal extent below the -10 to -15 interval (Sheet 5.87) until it is completely absent from the vertical section at -30 ft.

Recent silt and clay occurs from approximately 10 ft above sea level to -35 ft. It is present at the top of the Holocene sequence (directly below refuse/fill) in most of Landfill Section 6/7, in areas throughout Landfill Section 3/4, in the north and northeast portions of Landfill Section 2/8, and north and west portions of Landfill Section 1/9. It is rarely found above sea level, but where it does occur above sea level, it is probably related to Recent stream sedimentation in these locations. From about 0 to -10 ft in elevation it is found around the boundaries of Landfill Sections 1/9, 3/4 and 6/7. It occurs at higher elevations around the boundaries of the landfill sections probably because the refuse/fill is thinner and possibly did not compact the sediment as much as in the center of the sections, where the refuse/fill is thicker and heavier. From -10 to -20 ft it extends into portions of the center of Landfill Sections 1/9, 3/4 and 6/7. In Landfill Section 2/8 it occurs in limited areas of the northern and northeastern portion of the site from -10 to -15 ft (Sheet 5.86). From -20 to -30 ft it is gradually replaced by Recent sand in western Landfill Section 1/9 and by glaciolacustrine silt and clay, or Recent sand and glaciolacustrine silt and clay in northern Landfill Section 1/9 and Landfill Sections 3/4 and 6/7 (Sheet 5.88). It does not occur below an elevation of -35 ft.

Recent sand occurs between elevations of 10 ft to -70 ft. It occurs at the top of the Holocene sequence (directly below refuse/fill) in areas in the central and northern portions of Landfill Section 3/4 and in areas in the north and western portions of Landfill Section 1/9 (Sheet 5.78). Occurrences above sea level are rare. In the northern portion of Landfill Section 1/9 it extends vertically from an elevation of 0 ft to -25 ft. In west of Section 1/9 it extends down to -70 ft, although in the interval from approximately -5 ft to -25 ft, it is interfingered with Recent silt and clay and peat. From a depth of -30 ft to -70 ft it is in contact with some of the glacial and Cretaceous sands present in that portion of the section (Sheets 5.93 and 5.94). It is also in contact with glacial sand in two small areas in the northeastern portion of Landfill Section 1/9 (Sheet 5.93).

In Landfill Section 3/4 Recent sand first occurs in the central portion of the section from elevation 0 ft to -10 ft. The sand obtains its maximum lateral extent across the section in the interval from -10 to -25 ft, and is gradually replaced by glaciolacustrine silt and clay or glacial sand followed by glaciolacustrine silt and clay by elevation -35 ft (Sheets 5.86 through 5.88). In Landfill Section 6/7, Recent sand first occurs at elevation -10 ft in the southern portion of the site, and increases in depth of occurrence to -30 ft in the north. It overlies glaciolacustrine silt and clay or glacial sand then glaciolacustrine silt and clay (Sheets 5.86 to 5.88). It appears that Recent sand may be in contact with refuse/fill between elevations -15 to -20 ft in the northern

portion of the landfill section. Recent sand was encountered in Landfill Section 2/8 from -10 to -20 ft.

Recent sand appears to be in contact with glacial sand in three locations in the central portion of Landfill Section 3/4 and in one location in the western portion of Landfill Section 6/7 (Sheet 5.93).

Glaciolacustrine silt and clay usually occurs from elevations 5 ft to -85 ft. It occurs most often as the upper unit of the Pleistocene sequence in Landfill Sections 2/8, 3/4 and 6/7, and in the northern portion of Landfill Section 1/9. The highest elevations at which glaciolacustrine deposits occur are in the upland portions of the landfill site and against the kame features (Sheets 5.86 to 5.87). These deposits extend into most of Landfill Sections 3/4 and 6/7 and the northern portion of Landfill Sections 1/9 and 2/8. At elevation -35 ft, the glaciolacustrine silt and clay deposits are at their maximum horizontal extent. They are present in the northern portions of Landfill Section 1/9 and 6/7 and western Landfill Section 3/4 for tens of feet until they are totally replaced by either glacial till or residual clay at an elevation of -85 ft (Sheet 5.92).

Glacial sand occurs from elevations above sea level to -75 ft. It occurs at the top of the Pleistocene sequence in many locations across Landfill Section 6/7, in three locations in the western portion of Landfill Section 3/4 and in several locations in Landfill Section 1/9 (Sheet 5.79). Its main area of occurrence is in association with the kame features. In Landfill Section 1/9, the sand extends vertically from 10 ft to -45 ft. It is potentially in contact with refuse at 10 to 5 ft, 0 to -5 ft, and -15 to -25 ft. It appears to be in contact with Cretaceous sand in the interval from -20 to -50 ft (Sheets 5.87 to 5.90). The kame and associated sands in Landfill Section 3/4 extend vertically as a potentially correlative unit from -20 ft to -70 ft. It may be in contact with Recent sand to the north, which implies a possible indirect interconnection with refuse/fill. The glacial sand in this area is underlain by glacial till and residual clay. The kame sediments at both locations are capped by glacial till or glaciolacustrine silt and clay (Sheet 5.79), with the exception of the area near 1B91:IT505, minimizing the chance that the glacial sands are actually in contact with refuse/fill or Recent sand.

Glacial till/diamict occurs from above sea level to less than -100 ft. It occurs at the top of the Pleistocene sequence in the eastern portion of Landfill Section 6/7, the central portion of Landfill Section 3/4, and scattered portions of Landfill Sections 1/9 and 2/8. The higher elevation occurrences are lodgement till in the existing or former upland areas and non-lodgement till at the top of the kame features. In northern Landfill Section 2/8, it occurs close to sea level and

in association with glacial sands, suggesting a possible ice marginal (flow till) origin. From -30 to less than -100 ft it occurs beneath most of the landfill site. It is probably lodgement in nature in this interval. It occurs at the lowest elevations in the northern portion of the landfill site.

Cretaceous clay and silt extends from above sea level to -110 ft. It occurs at the top of the Cretaceous sequence throughout much of Landfill Sections 1/9 and 2/8 (Sheet 5.80). It occurs above sea level in the southern portions of Landfill Section 2/8 and the southeast portion of Landfill Section 1/9. Below sea level it gradually increases in depth as it extends northward. It is found interbedded with Cretaceous sand. It is absent from the landfilled areas of Landfill Section 2/8 at elevations deeper than -75 ft and absent from the northern portion of Landfill Section 1/9 at elevations less than -85 ft, being replaced by Cretaceous sand followed by residual clay. It is limited to the southeastern portion of Landfill Section 1/9 and the southern portion of Landfill Section 6/7 below -90 ft. The unit is totally replaced by Cretaceous sand then residual clay or bedrock before the depth of -110 ft is reached.

Cretaceous sand occurs from above sea level to an elevation greater than -140 ft. It is present at the top of the Cretaceous sequence in many portions of Landfill Sections 1/9 and 2/8 (Sheet 5.80). Cretaceous sands that occur along the southern border of Landfill Sections 1/9 and 2/8 from above sea level to -10 ft and in the southeastern portion of Landfill Section 2/8 apparently occur as isolated units, separate from Cretaceous sand strata that occurs below these sand units (Sheets 5.85 to 5.87). At depths below -5 ft the Cretaceous sands expand into the central portion of Landfill Section 2/8. Cretaceous sands are absent from the central and eastern areas of Landfill Section 2/8 at depths lower than -110 ft, being replaced by residual clay or bedrock. The unit occurs in the northern portion of Landfill Section 1/9 from elevations of -30 ft to -55 ft (Sheets 5.88 to 5.90).

Cretaceous sand first occurs in east central Landfill Section 1/9 at elevations of -5 to -10 ft and at the southern border of Landfill Sections 1/9 and 2/8 at elevations of -15 to -20 ft. The unit then gradually expands to the west with depth from the east central and southeastern areas of the section. The sand is correlative but extensively interbedded with Cretaceous clay and silt to an elevation of -70 ft. There is an area in the east central portion of Landfill Section 1/9 in which Cretaceous sand occurs vertically continuous from -5 to -70 ft (Sheets 5.86 through 5.92). Deeper than -70 ft, the Cretaceous sand and clay and silt occur separately, the sand in the south-central portion of the landfill section, and the clay and silt in the southern portion. With increasing depth, the sands expand to the southeast where they begin replacing the clay and silt until -110 ft in elevation where they totally replace the clay and silt. The sand unit gradually

migrates to the southeast where it is replaced by residual clay. No Cretaceous sand is present at Landfill Section 1/9 beneath elevation -130 ft. At higher elevation locations (above sea level to -25 ft) in the southeast corner and central portion of Landfill Section 1/9 and the central and southeastern portion of Landfill Section 2/8 the sand may be in contact with refuse/fill (Sheets 5.85 through 5.87).

The potential interconnection of the Cretaceous sand and Recent sands is limited to the western and south central portion of Landfill Section 1/9 (Sheet 5.94). It also has the potential for interconnection to the glacial sands related to the kame feature in western and north central Landfill Section 1/9 and west-central and central Landfill Section 2/8 (Sheet 5.95). These interconnections are important because they represent areas where pathways may exist between the refuse/fill and the Cretaceous sand (Sheets 5.85 through 5.92).

Residual clay occurs from elevations of -35 ft to elevations below -200 ft. The residual clay occurs at the top of the pre-Cretaceous sequence beneath Landfill Sections 1/9 and 3/4 and in portions of Landfill Sections 2/8 and 6/7. It first occurs in Landfill Sections 3/4 and 6/7 at -35 ft, northeastern Landfill Section 1/9 at -45, and western and eastern Landfill Section 2/8 at -50 ft (Sheets 5.89 to 5.90). In Landfill Section 3/4 it expands with depth until it covers much of the site at -80 ft, then is gradually replaced by bedrock to a depth of -120 ft where it no longer occurs. In northern Landfill Section 6/7 it occurs from elevations -35 to -100 ft. In the extreme southern portion of Landfill Section 6/7 is occurs from -115 ft to almost -150 ft. In the northern portion of Landfill Section 2/8 it occurs from -50 to -75 ft and in the southern portion from -70 to -130 ft. In the northern portion of Landfill Section 1/9 it occurs from -45 ft to -135 ft and in the southern portion from -65 ft to deeper than -200 ft.

Bedrock occurs at the top of the pre-Cretaceous sequence in portions of Landfill Sections 2/8 and 6/7 (Sheet 5.81). Serpentinite bedrock is found at the highest elevations, occurring as high as 20 ft below sea level in Landfill Sections 2/8 and 6/7. Newark Supergroup bedrock first appears at an elevation of -65 to -70 ft in the central portion of Landfill Section 3/4 and the northwest portion of Landfill Section 1/9. The lowest elevation bedrock surface occurs in the southern portion of the site.

5.5.2.3 Three-Dimensional Distribution of Coarse Grained Units

The previous two sections (5.5.2.1 and 5.5.2.2) presented an overview of the lateral and vertical extent of the stratigraphic units beneath the Fresh Kills Landfill site. To determine the three-dimensional spatial relationship of the unconsolidated sediments, and ultimately the potential pathways for leachate migration, all available interpretive methods must be utilized. These methods include:(1) sand unit maps; (2) surface contour maps; (3) isopach maps; (4) time-stratigraphic unit surface maps; (5) geologic cross-sections; (6) horizontal depth slices; (7) depositional models; and (8) historic topographic maps and aerial photographs.

Volumetrically, the unconsolidated sediments beneath the site are predominately fine grained. The coarse grained units distributed throughout the fine grained sediments represent potential pathways for lateral and vertical migration of leachate. The lateral distribution of the coarse grained units for the Recent, glacial, and Cretaceous stratigraphic sequences, summarized on Figures 5.32 through 5.34, together with unit thickness data provided in Tables 5.8 through 5.17, provides a starting point for the subsequent analyses of groundwater flow and solute transport. When appropriate, the interrelationship (i.e., interconnection and correlatability) of coarse grained units is discussed on a site-wide basis, rather than an individual section by section basis.

- **Recent Sand Spatial Relationships**

The uppermost coarse grained unit at Fresh Kills is the Recent sand. Based on the depositional model and observed distribution, it is interpreted that much of the Recent sand at the site was probably deposited as sinuous channel deposits in a transgressive depositional system. Review of historic topographic maps and aerial photographs indicates numerous tidal channels were present within the tidal marsh prior to the placement of refuse/fill. In a transgressive depositional sequence, channels migrate laterally and vertically over time. Therefore, it is possible that the channel sands may be more extensive than defined by the boring program. The sands may also be interconnected and extend inward toward the center of the landfill sections, even though they appear to be isolated lenses in plan and profile view in many cases. Potential vertical pathways for leachate migration into the lower, Recent sand units and/or other coarse grained sediments would be present if the channels eroded through the Recent silt and clay/peat layers and/or if the channel deposits occurred as continuous vertical or aggradational deposits (i.e., time transgressive sand sequences) through the Recent sequence. The Recent sands may also be in contact with a relatively large pre-landfill excavation that exists in the central portion of Section 1/9 (Sheet 5.83) that may provide an interconnection with lower elevation coarse grained units.

Recent sand has been interpreted to occur as fairly continuous sheet-like deposits in portions of each landfill section. The stratigraphic evaluation suggests that the sleet-like Recent sand deposits may be interconnected between landfill sections. These areas are Landfill Section 3/4, the PASNY site, and possibly the northern portion of Landfill Sections 1/9 and 2/8, and the northern and western portions of Section 6/7 (Figure 5.36). These occurrences of Recent sand have been delineated as Unit 1. The potential for the interconnection between the Recent sand in Landfill Section 1/9 and areas north of the Fresh Kills may be limited, however, due to scour of the Fresh Kill channel bottom (Figure 5.21C). The sand unit is continuous to all surface waters surrounding the site (i.e. Main Creek, Richmond Creek, Fresh Kills, Great Fresh Kills, and the Arthur Kill). In the northern and central portions of Landfill Section 3/4, and isolated areas in Landfill Sections 1/9, 2/8 and 6/7, the sand is in direct contact with refuse/fill. These areas provide potential pathways for leachate to migrate into the Recent sand and laterally across the site where the sand is interconnected.

Adjacent to the Arthur Kill, the Recent sand consists primarily of a thick lower layer and a thinner, more discontinuous upper layer (Sheets 5.6C, 5.36 and 5.37). The upper Recent sand layer (Unit 2) pinches out eastward toward the center of Section 1/9 (Sheet 5.7). The lower layer (Recent sand Unit 1) is overlain by what appears to be a mostly continuous Recent silt and clay layer. Peat is found interbedded with the silt and clay. These fine grained sediments were deposited in the tidal marsh environment that was present prior to the placement of refuse/fill. Most of the lower Recent sand unit along the Arthur Kill (Sheet 5.6) was probably deposited during the late-glacial/post-glacial period. It extends laterally approximately 500 to 1500 ft toward the center of the landfill. It is believed that at that time the depositional environment along the Arthur Kill was different than at present, allowing for the deposition of a thick Recent sand unit as a result of the removal of most of the glacial sediment in that area.

The portion of Recent sand Unit 1 along the western boundary of Landfill Section 1/9 also extends vertically in some locations to a contact with glacial and Cretaceous sand (Sheets 5.93 and 5.94). The interconnection between the Recent, glacial and Cretaceous sands may extend through the entire thickness of the unconsolidated sequence in this area. It should be noted that this interconnection does not occur everywhere at this location, but migrates laterally in a sinuous pattern with depth through the fine grained strata (Sheets 5.6 and 5.85 through 5.92). As mentioned previously, this sand sequence is limited in lateral extent to approximately 500 to 1500 ft in the western portion of the landfill; it thins and eventually pinches out to the east. The Recent sand also appears to become interconnected with Cretaceous sands near the south central

portion of the section (Sheets 5.15A, 5.16B and 5.22). This presumed contact provides a potential pathway for lateral migration of leachate in the Cretaceous sands.

In the northern part of Landfill Section 1/9, in the vicinity of well cluster location IT013, the depositional sequence of the Recent, glacial and Cretaceous sediments is very complex, with time stratigraphic units thinning or thickening across short distances. For example, Recent sand was not encountered in the deep piezometer borehole (1P91:IT013Z), however, a two to three foot Recent sand layer was observed in the adjacent intermediate and deep well boreholes (1W91:IT013I and D), as well as the correlation piezo-electric cone penetration test (1Z91:IT576). Cretaceous sand present in the intermediate depth well (IT013I) and deep piezometer borehole (IT013Z) thinned from approximately 12 ft to two ft in the deep well (IT013D). These wells are all located within 55 ft of each other. Given the stratigraphic complexities, it is possible that an upper Recent sand, to lower Recent sand, to Cretaceous sand pathway exists in this area.

- ***Glacial Sand Spatial Relationships***

The coarse grained sediments associated with the kame deposit in Landfill Section 1/9 (Figure 5.13, "A") may be vertically correlative to depth. The sand units within the kame deposit in Landfill Section 1/9 occur from elevation 10 ft to elevation -45 ft (Sheets 5.85 through 5.89). While thick sand units do occur, they are usually interbedded with glacial till/diamict (non-lodgement). In all but two borings (1B91:IT505 and 1B93:IT542) that penetrated the Section 1/9 kame deposit, the upper unit was a glacial till/diamict. In IT505 the upper unit was a glacial sand; in IT542 the upper unit was a glaciolacustrine silt and clay.

In boring 1B91:IT505, located on the western side of the kame deposit, glacial sand occurs directly below the refuse/fill at an elevation of -24 ft. The geophysical logs run in this boring indicate that the top of the glacial sand occurs at -15 ft. The 1911-12 historic topographic map (Sheet 5.83) shows that native soils should have been encountered at approximately 9 ft in this boring, indicating potential excavation of 24 to 33 ft of native soil, possibly as a part of landfilling activities. The exposure of glacial sand at the top of the sequence may be localized if due to excavation. Nevertheless, the presence of glacial sand in contact with refuse/fill in boring IT505 provides a potential vertical pathway for leachate migration in the coarse grained sediments associated with the kame deposit in Landfill Section 1/9.

The interconnection to other coarse grained sediments, namely Recent and Cretaceous sands, depends on the configuration of the fine grained units that may occur as the uppermost layer of the kame deposit. The degree and potential for downward vertical flow within the kame feature to lower coarse grained strata depends on the correlation and interconnection of the glacial sands within the kame deposit. Evaluation of existing data and general configuration of kame deposits suggests that potential vertical pathways may exist.

Six borings (1B93:IT542, 544, 545, 546, 547 and 548) were performed as part of a supplemental perimeter boring program along the eastern boundary of Section 1/9. These borings, performed at 200 ft lateral spacing, demonstrated the complex configuration of the interbedded sands, tills and occasionally silts and clays within the kame deposits. Based on available data, glacial sand encountered in 1W89:XW-11 (Sheet 5.95) and 1W89:XW-4 (Sheet 5.17A) appears to be in contact with Cretaceous sand. An interconnection between glacial sand and Cretaceous sand is also possible beneath the northern portion of the kame feature (Sheets 5.87 through 5.89 and 5.95).

Prior to landfilling, a stream was present along the eastern side of the kame in Landfill Section 1/9 (in the vicinity of what is now Route 440). The stream flowed in a northerly direction from the uplands (Sheet 5.83). Projections of the base elevation of the stream channel indicate that the stream may have eroded down into the glacial deposits, and in some locations may possibly be in contact with glacial sand. Most of this channel was subsequently filled with refuse/fill, which may place the refuse/fill in contact with the glacial sand at the base and sides of the stream channel.

The glacial sands associated with the Landfill Section 1/9 kame also extend eastward into Section 2/8, where they are less extensive vertically and laterally. The distribution of these sands is believed to involve deposition from meltwater streams flowing on or off of the glacier ice. The interconnection of the sands that extend away from the principal kame feature would be highly dependent on how far laterally the deltas or fans extended as they were deposited by the individual streams. If these depositional centers coalesced, they may extend as a continuous unit to the western portion of Landfill Section 2/8 (Sheet 5.46). These glacial sands may be in contact with Cretaceous sand in the west central to central portion of Section 2/8, which in turn, may also correlate laterally to glacial sands beneath Richmond Creek. These glacial sands extend only a short distance into Landfill Section 6/7 beneath Richmond Creek. They do not appear to correlate with other glacial sand or Cretaceous sand units in Landfill Section 6/7.

Another kame deposit is present at the site in the east central portion of Landfill Section 3/4 (Figure 5.13, "B"). The glacial sands within this deposit appear to be vertically correlative from depths of approximately -20 to -70 ft (Sheets 5.87 to 5.92). Laterally, the sands associated with the kame are limited to the central portion of Landfill Section 3/4, and the northwestern portion of Section 6/7. The potential for the glacial sands to be interconnected with Recent sand exists in the west and east central portions of Landfill Section 3/4. As mentioned during the discussion of the sands associated with the kame deposit in Landfill Section 1/9, the potential for vertical migration of leachate between the Recent sand and glacial sand depends on the interconnection of the glacial sands within the kame deposit and units overlying the kame (Sheet 5.93). The sequence in this area consists of a complex internal and external configuration of interbedded glacial sands, glacial till/diamict and glaciolacustrine silt and clay. The glacial sands associated with the kame deposit in Landfill Section 3/4 and which extend into Landfill Section 6/7 are underlain by fairly extensive glaciolacustrine silt and clay and/or residual clay layers. As discussed in previous sections, the glaciolacustrine silt and clay which extends beneath much of the landfill site is extremely thick in this area (tens of ft). The residual clay layer is 20 to 40 ft thick in this portion of the site (Sheet 5.70).

- ***Cretaceous Sand Spatial Relationships***

In south central Landfill Section 2/8, four borings (2W91:IT306, 2W92:IT321S, 2B91:IT804 and 2P91:IT806) encountered Cretaceous sediments directly below refuse/fill. The interpretation for the lack of glacial deposits in this area is that they were excavated as part of landfilling activities. Analysis of historic topographic maps and aerial photographs tends to support this interpretation. In boring IT806 only two feet of Cretaceous clay and silt was encountered above Cretaceous sand. The 1911-12 historic topographic map indicates that native soil should have been encountered at about 32 ft in this boring. It appears that approximately 33 ft of native soils are missing, probably due to excavation. Shallow monitoring well 2W92:IT321S was terminated after encountering two ft of Cretaceous sand below nine ft of refuse/fill. Due to the shallow penetration of this boring, it is difficult to determine the stratigraphic relationship of the sand to the Cretaceous sequence in Landfill Section 2/8. It is possible, based on the evaluation of borings IT321S and IT806, that at least locally, the Cretaceous sand present at the top of the Cretaceous sequence in Landfill Section 2/8 may be directly in contact with refuse/fill, providing a potential pathway for leachate migration (Sheets 5.10C and D and 5.16D). Direct vertical pathways to depth would occur in areas of channel sand deposits formed through aggradation, as established by the Cretaceous depositional model. No apparent interconnection between the higher and lower elevation Cretaceous sand units was defined by borings in central and eastern

Landfill Section 2/8, indicating that potential leachate migration would be limited primarily to lateral flow within the upper Cretaceous sand unit.

The major areas where vertical pathways may extend down to the laterally extensive basal Cretaceous sand unit are in Landfill Section 1/9. As discussed previously, a thick Recent sand present along the western boundary and which extend eastward toward the center of the landfill section is interconnected with the basal Cretaceous sand unit, providing a potential vertical pathway. In the east central portion of Landfill Section 1/9, a glacial sand associated with the kame deposit is in contact with refuse/fill. In specific portions of the east central portion of the landfill section, glacial sand is in contact with Cretaceous sand (Sheet 5.95). The Cretaceous sand just south of the kame deposit occurs as thick or stacked channel deposits (first observed in 1B91:IT512, and extending southward to the southeast portion of the section), potentially providing a direct vertical pathway. Cretaceous sand appears to contact weathered bedrock in isolated areas. The basal Cretaceous sand unit overlies weathered bedrock along a north-south trend in the central portion of Landfill Section 2/8; an area where residual clay is not present.

- ***Secondary Areas of Interest***

Other than the areas described above, the potential for vertical interconnection of coarse grained units is limited across the Fresh Kills site. In the northeastern portion of Section 6/7, an area of correlative glacial sand occurs. Vertically, the unit is correlative from elevation -10 to elevation -30. While it is possible that this unit may be associated with the kame deposit sands extending from Landfill Section 3/4, it is more likely that this unit was deposited by a stream flowing into the glacial lake that was present at the site, and therefore, associated with glaciolacustrine sedimentation. There does not appear to be a correlation between these sands and the glacial sands associated with the kame in the northwestern portion of the landfill section. It appears that these glacial sands are vertically and laterally isolated from these glacial sands to the west (Sheets 5.86 to 5.92).

Glacial sands are also in contact with Recent sands in the western portion of Landfill Section 6/7. The sand units in this area are underlain by fairly continuous glaciolacustrine silt and clay and glacial till deposits. The lateral extent of the interconnection of these sands is essentially limited to the northern portion of that landfill. The degree of lateral correlative extent of the Recent sand that is seen in Landfill Section 3/4 is not observed in Section 6/7, however areas of Recent sand in the western part of Landfill Section 6/7 are probably correlative (Sheets 5.39 and 5.40).

A glacial sand unit occurs in the southern portion of Landfill Section 6/7 that appears to be associated with glaciolacustrine silt and clay and possibly non-lodgement glacial till deposition (Sheets 5.87 to 5.89). It occurs at a depth between -5 and -50 ft in the section. Laterally it extends beneath the southern quarter of the section and off-site to the east. It appears to be isolated from the glacial sands associated with the kame feature in Landfill Section 1/9 that extend into Section 2/8 and possibly below Richmond Creek into Section 6/7 (Sheets 5.86 to 5.89). A glacial sand unit that extends between Landfill Sections 3/4 and 6/7 does not appear to be associated with either kame deposit that occurs at the landfill site, even though it is located between the two kames.

5.6 Summary and Conclusions

The interpretation of the site geology for the Fresh Kills Landfill site involved a multi-faceted analytical approach. A regional context was established through detailed literature review. Soil boring data from other projects in neighboring areas were studied to provide a more local context. The results of these reviews and studies were presented in the Hydrogeological Literature Review Report (IT Corporation and Wehran Envirotech, 1991a), and summarized in Sections 2.0 and 5.2 of this report.

The results of prior investigations at the Fresh Kills Landfill were reviewed, and when feasible, data were incorporated into this study. The current investigation represents the most detailed and comprehensive study of the geology in the region to date, especially at the sub-regional scale of the project site.

Four different analytical techniques were utilized to determine the geology and stratigraphy of the Fresh Kills Landfill site: lithostratigrahic, geophysical, microfossil, and piezo-electric cone penetration tests. As a result, an enormous volume of data have been collected and analyzed, resulting in a detailed site characterization. The site characterization lead to certain major conclusions that are presented below.

A stratigraphic sequence was defined, comprised of a series of lithologic units, in the following, descending order:

- Refuse and clean fill
- Recent Deposits - predominantly silt and clay, but with layers, lenses, and channel deposits of sand and peat.
- Pleistocene Deposits - predominantly glaciolacustrine silt and clay underlain by glacial lodgement till. Glacial sand mostly occurs associated with two kame-type deposits and lateral associations of the glacial sand (Columbia Group Deposits – primarily silty sands and silt/clay occurring in the southern portion of the site are included with the glacial sand.
- Cretaceous Deposits - sand and silt/clay strata. Most of the sequence consists of interbedded clay/silt and sand, with clay/silt predominating. A sand unit occurs at the base of the sequence.
- Bedrock - several Paleozoic and Mesozoic formations, overlain in most areas by weathered bedrock and residual clay.

The spatial geometry of these lithologic units constitutes the basic geology of the Fresh Kills site. The geology is depicted by various geologic maps, structural contour maps, isopach maps, unit maps, geologic profiles, horizontal depth sections, and schematic diagrams. The geologic framework illustrated by these maps, profiles, and diagrams can be summarized at several levels of scale and detail.

At a gross scale, the geology at Fresh Kills is relatively simple, consisting of three different lithologic units: refuse, overburden and bedrock. Two simplified schematics of the Landfill site lithologic units are presented in Figures 5.35 and 5.36. The overburden obviously contains important lithologic variations, but volumetrically is predominately fine grained material. The coarse grained sediment constitute the major pathways for leachate migration beneath the site. These pathways are comprised of singular or interconnected units of Recent sand, glacial sand, and Cretaceous sand. The primary lateral pathways at the site appear to be the Recent tidal marsh sands, the glacial sands associated with the kame features, and the Cretaceous sands (Landfill Sections 1/9 and 2/8). The primary vertical pathways at the site apparently occur within the Recent-glacial-Cretaceous sand complex in Landfill Section 1/9, at the kame features in Section 1/9 and 2/8 and 3/4 and 6/7 (Figure 5.13, A and B), and possibly in the south central portion of Section 2/8 where Cretaceous sand may be in contact with refuse/fill.

At a slightly smaller scale, the overburden lithologic variations can be described in terms of basic spatial patterns. From a descriptive point of view, it is most convenient to look first at the glacial lodgement till because it is an important component of the geologic or natural topography. This topography played a significant role for subsequent geologic events, and assists in the understanding the subsurface distribution of geologic materials across the site.

The glacial lodgement till was deposited as a relatively thick (approximately 20-40 ft) stratum by the Wisconsin age ice sheet that extended across much of North America in the Pleistocene Epoch. Geologically, the lodgement till constitutes ground moraine, a mostly continuous, laterally extensive deposit of compacted, fine-grained matrix with included coarser fragments.

The glacier advanced across an irregular, Cretaceous or weathered bedrock terrain, depositing the lodgement till as a widespread veneer. These variations in relief influenced the glacial topography. The glacially eroded pre-Pleistocene terrain greatly affected the shape and distribution of the lodgement till layer.

As the ice sheet receded, it was fronted to the south by proglacial lakes, dammed between the ice and the higher upland terrain. Deposited in these lakes were mostly fine-grained sediments now represented by the glaciolacustrine silt and clay. Erosional breaching of the morainal barriers by overflow and deglaciation of lower elevation outlets eventually led to the draining of the glacial lakes. Local till/sand knobs (kames) were also deposited within the landfill sections during recession of the glacial ice. The kames are evident as topographic highs on historic topographic maps. The sand units within and associated with the kames have potential vertical extent of tens of feet and potential lateral extent between landfill sections. Figure 5.33 shows areas in the Landfill site where correlative glacial sand occurs.

The post-glacial period was characterized by slowly rising sea levels and progressive inundation of low lying areas of the till/glaciolacustrine topography. The result was a Recent tidal marsh environment in which clay, silt, sand and peat were deposited. The Recent materials are mostly silt and clay, representative of tidal marsh backwater sedimentation, including peat. Within the tidal marsh, smaller tributary channels, perhaps similar to those shown on early topographic maps (Sheet 5.83), were the locale for localized fluvial channel sand deposits. The depositional environment was aggrading, which with lateral channel shifting, leading to irregular, elongated channel sand deposits within the finer grained materials. The geometry of such deposits is likely to be extremely complex, some appearing as isolated or localized lenses on geologic profiles. However, some of these channel sands may exist as sub-vertically oriented units that are

correlative through the Recent sequence. Additionally, in areas of the Fresh Kills Landfill site, a potentially laterally extensive Recent sand deposit exists, probably representing lateral aggrading fluvial channel deposits of stream channels or near shore deposits. Figures 5.36 and 5.37 shows areas in the Landfill site where correlative Recent sand occurs.

The lodgement till and glaciolacustrine silt and clay occur as a mostly continuous site-wide feature, with an important topographic expression. The topographic expression controlled or influenced subsequent geologic events, such as the deposition of the Recent sediments, as discussed above. This perspective provides a rational foundation, and provides confidence in the interpretation of the site geology.

Cretaceous silts/clays and sands represent the remaining significant units of interest within the unconsolidated overburden sediments. The geologic documentation serves to delineate the lateral extent of the Cretaceous sediments as being restricted to portions of Landfill Sections 1/9, 2/8 and 6/7. The northern margin of the Cretaceous is represented by the "Fall Line", which has been widely reported in the literature and supported by the present work. South of this boundary, the Cretaceous deposits consist of alternating layers and lenses of silt/clay and sand. These deposits primarily represent the time-transgressive, lateral shifting deltaic distributaries (sand) in a low, coastal floodplain/marsh (silt/clay) setting not unlike the post-Pleistocene deposition.

Numerous geologic studies in neighboring areas of the New Jersey Coastal Plan, extending over a period in excess of 100 years, have led to the conclusion that classical stratigraphic delineation of alternating sand-silt-clay strata in this area is futile due to the lateral facies changes and the vertical time-transgressive nature of the Cretaceous deposit. Simply stated, the New Jersey Cretaceous resembles more interfingering, discontinuous, and irregular distribution of varied lithologies, rather than the classic layer-cake analogy. The stratigraphic data for the Fresh Kills Cretaceous sequence supports a time-transgressive model, with two important exceptions. The first exception is that a fairly continuous, correlative sand layer has been identified at the base of the Cretaceous sequence (Figure 5.34). The second is that the microfossil analysis, although not conclusive, suggests that portions of the Cretaceous sediments at the Fresh Kills Landfill are Lower Cretaceous in age. Therefore, only a portion of the Cretaceous deposits at the site may correlate directly with the Cretaceous sediments in neighboring areas of New Jersey and Long Island.

The preceding discussion appears to suggest that the Cretaceous sediments are buried beneath younger Pleistocene and Recent deposits across the site. This is generally the case, however,

beneath the southern portion of Section 2/8 and the southeastern portion of Section 1/9, the younger sediments are not present, exposing Cretaceous age strata (including sand) to the base of the refuse/fill. The explanation for the lack of Pleistocene and Recent deposits includes post-glacial erosion and excavation associated with early landfilling or other activities. The time-transgressive nature of the Cretaceous sequence allows for the interconnection of upper sand units to deeper sand units in some locations.

The bedrock and related deposits at a site-wide scale, primarily Triassic and Ordovician Formations, includes an upper more weathered zone with recognizable relict bedrock features, and in most areas an overlying, relatively thick, stratum of residual clay. The spatial distribution of bedrock types is mapped and found to be generally consistent with published reports. A resistant serpentinite and associated schist occurs in areas of the eastern and southern portions of the Fresh Kills Landfill site. The remaining bedrock is composed of less resistant formations including siltstones, shales, and sandstones of the Newark Supergroup.

6.0 HYDROGEOLOGY

The delineation of the physical hydrogeology of a site represents a formalized, structured exercise in logic, using the scientific principles and methods of the science of hydrogeology as a framework. This exercise is aimed at a basic understanding of the hydraulic controls that govern the occurrence and movement of groundwater, and includes a diversity of practical issues, pertaining to definition of: (1) a rational for the observed distribution of groundwater contamination, (2) the characteristics that will govern migration and extent of contamination in the future, and (3) factors that will govern the effectiveness of various site remediation options.

In order to describe and analyze the issues described above, the hydrogeologist utilizes various tools of data reduction and analysis. The synthesis of these data culminates in the development of a conceptual model of groundwater through the area of interest. The conceptual model generally describes how groundwater flows through the area of interest, and the factors that affect its movement as it passes through this area. Where the groundwater flow system is complex, more sophisticated mathematical modeling techniques are developed to supplement the level of detail afforded by the conceptual analysis.

The development of the conceptual model entails description of two basic components of the flow system, namely the geologic materials that the groundwater is flowing through, and the hydraulic head, or groundwater elevation, that has developed within the geologic units. Both of these components are interrelated in that together they define the physical limits and boundaries of the ground flow system, and allow for definition of its pertinent characteristics (i.e., velocity and horizontal and vertical discharge).

This section of the report has been organized to discuss the conceptual model by first describing the geologic materials and their hydraulic properties, then describing the hydraulic head data, followed by discussions of the current flow and flux conditions of groundwater through the site and at site boundaries. This discussion is provided initially for the regional groundwater system, and then individually for each of the four landfill sections. The landfill section specific discussions form the basis for the development and description of two dimensional (cross-sectional) numerical flow models conducted for each section. These numerical models are presented to further refine the details of groundwater flow, and examine the sensitivity of various

hydraulic properties and their potential influence on the movement of solute within the groundwater flow system.

Finally, the development of a regional three dimensional (areal) flow model is described, which incorporates the findings of the detailed cross-sectional analysis into the regional conceptual framework, and provides a tool for the evaluation of leachate mitigation options in support of the requirements of Consent Order Appendix A-4.

The first step in the conceptual model development process is the description of area geology. Section 5.0 of this report provided a detailed description of both the lithology and stratigraphy of the geologic units at the Fresh Kills Landfill, along with current interpretations of both the continuity and areal extent of those units. This section of the report combines the information presented in Section 5.0 concerning site geology, with additional information on the hydraulic characteristics of each of the geologic units, to aid in development of a better understanding of the groundwater flow system. It will become apparent through the ensuing data presentations and discussions that many of the unresolved issues or hypothesis presented within Section 5.0 concerning the relative continuity and/or extent of individual geologic units become less important in terms of site hydrogeology, because many of the geologic units have similar hydraulic properties (e.g., hydraulic conductivity or K) that allow these units to be grouped into more general hydrogeologic categories, referred to as hydrostratigraphic units. The ability to group geologic units into broader hydrogeologic categories in many cases reduces the level of detail often required in geologic characterization, and enables a better description of the processes that move groundwater within and through a specific area. This concept is illustrated on Figure 6.1, which depicts a stylized cross-section through the southern area of Landfill Section 1/9. As indicated, the series of geologic units has been grouped into several hydrostratigraphic units based on the characteristic range of hydraulic conductivity associated with each material.

Another important factor in the definition of the conceptual model of groundwater flow relates for the establishment of "boundary conditions". Boundary conditions within the flow system are generally described as being source or discharge areas for groundwater and are normally used to define how groundwater enters and leaves the conceptual model area. In a hydrologic context, the interface of a river or stream channel with a saturated geologic unit represents a boundary condition that influences or controls the direction and rate of groundwater flow. In a geologic context, boundary conditions refer to abrupt changes in the hydraulic characteristics of the

material. These material changes can be natural, represented by contact with a low permeability competent bedrock through which very little groundwater may travel, or man-made, such as a soil-bentonite slurry wall installed to act as a barrier to the flow of groundwater.

Finally, it should be noted that the understanding of the conceptual model is rarely established with absolute certainty, and that the conceptual model represents a scientific hypothesis, i.e., an interpretation of the available data that best accommodates the facts at hand. The conceptual model is therefore based on a compilation of facts describing the hydrogeologic system, and can be tested, refined and, if necessary, modified.

In summary, the delineation of the hydrogeology of the Fresh Kills landfill site entails the initial definition of a series of physical and hydrologic parameters that formulate the development of a conceptual model which exhibits the fundamental elements required for an understanding of the groundwater flow system. This model serves as a basis for and guide to subsequent quantitative evaluations by analytical and numerical methods.

6.1 Regional Conceptual Model

The ultimate objective in describing the hydrogeology of the Fresh Kills Landfill is to develop conceptual groundwater flow models that are site-specific and tailored for each landfill section. In order to understand the variations between landfill sections it is convenient to begin with a composite of all sections. This approach provides a broader data base, and it promotes integration of a regional perspective. Sheet 6.1 provides a regional perspective of the Fresh Kills facility and serves as the base plan for the subsequent hydrogeologic analysis on a site-wide basis. This plan shows the locations of borings, wells, piezometers, and surface water gauges from which data were derived in support of the hydrogeologic evaluation of the entire Fresh Kills site.

6.1.1 Hydrostratigraphic Units

Section 5.0 of this document provides the basis for determining the physical framework of the groundwater system. However, in hydrogeologic practice, geologic materials or units are

evaluated relative to inherent hydraulic properties (i.e., hydraulic conductivity, porosity, isotropy/anisotropy, heterogeneity), to define a more meaningful or useful framework consisting of hydrostratigraphic units. The terms "aquifer", "aquiclude", "aquitard" and "confining" refer to types of hydrostratigraphic units. In general, hydrostratigraphic units are characterized in terms of their relative and absolute capability for storing, transmitting, yielding, restricting, or impeding groundwater flow. Those water-bearing and transmitting units with the potential to be affected by leakage of contaminants (including intervening confining layers) are referred to under 6 NYCRR Part 360 as the "critical stratigraphic section," and may include multiple or partial hydrostratigraphic units.

Information regarding the hydraulic conductivity (or permeability) of hydrostratigraphic units is an important requirement of hydrogeologic investigations. Hydraulic conductivity (K) relates to the capacity of the hydrostratigraphic unit to transmit water and is applied in the estimation of fluxes (discharge volumes) and velocities of groundwater flow. Moreover, data on hydraulic conductivity assist in defining the significance of potential migration pathways, should leakage through landfill leachate containment and/or collection systems occur. In quantitative terms, the velocity and quantity of groundwater flow is also related to the thickness of the individual hydrostratigraphic units (given uniform K). Thus, both hydraulic conductivity and thickness must be addressed. In situations where hydraulic conductivity and thickness vary spatially, the spatial distribution of these parameters must be considered.

An initial consideration in the description of the regional groundwater flow system relates to the issue of scale and complexity of hydrostratigraphic unit definition. The published research experience in the modeling of groundwater flow systems (both conceptually and numerically) in neighboring regions of New Jersey and Long Island has shown that a broader, more general perspective is appropriate despite detailed, complex geology (Zapecza, 1989; Vowinkel and Foster, 1981; Nemickas et al., 1989). For example, the New Jersey Coastal Plain geology includes detailed lithologic variations, but the current groundwater conceptual models group these variations into a few aquifer systems based on congruity of hydraulic properties. Similarly, the geologic data for Fresh Kills, as per Section 5.0 of this report, shows significant geologic variability, particularly within the overburden (unconsolidated sediments lying below refuse and above bedrock); however, in general it is difficult to establish site-wide correlation of certain individual geologic units at the regional scale. Thus, whereas the possibility of greater hydrostratigraphic subdivisions are acknowledged, and will be further explored in subsequent

subdivisions of this section, a convenient starting point is with the following simplified hydrostratigraphic units:

- Refuse
- Unconsolidated Overburden
- Weathered Bedrock and Bedrock

This is the simplest hydrostratigraphic subdivision possible, and may in some areas be considered oversimplified. There can be no further reduction in hydrostratigraphic units, inasmuch as the uniqueness of each unit is obvious. The question is whether additional units can be, or need to be, identified at the regional investigation scale. Within each unit, a number of characteristic differences are apparent. Physical differences in the character of refuse have been noted in association with all subsurface investigations performed at the site; for example, the presence of a low permeability basal layer of degraded refuse has been identified at a series of test locations (Section 4.5.2.1; Attachment 29). Within the overburden there can be extreme differences in the hydraulic characteristics of peat, clay, till, and sand. Likewise, the bedrock includes different lithologies, and the possibility of spatial differences in weathering and fracturing, with associated differences in hydraulic characteristics, can not be discounted. Thus, the possibility exists that the basic hydrostratigraphic subdivision may be more complex, with a greater number of units. However, it is also possible that the differences in the physical character within units are not significant in terms of groundwater flow, especially at a larger scale. At this initial level of conceptual model development, the scale of interest is regional (site-wide), and landfill section-wide, but not smaller.

6.1.1.1 Hydraulic Conductivity

Hydrostratigraphic units are characterized by distinctive hydraulic properties, notably hydraulic conductivity (K). The magnitude and spatial variation of K values between and within hydrostratigraphic units, under natural or imposed hydraulic loading and/or pumping, is largely responsible for the distribution of hydraulic head and associated groundwater flow patterns.

Report Sections 4.4 and 4.5 previously described the methods used to obtain laboratory K data and field in-situ K data, respectively. The basic data sets resulting from all K testing conducted

under this investigation are presented in Attachments 6 and 7. Table 6.1 summarizes all K data from each test boring or well by elevation and landfill section, and includes data derived from earlier subsurface investigations within and adjacent to the Fresh Kills Landfill. Table 6.2 is a summary of the same data contained in Table 6.1, but arranged by stratigraphic unit. Where data are available, these tables provide a tabulated summary of the variation in horizontal (Kh) and vertical hydraulic conductivity (Kv) in soil materials derived through in situ and laboratory testing. Tables 6.1 and 6.2 also include estimates of hydraulic conductivity derived through application of the Hazen Approximation Method (1911), which is based on soil grain size distribution. Hazen estimates of K were determined during the course of the hydrogeologic investigation to supplement hydraulic conductivity data obtained from laboratory and field testing, particularly in areas of limited K test data. It should be noted, however, that due to poor correlation with the more reliable field and laboratory K data, Hazen estimates of K were not incorporated into subsequent analytical and numerical analysis, and are presented in these summary tables for comparison purposes only. Similarly, in situ testing which resulted in insufficient data for accurate analysis are indicated on Table 6.1 and 6.2, but were not incorporated into subsequent analyses.

Table 6.3 is a summary of geometric mean values determined for each stratigraphic unit for the entire data set, and for each individual landfill section. As noted by Fetter (1988), the geometric mean (mean of the natural logs of the data) is often a more representative description of the average hydraulic conductivity of a geologic unit. This is because hydraulic conductivity values frequently vary by more than two orders of magnitude within the same unit, and an arithmetic mean of such a sample will give more weight to the more permeable values. Relative to this investigation, the utility of the geometric mean is evident from a comparative review of Tables 6.4 and 6.4A, which respectively provide a series of distribution statistics for the arithmetic and logarithmically transformed populations of hydraulic conductivity data derived in the field and laboratory.

The coefficient of variation (standard deviation divided by the mean) indicates the amount of variation in a population. Where this value exceeds 1.0, a normal distribution is generally not assumed. Skewness is a measure of the distribution of sample data relative to the mean. Where many very large or small numbers are present in a data set, the distribution of the "bell shaped" (normal) curve will be skewed, indicating a non-normal population distribution. For the sample sizes indicated in Tables 6.4 and 6.4A, a skewness much in excess of about 1.0 indicates

statistically significant deviation from a normal distribution (Snedecor and Cochoran, 1976). Kurtosis is a measure of the "peakedness" or flatness of the distribution curve relative to the normal curve. Kurtosis values much greater or smaller than about 3.0 indicate statistically significant deviation from a normal distribution (Snedecor and Cochoran, 1976). The statistics provided on Table 6.4 indicate that, with the exception of several clay units where the variability in K is low, the arithmetic sample data is poorly suited to a normal distribution. The statistics compiled on Table 6.4A indicate that average K is better represented by the geometric mean derived from a log normal distribution of the sample data. Only one of the log transformed data sets exhibits a markedly poor distribution (Recent silt and clay - lab Kv); this is due to an extremely narrow spread of measured K (5.9×10^{-8} - 5.6×10^{-7} cm/sec) coupled with a single outlier value of 10^{-5} cm/sec.

Figure 6.2 is a graphical plot of K data for all stratigraphic units, providing a visual depiction of the data distribution; differentiation of hydraulic conductivity data for weathered and unweathered bedrock by formation type is provided on Figure 6.2A. Finally, the horizontal distribution of K values for transmissive hydrostratigraphic units and sub-units is shown in regional plan view on Sheets 6.2 through 6.10. An overview discussion of the hydraulic conductivity of the identified regional hydrostratigraphic units and the spatial distribution of K is provided below.

- ***Refuse***

While the technical literature on the subject is scant, the K of refuse is generally regarded as being on the order of 10^{-2} to 10^{-4} cm/sec (Oweis, et al., 1990). Refuse K values are a function of refuse type, methods of compaction, degree of degradation, type of cover material, depth of burial, and other factors. Cover materials are generally believed to introduce a vertical anisotropy.

At Fresh Kills, refuse K testing was performed by in situ slug testing, which provides a local Kh value, predominantly at shallow depths near the water table. As indicated on Figure 6.2, K values range from 10^{-1} cm/sec to 10^{-7} cm/sec, with a clustering between 10^{-2} cm/sec and 10^{-3} cm/sec. The geometric mean value determined from the existing data base (Table 6.3) is 3.2×10^{-3} cm/sec. The distribution of Kh values (Sheet 6.2), obtained mostly from tests conducted at shallow depths in the refuse, exhibits variability but no discernible patterns. It

should be noted that it is not surprising that the horizontal distribution of K exhibits no discernible patterns. This is because the unit is man-made and, unlike most naturally occurring unconsolidated sediments that are deposited as a function of an energy relationship (e.g., fast moving stream deposition compared to lake deposition) where grain sizes can be separated out and selectively deposited, landfills are constructed as a function of material brought in and deposited in order to meet a final grading plan. The rate of filling can be a function of the time of year or current trends in packaging (e.g. plastic containers versus paper products). This concept of heterogeneity in refuse hydraulic properties is important in understanding flow within the refuse unit and will be discussed in more detail in the conceptual model sections that follow.

The vertical distribution of K within refuse, either generally in terms of literature studies or specifically at Fresh Kills, is largely unknown. However, it is significant to note that boring samples from each of the landfill sections indicate a vertical change in the nature of refuse materials (probably related to decay), typically approaching a gelatinous consistency near the base. From a qualitative perspective, this probably represents a decrease in K with depth. Quantitative data in support of this phenomenon is available from laboratory data provided by Woodward Clyde (Attachment 29), and in situ testing of basal refuse deposits performed by both Woodward Clyde and IT Corporation (Section 4.5.2.1 and Attachment 29). Laboratory data indicate a range in basal refuse K of 10^{-5} to 10^{-8} cm/sec under applied pressures approximating those expected at the Fresh Kills Landfill. The geometric mean K of seven in situ tests performed in basal refuse deposits across all four landfill sections is 2.1×10^{-5} cm/sec.

Figure 6.2B is a graph that relates all measured in-situ K data obtained during this investigation (Table 6.2) with the depth (thickness) of overlying refuse at each test location. The derived relationship is:

$$K = e^{(-0.082 \times \text{depth})} \times 0.018$$

Where, K = hydraulic conductivity (cm/sec)
e = base of natural logarithm (2.718)
depth =thickness of refuse (ft)

The effect of this apparent decrease in basal refuse K on the horizontal and vertical distribution of leachate flux has been evaluated numerically through cross-sectional model sensitivity analysis, and is described in subsequent sections of this report.

- ***Unconsolidated Overburden***

K values for unconsolidated overburden materials were obtained by in situ slug testing (Kh) in sand wells/piezometers, by laboratory testing of fine-grained materials (both Kh and Kv), and by the Hazen (1911) approximation method (based on grain size distribution) in coarser-grained materials. As might be expected, the total data base shows an extreme range, which is reflective of the lithologic differences. The varied lithologies and corresponding K values provide what is termed heterogeneity in the flow system, which may cause refraction of groundwater flow lines and the development of preferred pathways of groundwater flow, depending on the interconnectedness of geologic units. The governing K value for this hydrostratigraphic unit may not be characterized by a single statistical value, but may depend on the extent to which the individual clay and sand strata are continuous and connected. At one extreme, if low K material (clay lithologic unit) forms an effective hydraulic barrier, then a more representative K for the hydrostratigraphic unit as a whole would be that of clay. Conversely, if a higher K sand unit pathway exists and effects the flow system, a higher K value would be representative. However, it is again emphasized that the issue of interconnected pathways is a scale-dependent matter. The significance of such pathways rests with conceptual and quantitative modeling of flow systems at the appropriate scale.

The evaluation of the distribution of K data in the overburden can be obtained through segregation of the geologic materials described in Section 5.0 into two categories related to their ability to transmit groundwater: non-transmissive or "restrictive" units (low K); and transmissive units (moderate to high K), as follows:

	Kv	
Restrictive Units	**Range**	**Geometric Mean [a]**
Recent Silt and Clay	10^{-6} to 10^{-8} cm/sec	1.3×10^{-7} cm/sec
Glacial Clay	10^{-6} to 10^{-8} cm/sec	1.7×10^{-7} cm/sec
Glacial Till	10^{-5} to 10^{-8} cm/sec	1.3×10^{-7} cm/sec
Cretaceous Clay	10^{-7} to 10^{-8} cm/sec	8.4×10^{-8} cm/sec
Residual Clay	10^{-6} to 10^{-8} cm/sec	1.4×10^{-7} cm/sec

[a] Laboratory Kv data

	Kh	
Transmissive Units	**Range**	**Geometric Mean [b]**
Recent Sand	10^{-3} to 10^{-7} cm/sec	3.3×10^{-4} cm/sec
Glacial Sand	10^{-2} to 10^{-6} cm/sec	6.3×10^{-4} cm/sec
Cretaceous Sand	10^{-2} to 10^{-7} cm/sec	9.4×10^{-4} cm/sec

[b] In situ Kh data

This simple distinction between transmissive and non-transmissive units within the overburden underscores the contrast in hydraulic conductivity, and the potential significance of interconnected pathways versus barriers. Whereas the lithologic variability as described in Section 5.0 is great, the geologic material that describes the hydrostratigraphy of the overburden unit can be classified by mass as predominantly fine-grained, low K material interspersed with laterally correlative sand units of local or regional extent. These latter transmissive units are represented primarily by:

- Recent sand deposits, which occur beneath the majority of Section 3/4, nearly half of Section 6/7, and the western and northern portions of Landfill Sections 1/9 and 2/8. A detailed discussion of the occurrence, spatial distribution, and unit thickness of the Recent sand deposits is provided in Report Section 5.2.6. Top surface elevations, unit thickness, and the areal extent of the Recent sand deposits are provided on Sheets 5.35 through 5.40. Vertical distributions of individual unit thickness and sand unit correlation are depicted in profile on the geologic cross-sections contained on Sheets 5.6 through 5.27.

- Glacial sand deposits, which occur across the entire landfill, but occur primarily as localized sand units of limited extent that are not laterally or vertically continuous, but may potentially be in hydraulic communication with more areally or vertically extensive transmissive units (i.e., Recent and/or Cretaceous sand units). A detailed discussion of the occurrence, spatial distribution, and unit thickness of the glacial sand deposits is presented in Section 5.2.5. Top surface elevations, unit thickness and the areal extent of the glacial sand deposits are provided on Sheets 5.48 through 5.55. The vertical extent and correlation of the individual glacial sand units are depicted in profile on the previously referenced geologic cross-sections.

- Cretaceous sand deposits, which underlie Landfill Sections 1/9 and 2/8, and can largely be correlated to a regionally extensive continuous sand sequence originating beneath the Fresh Kills site and extending beyond the southern limits of the landfill. Report Section 5.2.4 provides a detailed discussion of the occurrence, spatial distribution, and unit thickness of the Cretaceous sand deposits; Sheets 5.62 through 5.67 provide this information in plan view. The vertical extent and correlation of the individual Cretaceous sand units are depicted in profile on the previously referenced geologic cross-sections.

The horizontal plan view distributions of hydraulic conductivity for the overburden transmissive sand units are presented on Sheets 6.3 through 6.9. Hydraulic conductivity values shown are representative of the individual overburden sand units described in Section 5.2. All hydraulic conductivity data indicated on Sheets 6.3 through 6.9 are based on in situ hydraulic conductivity testing conducted at intermediate sand well installations, as summarized on Table 6.2. At cluster well locations where wells screen multiple layers of Cretaceous sand Unit 1 (i.e., IT044I1, I2 and 13), hydraulic conductivity values obtained from the lowermost Cretaceous sand well were utilized in the construction of the map shown on Sheet 6.8.

- ***Bedrock***

Section 5.0 identified significant differences in the bedrock geology in terms of primary lithologies, weathered character, and secondary fracturing. The weathered bedrock geologic unit, although similar in appearance to the unconsolidated overburden material, exhibits relict structure and has K values more similar to the bedrock than to the overburden; therefore, this unit is included within the bedrock hydrostratigraphic unit. The residual clay geologic unit, normally found in contact with the bedrock, consists of fine-grained cohesive material with very low K values, more resembling the fine-grained silts, clays, and tills in the overburden. Therefore, the residual clay has been included with the unconsolidated overburden hydrostratigraphic unit.

The consolidated bedrock is known to be characterized by both primary and secondary permeability, generally representing groundwater storage and flow within the rock matrix (pores) and fractures, respectively. Fractures commonly provide localized pathways of much greater permeability. The determination of fracture permeability is a difficult proposition, involving specialized testing of the sort described in Report Section 4.5.2.2. The data derived from these

tests at Fresh Kills indicated a very low hydraulic conductivity within all bedrock horizons tested and did not provide additional insight into this issue. The available data from slug tests give relatively localized results which may be influenced by fractures to varying and unknown degrees. In general, the in situ K for the full spectrum of bedrock materials is low (10^{-7} cm/sec) to moderate (10^{-4} cm/sec) with a composite geometric mean value of 2.0×10^{-5} cm/sec. The geometric mean value of K for bedrock, excluding weathered bedrock material, is 4.4×10^{-5} cm/sec. The geometric mean value for weathered bedrock alone is 9.8×10^{-6} cm/sec, indicative of the clay derived from shale parent materials in the weathered zone.

Review of Figure 6.2A indicates a wide range in variation of the bedrock K distribution, with formation type acting to distinguish the data more than weathering characteristics (Section 5.3.2.1 previously defined the basis for distinction between weathered and competent bedrock as a function of RQD[1]). The weathered Stockton Formation bedrock (Tsw), and the serpentinite (Os) exhibit the lowest range of K (generally in the range 10^{-8} to 10^{-4} cm/sec). The weathered serpentinite (Osw), and the weathered and competent Lockatong Formation (Tlw, Tl) exhibit the highest range of K within the bedrock, generally within the range of 10^{-4} to 10^{-2} cm/sec. It should be noted that the relatively high observed permeability distribution of the Lockatong Formation in the project area is at variance with the literature regarding the water yielding capacity of this unit in New Jersey (Posten, 1984), where it is regarded as one of the poorest aquifers in the state. The weathered schist (Shw) and competent Stockton Formation (Ts) bedrock exhibit K data within a range central to those discussed previously (i.e., 10^{-6} to 10^{-3} cm/sec).

Sheet 6.10 shows the horizontal distribution of K data for the bedrock, and indicates considerable variability but with definite patterns, notably a zone of very low permeability extending northeast-southwest through Landfill Sections 6/7 and 1/9 and separating regions of higher permeability to the north, west, and south. This low permeability zone represents a large region of the Triassic Stockton Formation, as indicated on Sheet 5.82. The data are too sparse to evaluate the possibility of fracture zones.

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[1]Rock Quality Designation (RQD) is a classification index that describes the physical characteristics of the rock material recovered in a core. RQD equals the cumulative length of naturally separated core pieces, 4 in. or more in dimension, expressed as a percentage of the length of the core run.

A potential indirect indicator of variation in bedrock hydraulic conductivity is represented by Rock Quality Designation (RQD) reported on boring logs. The classic, common (but not universal) finding is an increase in RQD with depth, indicative of a decrease in fracturing with depth.

Considerable analysis was performed in an attempt to relate reported RQD values to variation in K. Figures 6.3 and 6.4 are graphical plots showing the distribution of RQD versus K, and RQD versus depth below bedrock surface, respectively. The random nature of the distribution of data points shown on these two figures are typical of other plots relating RQD to lithology, mid-point elevation, elevation, and depth intervals (Attachment 16). The randomness of these data suggest that groundwater flow within the bedrock to the depths investigated is not predominately controlled either by the primary or secondary porosity of the rock, and is probably influenced by an equal combination of both. Therefore, the distribution of K data presented on Sheet 6.10 represents a combination of hydraulic conductivity related to both primary and secondary porosity.

6.1.1.2 Hydrostratigraphic Unit Thickness

Similar to hydraulic conductivity, a second major variable influencing groundwater flow is the thickness of the hydrostratigraphic unit. The thickness variations of each unit as a whole is of particular interest. Likewise, the thickness of lithologic, structural, or other K-related elements may be significant, as for example, the thickness of sand strata within the overburden. However, other factors may represent important controls, determining the extent to which thickness may be effective hydraulically; for example the lateral continuity of materials: a sand unit may be highly permeable and have substantial thickness, but have little influence on potential migration of leachate if not spatially interconnected to other high K units. Furthermore, whereas the thickness (and K) of transmissive units is, a major determinant in the calculation of flow volumes, a relatively small thickness of a restrictive unit may be effective in reducing the rate of flow both laterally and vertically. This difference between transmissive versus restrictive units bears greatly on the ultimate functioning of the individual hydrostratigraphic units. To be consistent with the initial approach of hydrostratigraphic subdivision at the regional scale, the thicknesses of primary interest are those of the three identified hydrostratigraphic units (refuse, unconsolidated overburden, and bedrock).

Sheet 6.11 identifies the locations of the 18 regional hydrostratigraphic cross-sections developed for this investigation. Hydrostratigraphic cross-sections on Sheets 6.12 through 6.29 show the spatial variations of the major hydrostratigraphic units and depict the delineation of restrictive and transmissive sub-units within the highly variable stratigraphic sequences. In addition, the hydrostratigraphic cross-sections indicate vertical variations in hydraulic head, as well as thickness and hydraulic conductivity, so as to depict general hydraulic relationships between hydrostratigraphic units (as will be discussed subsequently). The areal distribution of thickness for the refuse and overburdden major hydrostratigraphic units as well as individual transmissive units are presented in plan view. Hydrostratigraphic unit thickness values were derived from Section 5.0 stratigraphic interpretation Tables 5.8 through 5.17.

- ***Refuse Unit Thickness***

The refuse unit is generally defined to be a transmissive unit based on its relatively high K distribution, as described in Section 6.1.1.1. Refuse thickness is of interest in regard to the horizontal flow component because in accordance with Darcy's Law, there is a direct, linear relationship between thickness and flow. Thickness is also of interest relative to the vertical flow component, as thicker refuse (and potential variation in K as noted in Section 6.1.1.1) can provide for greater heads, and consequently potentially greater downward driving forces. Not incidentally, the difference between total thickness versus saturated thickness for the refuse is an important distinction.

The estimated total thickness and saturated thickness of refuse is shown in plan view on Sheets 5.30 and 6.30, respectively. Refuse saturated thicknesses are also shown in profile in the hydrostratigraphic cross-sections, although it should be noted that the leachate mounds are largely interpretive due to limitations in data. Leachate mounds which form within the refuse unit generally are subdued replicas of the individual landfill section topography. As indicated on Sheet 5.30, landfill sections differ in their areal extent and thickness of refuse mounds. The saturated thickness distribution shown on Sheet 6.30 represents the difference between the synoptic water-level data averaged for the period June 17 through July 17, 1992 (Table 6.5), and the bottom of the fill/top of native deposits (Sheet 5.29). This shows relatively thick saturated thicknesses within Landfill Sections 1/9, 3/4, and 2/8, as compared to Landfill Section 6/7. The subdued saturated thickness within Landfill Section 6/7 is believed to be a reflection of the lower

physical refuse mound dimensions (relative to other sections), and the largely non-active status of the landfill during the course of this investigation.

Relative to the estimation of saturated thickness at all sections, it is important to note that the data indicated on Sheet 6.30 (and leachate mound head indicated subsequently on Sheet 6.32) are derived primarily from water level measurements obtained from shallow piezometers screened across the first encountered saturation during drilling. At several locations within the landfill where continuous samples were obtained for the refuse unit, unsaturated zones were encountered at depth below the first zone of saturation, suggesting that perched conditions may exist within the refuse material (logs of borings 1P92:ATW-D, 2P92:ATW-D, 3P92:ATW-D, 6P92:ATW-I). In addition, as discussed in Section 4.5.2.1, water level data derived from pairs of shallow/deep piezometers installed in the refuse (1P92:ATW-Z/ATW-S; 6P92:ATW-S/ATW-S2; 6P92:ATW-S2/ATW-S3) indicate a significantly lower head (30-60 ft) in the basal refuse deposits. The existing database is not sufficient to evaluate the areal or vertical extent of perched leachate zones; however, their importance in describing flow within the refuse unit is discussed subsequently in cross-sectional numerical model sensitivity analysis.

Given the available data on the vertical distribution of head in the refuse mounds and the presence of unsaturated zones at depth, use of head distribution data from the shallow piezometers in subsequent numerical modeling efforts should be viewed as a conservative approach relative to the estimation of the vertical flux of leachate from the refuse to the underlying overburden unit, in that the actual driving head at the base of the refuse may not be as high as true field conditions. Therefore, interpretation of model simulation results based on potentially higher water levels in the refuse will produce the potential for correspondingly higher vertical fluxes out of the base of the landfill.

- ***Unconsolidated Overburden Unit Thickness***

The overburden unit, unlike the refuse, is almost without exception fully saturated beneath each landfill section, and thus saturated thickness is considered equal to total thickness. Sheet 6.31 indicates the thickness of the overburden unit, derived by subtracting the elevation of the bedrock surface (Sheet 5.74) from either the land surface or, where present, the base of refuse (Sheet 5.29). As indicated, the thickness of this unit generally increases along a gradient extending from Landfill Sections 6/7 to 3/4, and Landfill Sections 3/4 to 1/9; i.e., from east to

west and north to south. The east-west gradient relates primarily to the rise of the bedrock surface to a high in the interior of Staten Island. The north-south gradient reflects a deepening of the bedrock surface oceanward.

As noted above, a difference exists in the effect of thickness depending on whether this unit is fundamentally transmissive versus restrictive. For a variety of reasons, to be explored in the report sections describing numerical analysis, the unconsolidated unit is regarded as relatively restrictive, which is a function of the overall presence of a sufficient thickness of low permeability materials within this unit. Of course, the higher permeability materials may serve as conduit-like pathways for local transmission of groundwater and contaminants, and are of interest from a water quality perspective. However, at the regional scale, the character of the overburden is variable, discontinuous but with a dominant presence of low permeability soil, generally greater than 20 to 30 ft thick. In the perspective of section-wide and site-wide groundwater flow systems, this is a significant aspect.

The most extensive mappable sub-units of higher permeability material within the unconsolidated overburden deposits are the locally continuous Recent sand deposits (primarily Unit 1; Sheets 5.36 and 5.39) correlated beneath the majority of Section 3/4 and portions of Sections 1/9, 6/7 and 2/8; and the more regionally extensive Cretaceous sand deposits (primarily Unit 1; Sheets 5.63 and 5.66) correlated beneath Landfill Sections 1/9 and 2/8. The areal distribution and variation in thickness of these transmissive hydrostratigraphic sub-units are illustrated in plan view on the above-referenced sheets, and discussed in detail in Sections 5.2.6 and 5.2.4, respectively. The hydrostratigraphic cross-sections (Sheets 6.12 through 6.29) provide in profile, a more detailed perspective of the spatial variation in thickness and correlation of these sand units. The hydrostratigraphic cross-sections also illustrate the spatial distribution and correlation of the discontinuous transmissive sand deposits as well as the restrictive confining units within the overburden sequence.

Whereas Recent sand Unit 1 and Cretaceous sand Unit 1 represent the primary hydrostratigraphic sub-units through which preferential groundwater flow will occur, the other less extensive sand units also represent potential migration pathways. In the development of the conceptual groundwater flow model, lateral and vertical correlation within and between these individual sand units represents an important consideration. Sheets 6.12 through 6.29 define the correlation of individual sands into hydrostratigraphic sub-units within the unconsolidated overburden sequence,

depicting the hydrostratigraphic framework within which groundwater flow will occur. Sheets 5.93, 5.94 and 5.95 indicate the areas in plan view where vertical continuity exists between transmissive sand deposits; specifically, Recent and glacial sands, Recent and Cretaceous sands, and glacial and Cretaceous sands, respectively.

It should be noted that while shallow Recent alluvial sand deposits may not be areally extensive from a regional perspective, they are often locally continuous, in many cases extending from exterior surface waters to beneath the central portions of the individual landfill mounds. These alluvial deposits represent remnant drainage channels present prior to the time of filling of the landfill, and can lie in direct contact with the refuse, as indicated through comparison of Sheets 5.29 and 5.35 and examination of the hydrostratigraphic cross-sections. In terms of a regional perspective, they are considered of minor importance, in that the relatively high permeability of these Recent alluvial sand deposits is similar to that of the refuse; conceptually they would be included as part of the refuse hydrostratigraphic unit. In terms of individual landfill section conceptual models, they play a more important role in determining the potential lateral migration of leachate from a specific section. These Recent alluvial sand deposits are evaluated in greater detail within the individual landfill conceptual model discussions, notably in the cross-sectional numerical analyses.

- ***Bedrock Thickness***

The thickness of the bedrock hydrostratigraphic unit is problematical. Geologically, the bedrock unit extends at least to the Precambrian basement, but this does not take into account the hydraulic character of the unit and is, therefore, not appropriate in describing the unit hydrostratigraphically.

RQD values are commonly used to show variations in bedrock properties that are inferred to be related to transmissive properties. Generally speaking, RQD values tend to show an upper, more transmissive zone overlying more competent and generally less transmissive bedrock. As previously noted, in terms of this investigation, the RQD data suggest a random relation with depth, and firm conclusions are not supported by the data base. An approach in common practice for establishing the base of the bedrock flow system is to recognize that there is an upper more active and transmissive zone. It is difficult to establish the thickness of this zone. In practice, reasonable estimates of the bedrock thickness can be assumed, generally on the order of a few

tens of feet. For the purpose of model delineation, a range of thickness can be utilized and, in this way, a reasonable thickness can be deduced. Hydraulic flow conditions may also be utilized to establish a representative bedrock thickness and this is discussed in later sections of this report.

6.1.2 Boundary Conditions

Broadly defined, the term "boundary conditions" refers to all elements that are external to the hydrostratigraphic units, or along their boundary in the context of site configuration, and which serve to directly, or indirectly, influence or control the direction of groundwater flow. Boundary conditions play an important role in the development of the conceptual model in that they generally describe and define how groundwater enters and leaves the area being studied. Boundary conditions can be naturally occurring, represented by rivers and streams that function as potential discharge/recharge areas for groundwater, or they can be man-induced, represented by pumping wells that serve as discharge points for groundwater. The following is a description of boundary conditions applicable to the Fresh Kills Landfill site.

- ***Recharge*** – The fact that Fresh Kills is located in the humid, northeastern United States is significant in that the long-term (climatic) condition is characterized by excess precipitation as compared to surface runoff and evapotranspiration, resulting in infiltration or recharge to the groundwater flow system.

  An initial estimate of a facility-wide, order of magnitude infiltration rate is provided by Ahmed and Khanbilvardi (1989) who provide average recharge values of 9.5 to 19.0 inches per year for the refuse mounds at Fresh Kills. This range of recharge is similar to the 10-15 inches per year determined by Lu, et.al. (1985) for recharge to landfills in the northeastern United States. Obviously, infiltration is not evenly distributed within the year or uniform from year-to-year, and as a consequence, groundwater levels and flows are temporally variable with a gross, dynamic equilibrium.

  The referenced estimate for recharge is also consideration an approximation, in that there may be spatial differences in the infiltration rates between individual landfill sections. This may relate to differences in cover soils, active versus inactive landfill sections, vegetation, slopes, etc. It is beyond the scope of this study to consider such spatial

variations in detail for every fill section, but they nevertheless may be significant in explaining variations in the height of leachate mounds between and within individual landfill sections. Regardless, it is possible to obtain a representative value of recharge for each landfill section by methods discussed in latter sections of this report.

- ***Sea Level*** – The fact that the Fresh Kills Landfill is in a coastal area is significant in that the associated estuarine environment represents an ultimate discharge zone for groundwater. The spatial geometry of discharge zones, relative to sources, is quite important relative to downward versus lateral flow potential. An aspect ratio can be defined relating the horizontal distance from the most remote point in a flow system to the discharge zone, versus the vertical difference in head. In this regard, despite the fact that the Fresh Kills landfill refuse mounds are impressive, distinctive features, the landfill's aspect ratio represents a relatively flat condition.

  As a consequence of the boundary condition imposed by the proximity of the Atlantic Ocean and the low relief of the project area, groundwater flow systems can be expected to be predominantly horizontal with relatively local vertical flow components. As discussed in a subsequent section, this is in fact the case, although it is impossible to distinguish the influence of heterogeneity, low permeability, and anisotropy versus sea level. In theory, however, the aspect ratio for the site would itself make downward flow relatively difficult and limited.

- ***Well Pumping*** – As discussed in the Hydrogeological Literature Review (IT Corporation and Wehran EnviroTech, 1991a; Attachment 44), well development on Staten Island has been limited, but in neighboring areas of Long Island and New Jersey municipal and private well field development has resulted in relatively large scale drawdown. This condition is being reversed in western Long Island, but as noted in the literature review, the drawdown being observed in Long Island is beyond the zone of potential influence for Fresh Kills.

  Similarly, pumping centers in New Jersey's Coastal Plain have been identified and associated cones of depression mapped. In proximity to Staten Island, the closest major pumping center is associated with a well field across the Raritan Bay in the Sayreville area. Groundwater in this well field is being pumped from the middle aquifer unit of the

Upper Cretaceous sequence, or Farrington equivalent. As presented in the literature review, drawdown from this pumping center may hypothetically extend beneath the Raritan Bay to the vicinity of the Fresh Kills Landfill, although data documenting this extent are limited.

Many pumping centers in the New Jersey Coastal Plain are in the upper and middle aquifer units of the Upper Cretaceous sequence, depending on location. Because the lowermost aquifer unit of the Upper Cretaceous sequence is deeper, withdrawals have historically been smaller. The pollen data discussed in Section 5.0 of this report places Fresh Kills in this lowermost unit within the Upper Cretaceous sequence, or within the Lower Cretaceous sequence, which suggests a limited potential for drawdown associated with neighboring well fields in New Jersey. Of course, the possibility of private industrial wells in New Jersey across the Arthur Kill from the Fresh Kills Landfill can not be dismissed. Such wells may not be in the public records, and would be more difficult to identify. Whether or not pumping centers in neighboring areas are boundary conditions affecting the Fresh Kills Landfill area can only be evaluated by detailed analysis of the hydrogeology and analysis of long-term (yearly) transient water level data from the potentially affected units. The analysis of available continuous water level data from the lower Cretaceous unit within Landfill Section 1/9 does not suggest the presence of any obvious pumping center within the immediate vicinity of the site.

An additional influence from well pumping in the immediate project area is represented by a deep (580 ft) industrial supply well located at the NYCDOS Muldoon Avenue garage. This well is operated periodically (primarily in the summer months) as a water supply for the washing of Sanitation Department trucks. While no influence from this well is noted in the water level monitoring record (Appendix J), the monitoring well array is sparse in this area. Due to the scheduled abandonment of this well by NYCDOS in January of 1994, any potential long term effect of this well pumpage on the local hydraulic head distribution will be eliminated.

- ***Tidal Fluctuations*** – Whereas sea level is a spatial boundary condition, as discussed in the preceding section, it can also be viewed from a temporal perspective. In the long term, this would include major changes in sea level, both above and below the present sea

level. Such major changes may have drastically altered groundwater conditions, especially chemically, and these may still have remnant effects.

Although there is the possibility of longer-term and larger sea level fluctuation effects, the primary item of interest here is the diurnal tidal fluctuation. Tidal fluctuations are less important in terms of general conceptual and numerical modeling of steady-state conditions, but may be significant for transient conditions.

Evidence of a tidal cycle in groundwater level fluctuations is provided by the literature, by previous studies at Fresh Kills, and by the present data base. This data base is presented in a subsequent portion of this section and discussed in the context of individual landfill sections.

- ***Salt Water Intrusion*** – The chemical/physical dynamics of the saltwater/freshwater interface are relatively well established, at least in principle. Evidence for the presence of a saline influence on groundwater (primarily in the Cretaceous sand unit) can be found in the regional published literature (e.g., Soren, 1988), previous studies at Fresh Kills, and the present data.

  The source of salt water (seawater) in the Cretaceous unit is not known, but is believed to associated either with: (1) residual (connate) sea water derived from the last eustatic high that has not yet been flushed from the sediments (Meisler, et al., 1984), (2) density driven migration through overlying Recent/glacial sediments in hydraulic communication with the Arthur Kill (possibly enhanced through channel dredging), (3) historic pumping activity in the bedrock or Cretaceous unit, resulting in localized areas of induced recharge from overlying sediments and the Arthur Kill channel, or (4) some combination of the above. As discussed previously in Section 4.1.2 the most likely explanation for its presence is the historical pumping of a Cretaceous sand irrigation supply well at the South Shore Golf Course, located to the south of Landfill Section 1/9.

  Under natural conditions, the presence of salt water intrusion results in a boundary defined by the density differences between saltwater and freshwater. The more dense saltwater tends to form a wedge below the less dense fresh groundwater. Fresh groundwater then tends to flow up and over the top of the saltwater, thus creating a conceptual model

boundary to the flow of the groundwater and, ultimately, the movement of any potential leachate contamination that may be present within the groundwater. Due to numerical model limitations, and the fact that induced recharge as a result of pumping would lead to mixing of seawater and fresh groundwater (rather than development of a classical salt water wedge), density defined boundary conditions were not implemented in the numerical analyses performed for this investigation.

- ***Bedrock Base*** – The base of the groundwater system is the bottom of the bedrock transmissive zone. This represents a no-flow boundary, as has been previously discussed.

- ***Landfill Alterations*** – The landfill sections essentially consist of refuse mounds overlying the unconsolidated overburden hydrostratigraphic unit. Of course, this simple description belies more subtle but possibly significant differences. For example, the landfills differ in their topography/slopes, vegetation, and cover material. Further, in some places landfill development has included perimeter leachate collection systems (i.e., Section 1/9), drainage controls, and other modifications.

  Landfill alterations, by definition, are man-made boundary conditions to the flow system. The most obvious landfill alteration is the Veteran Avenue recirculation system installed along portions of the eastern side slope of Landfill Section 1/9. This man-made boundary condition may be significant when determining the current conceptual flow model for Section 1/9. At present, the leachate that is collected within the drain system is reintroduced into Landfill Section 1/9 at another location so, although there may be no net loss or gain to the overall flow system, the man-made alteration may affect flow locally within the landfill section.

- ***Rivers/Streams*** – The most prevalent boundary condition for the refuse unit at the Fresh Kills Landfill site is the presence of the major surface water channels of the Fresh Kills, Arthur Kill, Richmond Creek and Main Creek. The rivers also can serve as the primary discharge zones for the shallow groundwater flow system in the unconsolidated unit, and are generally considered the major receptors for leachate discharge from the landfill. They can also serve as regional discharge boundaries for flow within the deeper unconsolidated overburden unit and may also influence flow within the bedrock unit. Stream channel elevation data used for the development of numerical model

boundary conditions were derived from bathymetric maps of the project area (Attachment 3 of the Hydrogeological Literature Review Report Addendum, IT Corporation and Wehran Envirotech, 1991c; Attachment 44).

Smaller streams within the individual landfill sections may also serve as local boundary conditions to specific hydrostratigraphic units. An example of this is the Richmond Avenue Creek which lies along the eastern toe-of-slope of Landfill Section 6/7, with discharge primarily to Richmond Creek. This tributary stream serves as a discharge conduit for groundwater flowing from the refuse mound at Landfill Section 6/7, and also receives groundwater discharge from the unconsolidated overburden unit locally. Other small streams within the project area include Sleight Creek (to the south of Landfill Section 1/9), Travis Creek (to the north of Section 3/4), and several tributaries of Richmond Creek within the property area of Section 2/8. In general, rivers and streams can be considered as head-dependent boundaries with groundwater moving into or out of the surface water as a function of the difference between the water levels in the surface water and surrounding groundwater. This concept becomes important in latter sections of this report describing numerical modeling.

6.1.3 Hydraulic Head

Sections 6.1.1 through 6.1.2 provide a basis for understanding the physical hydrogeology. The hydrostratigraphic units and their corresponding hydraulic conductivity and unit thickness distributions and boundary conditions are independent variables that combine to create the physical flow system. The general groundwater flow patterns that develop within this physical flow system are represented by the distribution of hydraulic head, the dependent variable, which can be viewed in both plan and profile. It is the distribution of head data that provides a reasonable basis for the delineation of equipotentials (contours of equal head), which in turn can be used to infer groundwater flow paths and directions (initially assuming isotropic conditions). Further, utilizing hydraulic head distributions, flow rates and fluxes can be estimated that ultimately describe and define the conceptual model.

The ensuing text describes the components of the hydraulic head data base available for application to the hydrogeological investigation, as well as supplemental factors requiring consideration when using the data for conceptual model analysis.

6.1.3.1 Hydraulic Head Data

Hydraulic heads are expressed as water-level elevations in monitoring wells and piezometers that screen discrete hydrostratigraphic units. The locations of the various monitoring wells/piezometers at the Fresh Kills site that were used to obtain water level elevation data are indicated on Sheet 6.1. As described in Report Section 4.8, water level elevation data were collected from these installations either periodically by manual measurement or continuously by electronic data logger and pressure transducer equipment for various time periods throughout the course of the hydrogeologic investigation. These data provide the basis for the assessment of both spatial and temporal head variations.

6.1.3.2 Synoptic Water Level Data

Both manual and continuously recorded water level elevation data were utilized in the development of a synoptic hydraulic head data base. Synoptic water level data allow for a general steady-state analysis of hydraulic head distributions and, in turn, groundwater flow patterns in both plan and profile. The data are termed synoptic in that the values all generally occur within the same time period. Synoptic head data were utilized in the construction of water-table and piezometric surface contour maps, hydrostratigraphic cross-sections, and piezometric profiles. In addition, these field data were utilized to determine both horizontal and vertical gradients, and were further utilized for calibration of numerical models.

Table 6.5 provides a summary of the synoptic water level elevation data. Synoptic head values were derived using average water level elevations for both manual and continuously recorded data. Where manual measurements were obtained, primarily from 1989 NYCDOS refuse wells and Phase II wells, an average of the high and low tide value for the mass measurement recorded on July 1, 1992 was utilized. At installations where continuous or transient data were collected, a time-averaged hydraulic head value was calculated over a 30-day period from June 17 to

July 17, 1992. At well locations where tidal fluctuations were evident in the water level record, the time-averaged value was calculated from the high tide peak of the first tide cycle to the high tide peak of the last tide cycle within the noted 30-day period. If a well was not tidally-influenced, the time averaged value was calculated using the entire water level record over the period. As an illustration of this method, Figures 6.5 and 6.6 graphically depict the time averaged values (horizontal lines) calculated for the 30-day period at Tidal Gauge A, and perimeter well cluster 1W91:IT001, respectively. It should be noted that both long term electronically collected water levels and manual water level measurement were averaged and used together in the subsequent analysis of hydraulic head and flow at the landfill site. Even though there were considerably more electronic measurements (approximately one every 30 minutes over the 30 day averaging period) as compared to the manual measurements (one at high tide and one at low tide) both averaged values are deemed representative of local groundwater levels. This is mainly due to the fact that the manual measurements were obtained at the approximate maximum and minimum water level elevations associated with the local tidal cycles. Any error associated with the manual water level measurements for a particular well location is not expected to significantly alter the general direction of local groundwater flow, since the magnitude of change between the high and low tide cycle groundwater levels at any particular well was generally small (Attachment 10).

6.1.3.3 Correction for Salt Water Influence

One assumption that is commonly applied to the steady-state analysis of groundwater flow is that groundwater of uniform density moves from high hydraulic head in the direction of decreasing hydraulic head. However, where fluid density varies from point-to-point, direct head measurements may not accurately represent true groundwater flow directions. Such is the case where salt water intrusion, which generally exhibits a greater density than freshwater, occurs within the groundwater flow regime. For monitoring points that contain salt water, the conversion to an equivalent head of freshwater can be computed so that in all cases the heads are representative of freshwater for consistent analysis.

The results of groundwater quality analysis and downhole geophysical logging indicate that salt water intrusion occurs beneath portions of the Fresh Kills Landfill. Accordingly, at locations where salt water intrusion is observed through review of water chemistry data, a conversion of

salt water head to freshwater head has been computed through application of the hydrostatic pressure equation (adapted from Kohout, 1960):

$$p = dgl$$

Where: p = pressure at casing terminus (psi)
d = density of water in the casing
g = acceleration due to gravity
l = measured length of water column

Equating the right term of the above equation for freshwater and salt water columns:

$$d_f g l_f = d_s g l_s$$

$$l_f = d_s l_s / d_f$$

where the subscripts of f and s refer to freshwater and salt water, respectively. The density of freshwater is assumed to be 1.00. Table 6.6 summarizes the salt water/freshwater correction computations.

Salt water densities in most bedrock wells were obtained directly from laboratory specific gravity analysis of groundwater collected during the July 1992 sampling quarter. Where data were not available for the July 1992 period (corresponding to the time averaged head period selected for water level analysis), a relationship between total dissolved solids and density was developed to estimate density in intermediate depth and remaining bedrock wells. For the intermediate depth Cretaceous sand wells, the relationship between TDS and density was developed based on a comparison of laboratory values of specific gravity and TDS collected in a series of wells during the January and April 1992 sampling quarters. July 1992 sample data was used to establish the relationship for the bedrock wells. A linear regression was performed for each of the data sets, and a best-fit line describing the equation of the relationship was developed for the Cretaceous sand and bedrock data, as indicated on Figures 6.7 and 6.8, respectively.

While a total of 24 density/TDS analyses were ultimately performed for the Cretaceous sand wells, only eight data sets were initially used to describe the relationship indicated on Figure 6.7. Subsequent analysis of additional data (excluding 3 outliers represented by sample from wells 1W91:IT007I, 008I, and 011I3) did not act to significantly alter the relationship observed in the initial data plot (i.e., equation of regression defined as 7.315 E-4 (x) + 1.0014 for the expanded

data set versus 7.274 E-4 (x) + 1.0013 for the initial data set). All data obtained for the bedrock were incorporated in the analysis indicated on Figure 6.8. The error associated with both data correlations is very small, with the coefficient of determination (r^2) and the standard error of the Y estimate (S_y) for the Cretaceous data set equal to 0.974 and 0.10%, and for the bedrock data set equal to 0.905 and 0.08%. The small unexplained variance from the correlations would result in errors on the order of several hundredths of a foot of less, not significant in terms of application and analysis of the head data for derivation of flow gradients.

Independent relationships were developed for the Cretaceous and bedrock units to minimize the potential for the natural water chemistry within a respective unit to influence the TDS/density relationship. Comparison of the two relationships suggests very little difference in calculated values. Based on a comparison of similar values for TDS, calculated values of specific gravity would be slightly higher (approximately 2 percent for a TDS of 10,000 mg/l and a salt water column of 100 ft) for the relationship developed for the Cretaceous sand unit relative to that developed for the bedrock unit. This variation is not significant in terms of application of the estimated freshwater head data.

6.1.3.4 Transient Water-Level Data

Continuous water-level elevation data can provide for a better understanding of the groundwater flow system under transient conditions (i.e., temporal variations). Groundwater and surface water hydrographs were constructed over a 30-day period from June 17 to July 17, 1992. These hydrographs illustrate the tidal effects on water-level elevations at specific monitoring locations, as well as short-term recharge events, barometric pressure changes and other potential outside influences on water levels. Continuous water level hydrographs for the 30 day period are contained in Appendix J. Consistent with the hydrogeologic analysis, hydrographs are grouped both by hydrostratigraphic unit and well cluster location to aid in planimetric and profile analysis. In addition, Map Sheets J.1, J.2, J.3, J.4 and J.5 contained in Appendix J provide available corrected long term water level data for monitoring well clusters IT001, IT405, IT306, IT163 and IT157, respectively. The period of record indicated on these sheets ranges from July 7, 1991 through December 16, 1992, for a total record length of 520 days.

6.1.3.5 Data Gaps in the Water-Level Record

Data gaps can occur within the overall water-level data base for various reasons. Technical problems with the transducers and/or data loggers (e.g., faulty connection, battery discharge, short circuit, etc.) precluded the collection of transient data at certain installations during all or part of the period of record selected for the current phase of analysis. Where problems were detected, manual measurements were recorded to provide interim estimates of hydraulic head distribution. Bi-monthly downloading of data from recording equipment allowed for timely identification of technical problems, and transducers and/or data loggers were repaired or replaced as quickly as possible. Recording equipment that experienced technical problems at times across the period of record included well locations: 6P91:IT654S, 654D, 659S, 659D; 664D; 6W91:IT151S, 151D; 156I, 156D, 161D, 162D; 1P91:IT504S, 504I, 504D, 507S, 507I, 507D, 515I1, 515I2, 515D; 1W91:IT005I1, 005I2, 005I3, 006I, 007S, 007I, 010I2, 013D; 2P91:IT806S, 806I, 806D; 2W91:IT307I, 307D, 308S, 308I1; and 3W91:IT403S, 403D, 404S, 404D, 405S, 405I1, 405I2, 406S, 406I, 406D, 407S, and 407D.

Another cause for a data gap or partial water-level record is that several installations were not equipped with transducers/data loggers until after the beginning of the 30-day period of record due to prior equipment failure and replacement. Well clusters falling into this category include 2W91:IT303, 304, 305; 3W91:IT405, and 3P91:IT910. Continuous water level records were later reestablished at wells 2W91:IT303D, 304D, 305I, and 305D in December 1991, and continued through December 1992. The water level record for location 2W91:IT305D continued through September 1991. A continuous water level record was established at location 3W91:IT405 in October 1991. The transducers and data logger were removed from this location in January 1992 due to interference from bridge construction activities in the vicinity of this well cluster.

Water level data for bedrock wells 1W91:IT004D, 005D, and 006D were not available in the early stages of the water level monitoring program. At each of these locations, estimates for hydraulic conductivity of the sedimentary rocks are very low, and water levels (as manually recorded in the early stages of the water level monitoring program) were determined to be far below the transducer in each of these wells. Given the low permeability, and a November 1991 well development/rehabilitation event, these wells were still recovering (rising head) during the January 1992 time averaging period used for the Interim Hydrogeological Report. Similarly, at well 1W91:IT007D, a bedrock well that also exhibits very low hydraulic conductivity, the water

level was anomalously high during the January 1992 time period, suggesting that this well was recovering very slowly from a prior in situ slug injection (falling head) test.

Several steps were taken in order to allow continuous water level records to be obtained from wells 1W91:IT004D, 005D, and 006D. Water quality sampling activities at these locations were postponed, either until the end of the sampling quarter or entirely for several sampling quarters, to allow water level equilibrium to be achieved. As a result of these efforts, the continuous water level monitoring record was reestablished at these locations during the spring and summer of 1992.

As indicated in Table 6.5, usable water level data are not available at many of the deep center piezometers due to suspected damage to the riser pipe subsequent to installation. Based on field observations and analysis of data obtained from these piezometers, an installation that exhibited a high probability of hydraulic interconnection with the refuse unit was considered suspect. Piezometers in this category include 6P91:IT654D; 1P91:IT504I, 504D, 507I, 507D; and 3P91:IT910I, 910D. Field observations that included well obstruction, high water temperature, leachate odor and/or staining, coupled with anomalous transient water-level data were used in the evaluation of each installation. Another possible well integrity problem was observed at well 6P89:YP6. Anomalous high water-level elevations were recorded from this installation that are inconsistent with earlier data from this point and are much higher than what would be anticipated at that location based on refuse wells nearby. Vandalism of well clusters 3W91:IT401 and IT402 precluded collection of continuous data from any of the installations at these locations. Finally, a number of existing wells that were listed as operational in the Groundwater Monitoring Well and Piezometer Survey Report (IT Corporation, 1990c; Attachment 43) and suitable for inclusion in this investigation either were not found or could not be accessed. These wells included: 1P89:XP10, XC1B, XC3A, XC3B; 6W81:C25D, C25S; 6W82:S10; and 3W81:S19.

Notwithstanding the above, available continuous data coupled with weekly manual measurement data and periodic tidal cycle measurement at non-instrumented locations (Attachment 10) provided an adequate database for evaluation of hydraulic relationships in plan and profile.

6.1.4 Conceptual Model of Groundwater Flow

Given the available data, the previous discussions have described the distribution of physical properties, boundaries and hydrologic data that form the basis for development of the regional conceptual model for the Fresh Kills Landfill site. Within this report section, these components are integrated to allow for creation of the conceptual model of flow for the entire landfill site. As an introduction to the individual landfill discussions, the regional hydrogeologic setting is described to provide a reference framework.

Based on an analysis of observed flow in streams across Staten Island, as well as water level data from a limited number of shallow wells, Soren (1988) developed a generalized, regional water-table map of Richmond County. In this work, a large scale, Island-wide groundwater mound is identified in the unconsolidated overburden geologic units, which is inferred to include the bedrock units. This groundwater mound establishes a gradient on which the Fresh Kills Landfill is superimposed; any alterations of the physical hydrology caused by the Fresh Kills Landfill must be viewed within the context of this regional gradient. According to the water-table distribution as presented by Soren (1988), a local groundwater divide exists to the south of Landfill Sections 2/8 and 1/9, and is on a line that trends northeast to southwest across Staten Island.

In the vicinity of the Fresh Kills Landfill, regional water-table information as presented by Soren (1988) suggests that flow within the shallow unconsolidated overburden system enters the landfill principally from two directions; from the east toward Landfill Section 6/7, and from the south toward Landfill Section 1/9 and 2/8 from the small, local groundwater divide. These data also suggest that the major surface water bodies of the Arthur Kill, Richmond Creek, Main Creek and the Fresh Kills act as discharge boundaries for the shallow flow system. It should be noted that Soren's description of the hydrogeology of Staten Island segregates the flow system into two basic hydrostratigraphic units, consisting of upper unconsolidated overburden material, and the bedrock. This segregation corresponds to the initial regional landfill conceptual model presented herein. Data are not available to construct a regional map of water level in the bedrock, although Soren's generalized cross-section of Staten Island suggests that mounding of groundwater in the bedrock is subdued but coincident with that of the water table. This suggests that flow of groundwater into the bedrock toward the Fresh Kills Landfill site is probably from the northeast toward the southwest with possibly a smaller component from the south to the north. This

southerly component may not be present and is dependent upon the potential for vertical leakage from the water-table mound south of the landfill to actually reach the bedrock unit. Potential for vertical leakage will be discussed in more detail later in this section.

A similar regional gradient condition can be envisioned for neighboring areas of New Jersey encompassing the glaciated bedrock terrain to the west, and the Coastal Plain area to the south and southwest. Approximate groundwater levels in this region can be estimated by using surface water elevations as a guide. This would indicate generally north-south equipotentials in the area west of Fresh Kills, with an overall easterly gradient. These can be continued southward into the Coastal Plain, showing a similar gradient from the uplands to coastal areas.

Thus, in the larger context, Fresh Kills is a low-lying area with major regional gradients from the northeast and west. It is inferred that a regional divide separates northward flows to New York's Upper Bay and Newark Bay, and southward flow to Raritan Bay, and that Fresh Kills Landfill is located south of such a divide. In summary, regionally, Fresh Kills Landfill probably is more closely related to the Staten Island "groundwater high" than to higher heads in New Jersey, and is located on the southwest flank of the high, with a southwesterly regional gradient.

Figure 6.9 provides a schematic illustration of the regional hydrogeologic setting of the Fresh Kills Landfill within Staten Island. This diagram indicates the generalized groundwater flow system within the unconsolidated overburden and bedrock hydrostratigraphic units at both the area-wide and local scale. Recharge to the regional flow system is derived from the upland areas to the east, with discharge from the bedrock unit to overlying overburden units in the vicinity of the landfill and the Fresh Kills estuarine system. As noted earlier, groundwater flow in the unconsolidated overburden materials is derived primarily from the east/northeast and is either discharged locally into stream channels, or continues as a regional flow component to the south/southwest. In the immediate vicinity of the landfill, that refuse mounds act as local sources for controlling the direction of groundwater flow, with the potential for discharge horizontally to adjacent stream channels, and vertically into underlying unconsolidated overburden materials.

6.1.4.1 Horizontal Head Distribution – Plan View Analysis

- **Refuse**

Sheet 6.32 depicts hydraulic head distributions for the refuse hydrostratigraphic unit, derived from the data base described in Section 6.1.3.2. As indicated, a groundwater mound is associated with each landfill section. Such mounds appear to be pronounced for Landfill Sections 1/9, 2/8, and 3/4, and more subdued for Landfill Section 6/7. The observed differences in mound configuration are presumed to be associated with differences in recharge owing to cover soils, operational aspect, vegetation, etc.; differences in refuse hydraulic conductivity; differences in leakage into the underlying unconsolidated unit; or some combination. As noted earlier, limited data is available to suggest that the indicated leachate mound elevation data is likely representative of perched conditions, with the true surface of saturated refuse significantly lower at Sections 1/9, 2/8 and 3/4 than that depicted on Sheet 6.32. Regardless, the basic horizontal flow pattern is radial from each of the landfill mound centers (some evidence of a small discrete mound in the northern portion of Section 1/9 is apparent, associated with the segregated Muldoon Avenue fill area).

The primary source of groundwater within the refuse unit is recharge derived from precipitation. The amount of precipitation that falls on the landfill and actually becomes groundwater recharge is a very complicated and difficult value to obtain. Several studies (Rovers, et al., 1973; Hughes, et al.,1968; Remson, et al., 1968; Fungaroli and Steiner, 1979) have attempted to determine the mechanisms by which precipitation enters and recharge flows through a refuse unit. Lu, et al. (1985), presents an excellent summary of analytical water balance techniques that have been modified from the soils engineering field, or developed from agricultural soil moisture studies.

Ahmed and Khanbilvardi (1989) developed a mathematical model for Fresh Kills Landfill Sections 6/7 and 1/9 in order to estimate the potential for leachate generation based on recharge through precipitation under unsteady flow conditions. The range of values they determined for the two landfill sections ranged from 9.5 to 19 inches per year, depending on the rate and distribution of recharge. Their work did not take into account the variation in hydraulic properties observed at the site, both areally and vertically.

Another useful method that can be applied to approximate groundwater recharge is to sum the total groundwater flux out of an area, and balance this value with total flux into the area at the appropriate boundaries. For the refuse unit, this involves estimating the sum of groundwater leaving the system either as horizontal or vertical flow components. Simple application of Darcy's Law at the site boundaries can be used to approximate groundwater flow out of the system; dividing this total outflow by the total surface area available for recharge, yields an approximate value of recharge. This analysis is discussed in detail in Section 6.1.4.4.

- ***Unconsolidated Overburden***

The regional unconsolidated overburden hydrostratigraphic unit as a whole has been described as being areally extensive and including all material from the base of the refuse unit to the top of the bedrock unit. In terms of the development of the conceptual model of regional groundwater flow, it is necessary to subdivide the overburden into subunits that further describe the regional flow system.

Water level data obtained from the unconsolidated unit generally represent measurement points completed within higher permeability sand units separated by lower permeability tills, silts and clays. Sheets 6.33 through 6.39 illustrate the distribution of water level elevation data available for the areally correlatable sand units within the overburden, as previously defined in Sections 5.2.4 through 5.2.6.

The low permeability "restrictive" units separating the more transmissive sand units have the potential to produce considerable head loss over relatively short distances. In the case of the Fresh Kills landfill site, where leachate in the refuse unit is at significantly higher water levels than natural groundwater elevations, the majority of flow within these low permeability units probably occurs vertically. This vertical flow potential and corresponding dissipation of vertical head with depth makes for difficult determination of the horizontal flow component, where observation points are completed at different depths within the overburden.

To illustrate this problem, consider two observation points, one which has a well screen located near the top of the overburden unit and the base of the landfill, and the other which has a well screen located at the base of the overburden and near the top of the bedrock. Water-level measurements within the well screened in the upper overburden unit will probably reflect

water-levels near those at the base of refuse, while the well screened at the base of the overburden will reflect water-levels closer to those of the bedrock unit. If significant water level elevation differences exist between the refuse and bedrock units (which they do at the Fresh Kills landfill), then to attempt to contour or draw inferences about the horizontal flow within the overburden based on plan view contours between the two measurement points could suggest a large horizontal flow, where in actuality it is a local vertical head loss that is being observed. Therefore, estimation of representative horizontal flow within the entire overburden sequence using plan view analysis is generally not possible, even though a considerable number of observation points are available, due to the fact that the observation points are generally completed at different elevations.

Two areas where it is possible to determine horizontal flow components within the unconsolidated overburden are within Recent sand Unit 1 (Sheet 6.33) and Cretaceous sand Unit 1 (Sheet 6.38). The relatively high permeability and areally extensive nature of these sand deposits allow for rapid dissipation of water levels in the vertical direction, with larger flow components developing in the horizontal direction. The spatial distribution of hydraulic head data available for these units allow for areal contouring of the data, which in turn allows for estimation of horizontal groundwater flow components within them.

Water level elevation data collected from Recent sand unit 1 wells suggest that lateral groundwater flow within these shallow deposits is controlled by local discharge to nearby surface waters, including the Arthur Kill, Fresh Kills, Main Creek, Richmond Creek and the tributary stream located north of Section 3/4 (Sheet 6.33). Available head data for this unit in Landfill Sections 3/4 and 1/9 indicate a general direction of groundwater flow within the sands away from the center of the landfills toward local surface water discharge areas. For example, beneath Section 3/4, it appears that a water level mounding condition exists coincident with the mounding observed in the refuse above, but to a much lesser extent. This observed mounding condition suggests radial flow in the Recent sand from the central portions of the landfill with discharge southward to Fresh Kills, eastward to Main Creek, and northward and westward across the PASNY site. Similarly, contoured head data within Section 1/9 suggest groundwater flow in the Recent sands from beneath the central portions of the landfill to the nearest surface water body (i.e., Arthur Kill to the west, and Fresh Kills to the north). Although available water level data for this unit in Sections 6/7 and 2/8 are limited, it is likely that horizontal groundwater flow within the Recent sands is similarly toward local surface water bodies in these areas. This

assumption is supported by the typically higher heads observed within the Recent sands relative to water level elevations observed in the adjacent stream channels.

Based on the elevation contours indicated on Sheet 6.33, horizontal hydraulic gradients range from 0.0019 ft/ft to 0.0429 ft/ft. As indicated, hydraulic gradients in the Recent sand within Section 3/4 appear to steepen or increase along discharge boundaries, with generally less steep or decreased gradients observed toward the center of the landfill. Within Section 1/9, relatively low gradients are observed along the western boundary from the central portions of the landfill to the Arthur Kill. Conversely, in the northern portion of Section 1/9, where the sands are less extensive and possibly representative of a distinct channel deposit, the hydraulic gradients are much steeper, and increase downgradient toward the surface water discharge areas.

Sheet 6.38 shows the areal distribution of hydraulic head for the Cretaceous sand Unit 1 hydrostratigraphic sub-unit. The water levels indicated on this Sheet have been adjusted for density variations, as discussed in Section 6.1.3, and represent an equivalent freshwater head for comparison with other areal water-level distribution maps. At well cluster locations where multiple wells screen the Cretaceous sand unit (i.e., 1W92:IT044I1, I2 and I3), an average of the hydraulic head values obtained from the multiple Cretaceous sand wells was utilized in the construction of the water level contour map shown on Sheet 6.38 (refer to Table 6.5).

Regional flow within Cretaceous sand Unit 1 is generally to the southeast, with groundwater flowing from the western edge of Landfill Section 1/9 and from the eastern portion of Landfill Section 2/8 to the southern boundaries of both landfill sections. Hydraulic gradients range from 0.00036 ft/ft beneath the central portion of Landfill Section 1/9, to 0.00429 ft/ft beneath the central portion of Landfill Section 2/8. Due to apparent mounding within the Cretaceous unit, an eastward and westward regional component of flow is also observed within the south central portion of Landfill Section 2/8 (Sheet 6.38).

- ***Bedrock***

The work by Soren (1988) suggests that regional groundwater mounding within the shallow (overburden) flow system also creates similar regional mounds within the bedrock flow system through vertical recharge from the shallow flow system to the deeper flow systems. Regional cross-sectional analysis indicates that any water-level mound development in the bedrock would

be approximately an order of magnitude less in elevation than a corresponding water-table mound above it. Extending the work by Soren from the shallow system to groundwater flow in the bedrock unit would suggest a flow component in the bedrock that is predominantly from the northeast to southwest, with possibly a smaller flow component from the south to northwest.

Sheet 6.40 indicates the regional head distribution within the bedrock hydrostratigraphic unit. As with many data bases, it is possible to vary contour delineation locally, but the piezometric surface for the bedrock is clearly established areally. A regional gradient from the north and east to the south is apparent. Local groundwater mounding is evidenced in reasonably good agreement with Landfill Sections 1/9, 3/4 and 6/7, separated by lows that roughly correspond to surface channels.

The presence of groundwater mounding in the bedrock is a characteristic not evidenced in previous investigations at Fresh Kills. Due to the difficulty encountered in installing and maintaining the deep bedrock piezometers located within the landfill mounds, from which the most direct evidence of mounding within the bedrock unit is obtained, a degree of uncertainty is associated with the veracity of data obtained from them. Assuming these data are representative, they suggest localized areas of radial flow in the plan view perspective except where the flow system is dominated by the regional gradient. The cause for such a pattern can only be either: 1) hydraulic loading, i.e., a downward flux from shallow levels, presumably the landfills; or 2) a pressure effect caused by depression/compaction of the overburden strata due to the weight of the refuse; 3) irregularities in the bedrock piezometric surface associated with an appearance of mounding owing to data limitations; or 4) some combination of the above.

The effects of hydraulic loading from overlying hydrostratigraphic units is discussed in subsequent report sections for the individual landfills and quantified through the use of both two-dimensional, cross-sectional and three-dimensional groundwater flow numerical models.

The pressure increase that can be created by the addition of overburden pressure, such as a landfill, is best described by the theory of consolidation according to Terzaghi (1963). When certain low-permeability soils are loaded (i.e., buildings or landfills are constructed on them) there is at first a slight compaction of the underlying soils. However, eventually, sometimes after a long period of time, compaction of the soil may be considerable. This phenomenon of compaction over time is termed consolidation. Terzaghi has shown that the phenomenon of

consolidation is caused by the slow outflow of the interstitial water contained in the underlying soil. Clay soils are especially suseptable to consolidation.

The theory of consolidation assumes that:

1. The outflow of the interstitial water obeys Darcy's Law.

2. The permeability of the soil does not vary during the consolidation process.

3. The water and the solid elements in the soil are incompressible; compression then means a decrease in porosity.

4. The compressibility of the soil (decrease in porosity) is "elastic", i.e., there is a linear relationship between the effective compression stress and decrease in soil volume.

The mechanism of consolidation assumes that an external overload applied to the soil is absorbed in part by the solid phase (an increase in effective stress) and in part by the interstitial water (an increase in fluid pressure). As a result of this increase in pressure, a transient flow is initiated, the water is drained, and the effective stress gradually increases, causing compaction.

At the beginning of the consolidation process, the excess load is entirely absorbed by an increase in pressure which is slowly transformed into the increased effective stress until the pressure reaches a hydrostatic equilibrium, or there is no water outflow in the soil. Consequently, depending on how the soils react to the stress and the hydraulic characteristics, the pressure change may be quick (high permeability soils) or slow (low permeability soils). The actual pressure change that occurs with depth due to the landfill overpressure is difficult to determine analytically due to the varying thickness and extent of underlying soil material. Cross-sectional numerical model simulations presented latter in this report describe the potential for pressure increases in the bedrock for particular locations within the landfill.

It is possible to approximate an average water flux from a typical Recent silt and clay unit below the landfill (Attachment 40). Assuming a Recent silt and clay thickness of 20 feet, a final refuse thickness of 400 feet and a 20 year consolidation time yields an average consolidation water flux of 55 gal/acre/day or 1.69×10^{-4} ft^3/day. It is apparent that this slow rate of water removal from the low permeability units has the potential to maintain elevated pressures in the underlying low permeability materials (observed as increased, or mounded, water levels).

A comparison of data indicated on Sheets 6.30 through 6.40 clearly shows that the heads in the refuse are higher than in the bedrock, but that the heads in the overburden Recent, glacial and Cretaceous sand units (Sheets 6.33 through 6.39) generally are lower than both overlying and underlying units. This clearly establishes that some areas of bedrock mounding cannot be a flow phenomenon, except potentially at Landfill Section 2/8, which appears to exhibit lower heads in the bedrock relative to other sections. Numerical analysis, provided in later portions of this text, indicate that mounding within the bedrock unit can result from the imposition of compressional forces derived from overlying soils and refuse. The implausibility of a downward groundwater flux as a cause of bedrock mounding, can be further demonstrated by examination of heads in profile, as discussed subsequently.

The need to resolve the cause for mounding is tempered by information presented elsewhere in this report, indicating that groundwater flow from refuse is predominately horizontal. In this context, the issue of mounding in the bedrock hydrostratigraphic unit may be largely academic.

6.1.4.2 Vertical Head Distribution – Profile Analysis

The differences in heads between the three major regional hydrostratigraphic units indicate vertical gradients. These vertical gradients have been calculated between the refuse and the first confined underlying transmissive unit, and between the bedrock and the first overlying transmissive unit. Table 6.7 provides a summary of the vertical gradients determined between major hydrostratigraphic units across the entire landfill, based on the synoptic water level elevation data (Table 6.5). Whereas vertical gradients provide an indication of the potential for upward flow (negative gradient) or downward flow (positive gradient), this is only at individual locations (i.e., one dimension only). Sheets 6.41 and 6.42 illustrate in plan view the distribution of vertical gradients between the refuse and the first confined underlying transmissive unit, and the between the bedrock and the first overlying transmissive unit, respectively. Each of these maps include a notation of the geologic units from which data were obtained to estimate the vertical gradients. Sheets 6.41 and 6.42 provide a general indication of the areas across the landfill where downward (positive) and upward (negative) groundwater flow may potentially occur.

Examination of Table 6.7 suggests that potential large vertical gradients between the refuse and lower units can occur at certain locations within each landfill section. Closer examination of these higher gradient locations suggests that they may not represent the true vertical gradient at the base of the landfill, but are rather an artifact of the data available. The calculation of the vertical gradient was performed at monitoring well locations where, at a minimum, two water levels were available; one in the refuse unit and one below the refuse unit. For most cases, the water level below the refuse unit represents a Recent, glacial, or upper Cretaceous sand unit near the base of the refuse. For several of the vertical gradient calculations locations, however, the only water level available was in the bedrock unit. When coupled with water levels from mounded locations within the center of the landfills, a significant water level difference was calculated at such locations, which in turn resulted in the estimation of large potential vertical gradients. Smaller positive gradients would be exhibited at these locations if data from the base of the landfill and shallower sand units were available for analysis.

A more meaningful, systematic approach to examining vertical flow is through the use of piezometric profiles, bearing in mind that horizontal gradients, in this case radial, also exist. The piezometric profile analysis must take into account the following pertinent observations:

- Generally higher heads in refuse and bedrock than overburden
- Radial flow (plan view) from groundwater mounds in the refuse and, potentially, within areas of the bedrock
- Regional southward gradient

Sheet 6.11 shows the location of the hydrostratigraphic cross-sections. The vertical and horizontal distribution of heads along each section are illustrated in profile on the hydrostratigraphic cross-sections presented on Sheets 6.12 through 6.19. In addition, the vertical and horizontal distributions of hydraulic head were contoured in profile along four selected hydrostratigraphic cross-sections HB, HG, HK and HO, and are shown on Sheets 6.13, 6.18, 6.22, and 6.26, respectively. Hydraulic head data (Table 6.5) were plotted on the selected hydrostratigraphic cross-sections and contoured to provide equipotentials in profile extending from the zone of saturation (water-table) into the bedrock unit. These piezometric profiles illustrate the general hydraulic relationships between hydrostratigraphic units across the site. The delineation of equipotentials in profile reflect the vertical gradients (and where along the

predominate horizontal flow path, the horizontal gradients) between and within the refuse, unconsolidated overburden deposits, and bedrock. It should be noted that where these profiles deviate from established horizontal flow paths, the perspective of horizontal flow with respect to ultimate recharge/discharge relationships can not be considered entirely valid. The selected piezometric profiles are schematic in that the equipotential geometries could be changed to show varying degrees of curvilinear horizontal/vertical flow due to the influence of heterogeneities in the hydrostratigraphic units. However, the profiles provide a graphical indication of hydraulic head relations for the Fresh Kills landfill conceptual groundwater flow models. The analysis of hydraulic head data in profile is considered in more detail during the discussion of each landfill section.

6.1.4.3 Temporal Head Variations

The preceding flow system analysis has been based on assumed steady-state conditions and represents an average of water levels for the period June 17 through July 17. 1992. Over this time period, water-levels fluctuated in response to individual meteorologic events, seasonal and longer-term weather variations, barometric conditions, and tidal influences. The analysis of transient water level data can give insight into how the flow system responds to these events, and their significance in potentially effecting the migration of leachate.

Transient water-level data were evaluated at the Fresh Kills landfill site for evidence of barometric pressure changes, recharge through precipitation and diurnal tidal effects. A total of 85 individual monitoring points was examined with data from the time period June 17 through July 17, 1992. Appendix J presents plots of water levels utilized for the analysis of the transient data for this time period by monitoring well cluster, along with river stage data from three tidal gauges located along the Fresh Kills, Richmond Creek, and Main Creek. In addition, long term water level data for well clusters IT001, IT405, IT306, IT163, and IT157 are presented in Appendix J on Sheets J.1, J.2, J.3, J.4 and J.5, respectively. The period of record for these long term hydrographs range from July 7, 1991 to December 16, 1992 for a total record length of 520 days.

Table 6.8 summarizes the results of this analysis by landfill section for the available transient data, relative to the ability to distinguish discernable tidal effects, barometric effects, and recharge

effects. Evaluation of the analysis presented in Table 6.8 suggests regional trends which can be summarized as follows:

- Tidal effects are generally not observed within the refuse unit, except possibly at the landfill margin where the shallow wells may screen refuse at elevations below sea level and/or screen Recent or glacial sand units. Minor tidal fluctuation observed within the refuse wells can be considered negligible as these temporal head changes have no impact on the general hydraulic relationships within and between hydrostratigraphic units identified at each location (Appendix J).

- Tidal influences within the unconsolidated overburden unit are mixed and are probably more related to their individual distances from the surface water bodies and local stratigraphic continuity.

- Tidal influences within the bedrock suggest that they are not directly in contact with sea water but are dependent on the static pressure changes which occur as the tides fluctuate. Tidal effects within the bedrock also appear to be related to hydraulic conductivity. An example of this is to note that tidal effects are not observable in observation wells IT-405D and IT-406D beneath Landfill Section 3/4, while they are evident in monitoring wells within the bedrock beneath Landfill Section 6/7, immediately across the Main Creek. The difference between those monitoring locations is that the hydraulic conductivity of the bedrock beneath Landfill Section 3/4 in this area is approximately 2.5×10^{-6} cm/sec, while the bedrock beneath Landfill Section 6/7 in this area exhibits an hydraulic conductivity of approximately 2.2×10^{-4} cm/sec.

- Barometric pressure effects were observed to occur in both the bedrock and overburden units where tidal effects were relatively small or not observed. Barometric effects were also observed in the refuse unit, with the most noticeable effects in Landfill Section 1/9 and the least effect in Landfill Section 6/7. The relative importance of this effect will be discussed in greater detail within the description of the conceptual flow system for the individual landfill sections later in this section.

- Recharge through precipitation was generally most noticeable at Landfill Section 6/7 and least noticeable at Landfill Section 1/9.

- Local surface waters, including the Arthur Kill, Fresh Kills Main Creek, and Richmond Creek, are all tidally influenced, and all relatively to the same extent.

- Analysis of the long-term water level hydrographs (Sheets J.1 through J.5) indicates that the flow system is generally in a steady state condition, with little overall trends for an increase or decrease in water levels. This supports the results of the analysis of the 30-day period of record hydrographs (June 17 - July 17, 1992) provided above.

6.1.4.4 Regional Flux Analysis

A conceptual model analysis is not complete without a description of the general quantitative distribution of groundwater across the model boundaries, and to the extent possible, between major hydrostratigraphic units within the model area. For the Fresh Kills Landfill an analytical analysis was performed using Darcy's Law to solve for the rate of groundwater flow vertically between the three major hydrostratigraphic units of refuse, unconsolidated overburden, and bedrock, and horizontally across a set of defined lateral boundaries.

The selection of the lateral boundaries was based on the availability of hydrogeologic information along the perimeter of the site. The perimeter cross-sections as presented in report Section 5.0 and shown on Sheets 5.24, 5.25, 5.26, and 5.27 for Landfill Sections 1/9, 2/8, 3/4, and 6/7, respectively, were selected as describing the lateral boundaries in significant geologic detail. The location of the perimeter cross-sections (refer to Sheet 5.5) define the surface areas used in the flux analyses conducted for the individual landfill sections presented in subsequent sections of this report. The areas determined for each landfill section based on the location of the perimeter cross-sections are as follows:

Landfill Section	Area (ft^2)
1/9	20,194,301
6/7	13,135,496
2/8	9,977,608
3/4	7,866,495

A discussion of the procedure applied for the derivation of vertical and horizontal flux estimates is provided below. Attachment 31 provides a summary of the detailed flux analysis including all data inputs, calculations, summary tables, planimetric maps and cross-sections.

- ***Vertical Flux Calculations***

Estimates of vertical flux were derived from field-collected data and Darcy's Law to quantify the volume of groundwater moving vertically between the major hydrostratigraphic units underlying the Fresh Kills Landfill site, including the refuse, overburden and bedrock. Vertical flux

estimates were determined for individual landfill sections based on the spatial distributions of hydrogeologic data presented in this report, including stratigraphic, hydraulic conductivity and hydraulic head data. The perimeter cross-section locations shown in plan view on Sheet 5.5 define the areas within each landfill section for which vertical flow was approximated.

To calculate vertical flux, an analytical analysis was performed employing Darcy's Law in the form:

$$Q = KIA$$

Where:
- Q = groundwater flux, in ft^3/day
- K = hydraulic conductivity, in ft/day
- I = hydraulic gradient, in ft/ft
- A = planar area, in ft^2

The Darcy approximation for groundwater flux assumes that flow is laminar and that inertia can be neglected.

The first step in determining the vertical flux between the hydrostratigraphic units was to quantify the vertical leakage occurring at discrete locations where hydrogeologic data were available. Vertical leakage is the velocity term of the Darcy equation which represents the rate of vertical groundwater flow from one unit to another. In the case of the refuse hydrostratigraphic unit, vertical leakage was determined between the refuse and first underlying transmissive unit (sand or bedrock) separated from the refuse by a low permeability restrictive or confine unit. Similarly, in the case of the bedrock hydrostratigraphic unit, vertical leakage was determined between the bedrock and the first overlying transmissive unit (sand or refuse).

Vertical leakage was determined at discrete locations by multiplying the vertical hydraulic conductivity (K) of the low permeability confining unit by the vertical hydraulic gradient (I) calculated across the entire thickness of the confining unit. Tables A31.1 and A31.2 in Attachment 31 provide summaries of the vertical leakage calculations between the refuse and first underlying confined transmissive unit; and between the bedrock and first overlying transmissive unit, respectively. Positive values of vertical leakage between the refuse and first underlying transmissive unit indicate downward vertical flow while negative values indicate upward flow

between these units. Likewise, positive values of vertical leakage between the bedrock suggest downward flow to the bedrock from the overlying units while negative vertical leakage indicates upward discharge from the bedrock.

Values of vertical hydraulic conductivity used in calculating vertical leakage were obtained from laboratory permeability test results of fine-grained soil samples collected from the confining unit horizon (Table 6.2). If multiple K data were available at a location, a geometric mean of these data were utilized in the calculation. At boring locations where hydraulic conductivity data were not available for an intervening confining unit, the geometric mean value (Table 6.3) for the specific landfill section and lithologic unit was applied in the calculation.

Vertical gradients (indicated on Sheets 6.41 and 6.42) were calculated at well cluster locations where well installations screened multiple transmissive horizons (i.e., refuse, sand, bedrock). Vertical gradients were determined as follows:

$$I = \frac{H_1 - H_2}{L}$$

Where:

	I	=	hydraulic gradient, in ft/ft
	H_1	=	hydraulic head of first unit, in ft
	H_2	=	hydraulic head of second unit, in ft
	L	=	distance between head measurements, in ft

The distance (L) between H_1 and H_2 was determined by subtracting the elevation of the midpoint of the well screen interval of the H_2 monitoring well from the elevation of the midpoint of the screen interval for the H_1 installation.

In addition to determining vertical gradients at monitoring well clusters (which were predominantly located at the landfill perimeters), vertical gradients were also approximated at single well locations within the central portions of the landfill sections by interpolating hydraulic head data and confining unit thickness data depicted on the hydrostratigraphic cross-sections. At these locations, a single head value was available, typically H_1 and a second H_2 head value was inferred from available hydraulic head distributions. The distance (L) between H_1 and H_2 values was assumed to be the thickness of the intervening confining unit. Vertical leakage data

interpolated from hydrostratigraphic cross-sections and hydraulic head data are included on Tables A31.1 and A31.2 in Attachment 31.

The next step in determining vertical flux was to delineate the areal distribution of vertical leakage across the entire Fresh Kills Landfill site. This was accomplished by plotting the vertical leakage estimates summarized in Attachment 31 Tables A31.1 and A31.2 at their respective locations, gridding, and then contouring these data to illustrate the spatial distribution of vertical leakage across the landfill. The vertical leakage data were gridded, contoured and plotted using the SURFER graphics program (Golden Software, Inc.). Plots of the distribution of vertical leakage were then imported into AutoCad and superimposed on the hydrogeologic base plan. Sheet A31.1 in Attachment 31 illustrates the distribution of vertical leakage between the refuse hydrostratigraphic unit and the first confined transmissive unit. Sheet A31.2 in Attachment 31 illustrates the distribution of vertical leakage between the bedrock hydrostratigraphic unit and the first overlying transmissive unit. On each of these maps, areas of positive (downward) and negative (upward) vertical leakage have been highlighted within the perimeter cross-section boundaries of each landfill section. A summary of the areas of positive and negative vertical leakage is included within the legend of each map. Vertical leakage contour intervals, generally one half order of magnitude, are also presented in the legend of each map.

The final step in determining vertical flux was to calculate the volume (Q) of downward or upward vertical flow from or to the refuse and bedrock hydrostratigraphic units by multiplying the vertical leakage term by the areas defined within each of the perimeter cross-sections. This was accomplished by using the SURFER "Volume Cut and Fills" option, which computed net volumes (flux, ft^3/day), planar areas of cuts (positive leakage) and fills (negative leakage), and volumes (flux, ft^3/day) of the positive and negative leakage components. This program integrated the area under each of the individual contoured values of vertical leakage (at gridded node locations) then summed these volumes to obtain the positive (downward) vertical flux, the negative (upward) vertical flux, and net vertical flux for each individual landfill section.

The Cut and Fill calculations were completed for both the refuse hydrostratigraphic unit and bedrock hydrostratigraphic unit for each landfill section, with results included in Attachment 31. Table A31.3 of Attachment 31 provides a summary of the results of the vertical flux analysis, presenting the positive and negative vertical fluxes for the refuse and bedrock, and the resultant net vertical flux within each landfill section.

- ***Horizontal Flux Calculations***

A plan view of the perimeter cross-section locations for each of the landfill sections is shown on Sheet 5.5 as well as in Attachment 31 on Sheet A31.3. Landfill perimeter hydrostratigraphic cross-sections were developed to define the distribution of hydrostratigraphic units and hydraulic head along the lateral boundaries, and are illustrated on Sheets A31.4 through A31.17 in Attachment 31. To facilitate horizontal flux analysis, each perimeter hydrostratigraphic cross-section was divided into smaller segments and assigned a segment number. Segment numbers for each landfill section are also shown on Sheet A31.3 in Attachment 31. Horizontal flux calculations were then performed for each individual segment number in each landfill section. It should be noted that the regional horizontal flux calculation contains only those segments from the individual landfill sections that are along a lateral boundary exterior to the entire landfill complex. Additional segments were needed to span between the individual landfill sections and make the circumferential boundary complete. These additional section locations are indicated on Sheet A31.3 of Attachment 31 as segments 1C -5C. Figure 6.10 shows a typical segment from the hydrostratigraphic cross-section from Landfill Section 1/9.

Similar to the vertical flux calcuations, to solve for horizontal flux using Darcy's Law, values of hydraulic conductivity, cross-sectional area and horizontal gradient are required. The cross-sectional areas for the individual hydrostratigraphic units were obtained from the perimeter hydrostratigraphic cross-sections contained in Attachment 31. Values of hydraulic conductivity for hydrostratigraphic units were obtained from available in situ or laboratory test results within each individual perimeter cross-section segment. For the case where more than one hydraulic conductivity value was available, a geometric mean value was calculated and applied to the individual unit within that segment. Horizontal gradients for the individual hydrostratigraphic units were obtained directly from the distribution of water level elevation data available for each unit, as illustrated in plan view on Sheets 6.32 through 6.40, and illustrated in profile on the hydrostratigraphic cross-sections (Sheets A31.4 through A31.17 in Attachment 31). For individual units where water level elevation data were not available, gradients were estimated from the vertical distribution of hydraulic head across various confining units. Finally, the total horizontal flux was calculated by summing the individual fluxes within a segment for a major hydrostratigraphic unit, and then summing the major hydrostratigraphic unit fluxes from each segment for the entire landfill boundary to produce a net flux of groundwater for the major hydrostratigraphic units.

Positive values of horizontal flux indicate groundwater flow out of hydrostratigraphic units across model boundaries while negative values of horizontal flux indicate flow into hydrostratigraphic units across lateral boundaries. The hydrogeologic data input and results of the horizontal flux analysis are provided in summary tables contained in Attachment 31.

- ***Results of Regional Flux Analysis***

The results of the vertical and horizontal flux analysis for the regional area described above are illustrated schematically in Figure 6.11. Examination of the net fluxes for the regional area shows that in general, groundwater flow is mainly horizontal within the refuse unit, with a downward flux into the unconsolidated units. The unconsolidated unit also receives a net influx of water from the bedrock which, combined with that from the refuse, leaves as a horizontal component. At the regional scale, net vertical downward flux represents about 18 percent of the total flux out of the refuse unit. It should be noted that in the analytical flux analysis, shallow overburden sand units in direct hydraulic contact with the refuse unit are included with the refuse unit in the estimation of vertical flux. While this results in somewhat of an underestimation of vertical flux to the overburden, flow in these shallow sands is primarily lateral to surface waters (as in the refuse); consequently, their incorporation with the refuse unit does not significantly effect the estimation of flux to deeper transmissive units within the overburden or to the bedrock.

The regional fluxes presented are generally not amenable to detailed analysis, nor do they balance because they do not consider the horizontal flux from the refuse/unconsolidated units to internal surface water boundaries. Individual net flux calculations for each landfill section (provided subsequently) provide a better description of the net flux across vertical and lateral boundaries for each landfill section and allow for mass balance determinations.

6.1.4.5 Well Pumping

The present conceptual model indicates primarily local and shallow flow for leachate within the refuse unit. Furthermore, based on available data, the Cretaceous units at Fresh Kills are believed to be representative of Lower Cretaceous or lower Upper Cretaceous sediments, as compared to pumping centers in the middle and upper units of the Upper Cretaceous in adjacent areas of

New Jersey. Thus, the potential for hydraulic connection between the units is presumed to be low given extensive thicknesses of confining units between the Cretaceous aquifer units.

Within the context of scientific inquiry, the potential for connections between Fresh Kills and pumping centers can be briefly considered. Data pertaining to head distributions in major aquifers in New Jersey, including pumping center effects, are provided in the Hydrogeological Literature Review (IT Corporation and Wehran EnviroTech, 1991a; Attachment 44):

- **Sheet 55** – Middle Cretaceous aquifer; more or less equivalent to Farrington Sand; heads in the nearest pumping center range from -75 at its center, to significantly below sea level along the south shore of Raritan Bay.
- **Sheet 56** – Upper Cretaceous; more or less equivalent to Old Bridge Sand; maximum heads at -40 feet, also with heads well below sea level along the coast.
- **Sheet 57** – Upper Cretaceous; more or less Englishtown formation; apart from the heads at pumping center, the distribution of the outcrop pattern for this unit makes a connection with the Fresh Kills Landfill unlikely.

Thus, the available data suggest heads south of Fresh Kills related to pumping centers that are well below sea level, and have southward gradients in relation Fresh Kills. This compares with a southward gradient at Fresh Kills for the Cretaceous, with heads at the downgradient margin which are slightly below sea level.

If the geologic units are continuous (i.e., the same Cretaceous units), the indication from the head relations would be either: 1) natural flow at Fresh Kills could be southward toward and into a pumping center; or 2) the cone of depression could extend beneath Fresh Kills. In either case, the potential for a hydraulic connection would exist. Available information from microfossil analyses and literature review in Section 5.0 suggest that Cretaceous strata in the Fresh Kills area are likely separated from primary water supply aquifers in New Jersey by thick, overlying confining beds of silt and clay. Seawater degradation of the Cretaceous sands at Landfill Section 1/9 (as described in Report Section 7.0) mitigates against the potential effects of a dilute leachate influence in this unit on possibly correlative strata to the west and south.

6.1.4.6 *Primary-Principal Aquifer and Critical Stratigraphic Section*

6 NYCRR Part 360 regulations contain a variety of elements that relate to issues bearing directly on matters of public health and resource protection. One of these relate to "Primary Water Supply Aquifers" and "Principal Aquifers". Both designations refer to highly productive water supply aquifers; the only difference in their assignment is that the former represents an aquifer that is currently used as a source of public water supply by major municipal water supply systems, while the latter represents a geologic unit (or units) that are known to be highly productive (or whose geology suggests abundant water supply) but is not used as a public water supply at the present time. In the case of this investigation, as public withdrawals of potable water from groundwater are not permitted on Staten Island (IT Corporation, 1991a), the issue is if any aquifers exhibiting a significant water supply potential exist within a potential zone of influence of the Fresh Kills Landfill. The obvious candidate is the Cretaceous sand unit located primarily beneath Landfill Sections 1/9 and 2/8.

Based on NYSDEC criteria (TOG 86W57) relating to resource potential (i.e., thickness, areal extent, and yield potential), the Cretaceous sand unit would qualify as a Principal Aquifer. However, from the perspective of water quality, the Cretaceous unit beneath portions of Landfill Section 1/9 is not potable owing to saltwater intrusion. (Reference is made to the geophysical results presented in Section 5.0 and the water quality analytical results presented in Section 7.0 of this report). Based on the available data, the conclusion is reached that although a Principal Aquifer may exist in the zone of influence of Fresh Kills Landfill, the future potential usability of the resource may be questionable due to natural water quality properties, at least in the immediate vicinity of Section 1/9. It should be noted that evidence of saltwater intrusion within the Cretaceous unit is noted in the literature within Staten Island (Soren, 1988), and is present to the south of the landfill, relative to the abandonment of the South Shore Golf Course irrigation supply well due to progressive increases in the chloride content of the well discharge (Section 4.1.2).

The bedrock water bearing unit underlying the project area represents a potential water supply aquifer, although its yield characteristics are highly variable. Due to the regional extent of bedrock aquifer systems (complicating the ability to map specific land areas where these aquifers would be vulnerable to contamination from overlying land areas), NYSDEC does not currently include bedrock aquifers within the Primary or Principal aquifer designations.

Within the context of 6 NYCRR Part 360, the critical stratigraphic section pertains to those stratigraphic units exhibiting a reasonable potential to be affected by the migration of landfill leachate contamination. The term "potential" in this case pertains to both physical and chemical aspects (i.e., flow and transport), and to both short- as well as long-term perspectives.

Based on the results of stratigraphic analysis, and the findings of the ensuing numerical groundwater flow analyses, such a potential exists within the shallow unconsolidated overburden deposits (Recent/glacial sands) underlying all landfill sections, as well as the deeper Cretaceous sand units underlying Landfill Sections 1/9 and 2/8. The observed hydraulic head distribution, and the results of numerical flow and solute transport analyses indicate a very limited potential for leachate migration to the bedrock. However, since such a potential does exists (primarily in the northern portions of the project area where thick Cretaceous sediments are absent), the bedrock unit must also be considered within the critical stratigraphic section.

6.2 Landfill Section 6/7

6.2.1 Conceptual Model

6.2.1.1 Hydrostratigraphic Units

The major hydrostratigraphic units of refuse/fill, unconsolidated overburden, and bedrock described for the regional conceptual groundwater flow model in the preceding sections also comprise the basic hydrostratigraphy beneath Landfill Section 6/7. These primary hydrostratigraphic units provide the framework for evaluating groundwater flow within and across landfill section boundaries from both a qualitative and quantitative perspective. As previously described, the overburden unit can be further divided into hydrostratigraphic sub-units consisting of transmissive units (sands) and restrictive fine-grained units (silt and clay, glacial till). The hydrostratigraphy of Landfill Section 6/7 is best illustrated in profile on north-south trending hydrostratigraphic sections HE, HF, HG, HH and east-west trending sections HK, HL, HM, HN, HO and HP shown on Sheets 6.16 through 6.19, and 6.22 through 6.27, respectively.

The refuse/fill hydrostratigraphic unit covers almost the entire landfill section (Sheet 5.30) extending east of Main Creek, northeast of Richmond Creek, and west of Richmond Avenue

Creek (the small tributary stream lying to the east of the landfill mound and west of Richmond Avenue). The majority of the refuse/fill unit is underlain by fine-grained Recent deposits of silt, clay and peat that exhibit low permeability characteristics. Refuse/fill overlies glacial till or glaciolacustrine silts and clays in the former upland area located in the eastern portion of Landfill Section 6/7. The refuse unit is generally not in direct contact with transmissive sand horizons with the exception of a localized lense of Recent sand in the northeast (6B91:IT654 and 6Z93:IT792) and an isolated pocket of glacial sand at the 6W89:YW-2 well location. At each of these locations, the discontinuous sand units are separated from other transmissive sand and/or bedrock units by substantial thicknesses of low permeability deposits.

The unconsolidated overburden hydrostratigraphic unit beneath Landfill Section 6/7 consists predominantly of fine-grained low permeability silt and clay deposits which act to restrict groundwater flow. Restrictive hydrostratigraphic sub-units include Recent silt and clay, glaciolacustrine clay, glacial till, Cretaceous clay, and residual clay, where present. The dense glacial till unit is primarily comprised of a fine-grained matrix that acts to limit the permeability of this unit. However, due to the heterogeneity of this restrictive unit, the glacial till deposits are differentiated on the hydrostratigraphic cross-sections. A detailed discussion of the occurence and spatial distributions of the restrictive units is presented in Section 5.4.1.

Within the predominantly fine grained overburden sequence, transmissive sand units occur as distinct horizons where preferential groundwater flow may occur. Transmissive hydrostratigraphic sub-units beneath Section 6/7 include Recent, glacial and Cretaceous sands. Recent sand deposits underlying Landfill Section 6/7 have been correlated to Recent sand Units 1, 6 and 7 (Sheets 5.36 and 5.37). Recent sands tend to occur at the base of the Recent silt and clay and most likely were deposited as channel sands in a marsh environment. Recent sand Unit 1 is the most areally extensive transmissive unit beneath Section 6/7. Unit 1 occurs beneath nearly one-third of the landfill, extending beneath the central portions of the fill area and also across Main Creek and Richmond Creek into Sections 3/4 and 2/8, respectively. Recent sand Units 6 and 7 occur within the southernmost area of the landfill and appear to be of limited extent.

Glacial sands occur scattered throughout the glacial sequence beneath Section 6/7 and occur above or within the glaciolacustrine silt and clay, and above, below and within the glacial till. Glacial sand deposits within Section 6/7 have been correlated to glacial sand Units 1, 2, 3, 4, 5,

11, 12, 16, 19, 21, 22, and 23A (Sheets 5.49 and 5.50). These transmissive units typically occur as individual sand lenses varying in areal and vertical extent, and are generally not correlatable. However, glacial sand Unit 1 located in the northwest area of the landfill, and Unit 5 located in the southwest portion of the landfill, may be correlative to glacial sands across Main Creek into Section 3/4 (Sheet 5.49).

As depicted on Sheet 5.93, Recent sand deposits were found to be vertically in direct contact with glacial sand deposits at a single location beneath landfill Section 6/7 (6B93:IT722). The combined sand unit beneath the western central portion of Section 6/7 is interpreted as being of limited areal and vertical extent (Sheet 6.19). Likewise, the lateral interconnection of Recent and glacial sand units is limited across the landfill section such that most sand layers, with the exception of those previously discussed, are of limited extent both laterally and vertically.

Cretaceous sand deposits were encountered in only two borings in the southernmost portion of Section 6/7. These Cretaceous sand deposits were correlated to Cretaceous sand Unit 6 (Sheet 5.64) and are correlated as being of limited extent, and not interconnected with other transmissive units within the landfill boundaries. These deposits are interpreted as being located adjacent to the "Fall Line" boundary, where the Cretaceous sequence originates and the bedrock surface slopes steeply to the south.

The bedrock hydrostratigraphic unit is comprised of the Triassic Stockton Formation in the northwest and Ordovician Serpentinite in the southeast; a chlorite schist was encountered in the southernmost portion of the landfill (Sheet 5.82). The bedrock occurs at relatively shallow depths in the northeast and dips westward over most of landfill Section 6/7. In the south central portion of the section, a bedrock saddle occurs. South of the saddle, the bedrock surface dips steeply to the southeast (Sheet 5.74). The upper surface of the bedrock is characterized as weathered bedrock across the majority of the landfill (Sheet 5.71), with the exception of two areas within the central portion of the landfill, where competent bedrock occurs at the surface of the bedrock unit. The bedrock hydrostratigraphic unit is predominantly overlain by low permeability deposits of residual clay, glacial till or glaciolacustrine sediments. There are exceptions, however, where discontinuous pockets of glacial sand at the base of the glacial sequence are in direct contact with the bedrock unit (refer to Sheets 6.18, 6.19 and 6.22).

6.2.1.2 Hydraulic Conductivity Distribution

Figure 6.12 presents the distribution of hydraulic conductivity by stratigraphic units for Landfill Section 6/7. The areal distributions of K data available for transmissive horizons underlying landfill sEction 6/7 are shown on plan maps 6.2 through 6.10. Refuse permeability values range from a minimum of 5.1×10^{-6} cm/sec to 3.6×10^{-1} cm/sec as estimated through in situ testing. The geometric mean value for refuse hydraulic conductivity in Landfill Section 6/7 is estimated as 5.7×10^{-3} cm/sec. Refuse K tends to cluster in the 10^{-4} to 10^{-2}cm/sec range (Tables 6.1, 6.2 and 6.3).

The unconsolidated overburden deposits within Landfill Section 6/7 are comprised predominantly of silt and clay materials exhibiting very low permeability. The hydraulic conductivity of the restrictive and transmissive sub-units within this deposit are summarized, as follows:

Restrictive Units	Kv	
	Range	**Geometric Mean [a]**
Recent Silt & Clay	10^{-7} to 10^{-8} cm/sec	1.3×10^{-7} cm/sec
Glacial Clay	10^{-6} to 10^{-8} cm/sec	2.3×10^{-7} cm/sec
Glacial Till	10^{-5} to 10^{-8} cm/sec	2.0×10^{-6} cm/sec

[a] Laboratory Kv data

Transmissive Units	Kh	
	Range	**Geometric Mean [b]**
Recent Sand	10^{-3} to 10^{-5} cm/sec	1.4×10^{-4} cm/sec
Glacial Sand	10^{-2} to 10^{-3} cm/sec	7.5×10^{-3} cm/sec

[b] In situ Kh data

Limited or no hydraulic conductivity data is available for Cretaceous clay and residual clay in Landfill Section 6/7, and these units have been grouped as restrictive sub-hydrostratigraphic units in accordance with lithologic descriptions of the material, and correlation with hydraulic conductivity values for these units across the site (Figure 6.2). Data for the transmissive units

is based on a limited number of hydraulic conductivity estimates derived from in situ testing. In situ hydraulic conductivity estimates for undifferentiated bedrock (including weathered bedrock) range from 3.61 x 10^{-8} cm/sec to 1.7 x 10^{-3} cm/sec (Sheet 6.10). The geometric mean value for all undifferentiated bedrock permeabilities is 3.7 x 10^{-5} cm/sec. The geometric mean value for bedrock, excluding weathered bedrock, is 3.5 x 10^{-5} cm/sec. The geometric mean value for wells screened in weathered bedrock only, is 1.4 x 10^{-5} cm/sec. Figure 6.2A indicates the bedrock hydraulic conductivity distribution by formation type and weathering characteristics for Landfill Section 6/7.

6.2.1.3 Thickness Distribution

The total thickness of the refuse, the saturated thickness of the refuse, and the thickness of the overburden hydrostratigraphic units are shown in plan view on Sheets 5.30, 6.30, and 6.31, respectively. Hydrostratigraphic unit thickness distributions for Landfill Section 6/7 are presented in profile on Sheets 6.17 to 6.19 (north-south trending sections), and Sheets 6.21 to 6.27 (east-west trending sections). As indicated, refuse thicknesses generally are on the order of 40 to 70 ft, resembling a broad area-fill. Of greater significance, the saturated thickness of the refuse appears to be less than 10 ft across the entire section (Sheet 6.30). Overburden thicknesses vary, with increasing thickness from east to west, and notably thicken in the southeast, where a Cretaceous sequence develops. Overburden thickness ranges from 8 ft at 6B91:IT656 to greater than 145 ft at 6W91:IT157 (refer to Sheet 6.31 and the previously referenced hydrostratigraphic sections).

The Recent sand channel deposits range in thickness from 0.5 to 9.5 ft, and are typically less than 5 ft thick beneath Section 6/7 (Sheet 5.38). The glacial sand deposits underlying Landfill Section 6/7 range in thickness from 0.5 ft to 21 ft and are generally less than 10 ft thick (Sheet 5.55). The Cretaceous sand deposits found in the southernmost section of Landfill Section 6/7 range from 10 to 23 ft thick (Sheet 5.67). The hydrostratigraphic cross-sections (Sheets 6.12 - 6.29) provide in profile a more detailed presentation of the spatial variations in thickness and correlation of the transmissive sub-hydrostratigraphic units as well as the restrictive confining units within the overburden sequence.

6.2.1.4 Boundary Conditions

The boundary conditions for Landfill Section 6/7 include many of the same elements identified for the regional flow system:

- Surface waters
- Infiltration
- Bedrock base
- Regional gradients

The refuse unit for Landfill Section 6/7 has lateral surface water boundary conditions that consist of the Main Creek on the north and west, Richmond Creek on the southwest, and the north and south branches of the Richmond Avenue Creek on the east. The upper boundary of the refuse is open to the atmosphere and receives recharge through precipitation, while the lower boundary for the refuse is the contact with the underlying unconsolidated overburden unit. The unconsolidated overburden unit lateral boundaries are generally considered flux boundaries, as the units are areally extensive across the entire landfill site. The upper portion of the unconsolidated unit has the Main Creek and Richmond Creek as lateral boundaries on the north, west, and south, depending on the depth of each surface water body (refer to the hydrostratigraphic cross-sections). The small Richmond Avenue Creek on the eastern side of 6/7 also serves as a boundary to flow in the upper portion of the unconsolidated unit, again depending on the bottom elevation of the stream which flows through the unit. The unconsolidated unit has the contact with the refuse unit as its upper boundary and the contact with the bedrock unit as its lower boundary. The bedrock lateral flow boundaries are considered flux boundaries, again, due to the areally extensive nature of the unit. The upper bedrock boundary is the contact with the unconsolidated unit.

6.2.1.5 Conceptual Model of Groundwater Flow

As discussed in the conceptual model for the regional flow system, the conceptual model of groundwater flow is derived based on the distribution of hydraulic properties, corresponding thicknesses, boundary conditions, and fluxes. The synthesis of these conditions produces the three-dimensional distribution of hydraulic head. The description of this three-dimensional

system can be divided into plan and profile view analysis to determine both the potential for horizontal and vertical groundwater flow, respectively, within the flow system.

6.2.1.5.1 Plan View

The horizontal distributions of available hydraulic head data for the refuse, differentiated unconsolidated overburden, and bedrock units are shown on Sheets 6.32 through 6.40. As discussed earlier, groundwater levels within the refuse unit can be affected by the presence of stratified unsaturated zones. At Landfill Section 6/7, this condition was observed in the refuse unit at test well locations 6P92:ATW-I and ATW-S4. Comparison of water levels between shallow/deep piezometer pairs installed in Section 6/7 (6P91:ATW-S/ATW-S2; 6P92:ATW-S3/ATW-S4) indicate perched conditions in the upper refuse (head elevation 40 - 50 ft). Head measured in the basal refuse deposits exhibit an elevation in the range of 5 - 8 ft. These latter data were used in the construction of refuse water level elevation contours on Sheet 6.32 (insufficient data were available in other landfill sections to estimate the head distribution in the lower, fully saturated refuse deposits).

Horizontal groundwater flow within the refuse unit is radially outward from the central portion of the landfill toward the surface water bodies that surround the landfill section. The horizontal gradient is fairly uniform outward from the central portion of the landfill section and ranges from approximately 0.002 to 0.005 ft/ft. This fairly uniform and generally low gradient suggests that the refuse materials may be fairly uniform and exhibit a high permeability. This hypothesis is supported by the data presented in Figure 6.12, which indicates refuse hydraulic conductivity values obtained from in situ testing in the range of approximately 10^{-1} to 10^{-3} cm/sec.

Available hydraulic head data for overburden transmissive sub-hydrostratigraphic units are limited and do not allow for planimetric analysis of groundwater flow within these units. However, as described earlier in Section 6.1.4.1, it is not unreasonable to assume that for the areally extensive REcent sand unit 1 deposits, horizontal groundwater flow is generally away from central portions of the landfill toward local surface water bodies. Again, this is supported by the limited available head data for Recent sand unit 1 which were higher than the head observed in nearby stream channels.

As illustrated on Sheet 6.40, horizontal flow within the bedrock unit generally corresponds to the regional flow system as presented by Soren (1988), with flow generally from the east toward the west, with components toward the northwest and southwest, and a small component to the southeast in the southern area of the landfill.

An interesting feature of flow within the bedrock unit beneath Landfill Section 6/7 is the presence of a local groundwater trough along the western boundary of the landfill. Groundwater in the bedrock appears to flow from both the east and west toward this trough, with the main discharge axis of the trough toward the south. Available data suggest that the axis of the trough is located beneath the Landfill Section 6/7 western boundary. It is possible that this axis actually follows the centerline of the Main Creek, which would naturally serve as a potential regional discharge point for flow within the bedrock. Further, examination of Sheet 6.10 indicates that the undifferentiated bedrock hydraulic conductivity is generally higher within this groundwater trough area, allowing for the development of a localized hydraulic sink which, in turn, can act as a regional discharge conduit by enabling groundwater to be conveyed more rapidly to the south and the southwest within the bedrock unit.

6.2.1.5.2 Profile View

The vertical distribution of water levels and the general flow of groundwater at Landfill Section 6/7 is shown in the east-west piezometric profile illustrated on Sheet 6.26, and in the north-south piezometric profile illustrated on Sheet 6.18. It should be noted that while neither of these profiles were aligned to be along a flow path, (with the vertical head distribution therefore potentially affected by horizontal flow components), they do serve as a means to generally describe the vertical flow component at the site, and to draw conclusions as to the sources of recharge/discharge within the vertical flow system.

The vertical distribution of water levels for the east-west profile shown on Sheet 6.26 suggest that flow is generally horizontal in the bedrock with an upward gradient indicating potential discharge to the Fresh Kills or Main Creek. Shallow flow components within the refuse unit indicate a mound that discharges laterally to the Richmond Avenue Creek on the eastern landfill boundary, and to the Fresh Kills or Main Creek on the western landfill boundary. Groundwater

flow within the overburden is horizontal away from a sleight groundwater mond or divide beneath the e\center of the landfill with potential discharge to nearby surface waters.

The vertical distribution of water levels for the north-south profile shown on Sheet 6.18 suggest a flow system similar to that depicted in the east-west profile. Flow in the deeper bedrock system is generally horizontal with vertical upward gradients tending toward Main Creek to the north and Richmond Creek to the south. Downward vertical gradients from the overburden to the bedrock can be observed beneath the central portion of the landfill coincident with minor mounding in the refuse above. Groundwater flow in the overburden is controlled at the lateral boundaries by the surface water discharge areas. Groundwater mounds within the landfill refuse unit do not appear to significantly affect groundwater flow in the unconsolidated or bedrock units beyond the central portions of the fill area.

In addition to the piezometric profiles, vertical distributions of hydraulic head are depicted on the hydrostratigraphic cross-sections without equipotentials contoured. The general flow relationships between major hydrostratigraphic units are illustrated by the vertical distributions of head and are graphically summarized in plan view on Sheets 6.41 and 6.42. As shown on Sheet 6.41, positive or downward vertical gradients generally occur between the refuse and first confined underlying transmissive unit along the eastern to central portions of the landfill, and negative or upward vertical flow components occur along the western, northern and southern portions of the landfill along potential discharge areas. As illustrated on Sheet 6.42, positive or downward vertical gradients generally occur between the bedrock and first overlying transmissive unit within the central portions of Section 6/7, and along the eastern landfill boundary. Negative or upward flow components occur from the bedrock along the landfill periphery to the west, north and south along surface water discharge zones.

6.2.1.5.3 Temporal Head Variations

Tidal influences are evident in Landfill Section 6/7 monitoring wells. Table 6.8 summarizes those wells that are affected by tides, barometric pressure changes, and recharge. Generally, tidal effects are negligible in the refuse unit as illustrated in the composite hydrographs of Landfill Section 6/7 refuse wells, Figures 6.13 and 6.14. Recharge through precipitation is evident at several monitoring well locations within the refuse. Figure 6.15 shows a composite graph of

barometric pressure change and precipitation, (both in inch units) for the 30-day period, June 17 through July 17, 1992. Hourly (Figure 6.15) and average daily (Appendix J) barometric pressure data were recorded by the National Weather Service in Newark, New Jersey. Precipitation was recorded at 15 minute intervals at the Fresh Kills Landfill meteorological station operated by NYCDOS. Comparison of Figure 6.15 to the hydrographs for the refuse wells for the same time period (Figures 6.13 and 6.14) indicates that monitoring well location YW-6 shows a clear response to all precipitation events, while the majority of the refuse wells show a possible response only to a precipitation event that occurred approximately on day 22. It is possible that a majority of the refuse wells only show a clear response to a single precipitation event because water level change is not directly related to the recharge of groundwater, but to a very rapid change in barometric pressure. A rapid downward change in barometric pressure would act similarly to removal of a slug of water, where water levels would increase rapidly over a short span of time. Figure 6.15 indicates that such a phenomenon did occur on day 22 of the record.

Water level response to barometric pressure would suggest that the shallow flow system within the refuse unit is under confined/semi-confined conditions. Alternative explanations for this condition are: (1) the presence of a confining unit comprised of low permeability cover material, although it would be improbable for this layer to be equally distributed areally due to the nature in which the refuse is placed, and (2) development of a positive pressure boundary between the leachate and the atmosphere by the gases that are generated during the microbial degradation of the landfill material. Positive gas pressures are known to exist within the landfill, and in some locations prohibit accurate measurements of water level.

Figure 6.16 indicates the composite hydrographs for the 30-day period June 17 through July 17, 1992, for the intermediate (unconsolidated overburden) wells, along with stage data for tidal gauge B located along Main Creek. All of the wells shown are completed in glacial sands except 6W91:IT157I which is completed in the Cretaceous sand unit in the southern area of the landfill section. Examination of Figure 6.16 indicates that all the intermediate wells exhibit tidal effects consistent with the tidal gauge. Potential barometric effects are overshadowed by the range of tidal effects, and immediate response to recharge through precipitation is not a factor within these deeper wells.

Figures 6.17 and 6.18 indicate the composite bedrock well hydrographs for the 30-day period June 17 through July 17, 1992, together with stage data for tidal gauge B. Examination of this

figure indicates that, in general, tidal effects are most obvious in bedrock wells located adjacent to Main Creek and Richmond Creek, and less obvious along the eastern landfill boundary. These data support the concept that the tidal effects observed within the bedrock are likely due to hydrostatic pressure effects transmitted down to the bedrock unit, as opposed to the result of a direct tidal flux. Barometric effects can be observed within several of the bedrock wells, most clearly at well 6W91:IT154D during day 22. Recharge through precipitation is not a factor in the short term transient analysis of the bedrock wells.

Figure 6.19 shows the hydrograph for groundwater levels at monitoring well cluster location 157 for the 30-day time period June 17 through July 17, 1992. The data from this location is typical of water level responses at other cluster locations within Landfill Section 6/7, and shows the relationship of transient changes between the shallow, intermediate, and deep hydrostratigraphic units. Appendix J contains the full suite of hydrographs for all well clusters instrumented with continuous water level recorders, across the 30-day June 17-July 17, 1992 period. In addition, long term water level data for well clusters IT163 and IT157 are presented in Appendix J on Sheets J.4 and J.5, respectively. In general these data support the interprotation that Section 6/7 groundwater flow regime is generally in a steady-state condition with little transient trends for changes in flow conditions.

6.2.1.5.4 Groundwater Fluxes

The synthesis of all hydraulic, water level, physical, and boundary condition information for Landfill Section 6/7 is utilized to complete the conceptual model of groundwater flow, in terms of determining the flux of groundwater through the flow system. The analytical methods described for the regional conceptual model (Section 6.1.4.4) were used to generate similar flux information for Landfill Section 6/7. Values for both total vertical flux between the refuse and unconsolidated overburden units and between the unconsolidated overburden unit and bedrock were determined for the landfill section, as well as horizontal fluxes for each of the three primary hydrostratigraphic units. Sheet 5.5 shows the location of the landfill section perimeter boundary (corresponding to geologic perimeter cross section GP-6/7) and segment numbers across and within which fluxes were calculated. The total surface area inside the Landfill Section 6/7 perimeter boundary as delineated on Sheet 6.31, is 13,135,496 ft^2. Attachment 31 summarizes

the computed flux values by segment number and hydrostratigraphic unit; these fluxes are summarized schematically on Figure 6.20.

Leachate that leaves the refuse unit to the underlying unconsolidated unit is estimated to represent an extremely low percentage of the total recharge (about one percent), which is probably due to the extensive low permeability units that underlie the refuse.

Net flux into the unconsolidated unit is from downward vertical flow from the refuse, 188 ft^3/day (1,406 gal/day), and upward vertical flow from the bedrock, 643 ft^3/day (4,810 gal/day). Net lateral flux out of the unconsolidated unit is laterally 831 ft^3/day (6,216 gal/day). It should be noted that these data have been rounded to allow for a water balance between each unit. Due to the analytical nature of the flux calculations and the averaging of values within specific horizontal flux segments, a mass balance error of approximately one percent of the net total flux is observed in the detailed calculations.

Net flux into the bedrock unit is represented by both a vertical upward flux of 533 ft^3/day (3,987 gal/day), and a lateral component of 110 ft^3/day (823 gal/day) which together are routed to a vertical upward component into the overburden, 643 ft^3/day (4,810 gal/day).

An approximate average vertical gradient within the bedrock can be computed by rearranging Darcy's Law to solve for the gradient, as follows:

$$I = Q/A \cdot K$$

where:
- I = gradient (L/L)
- Q = flux rate (L^3/t)
- A = area (L^2)
- K = hydraulic conductivity (L/t)

Using a flux rate of 533 ft^3/day, a geometric mean hydraulic conductivity of 3.7×10^{-5} cm/sec (0.1049 ft/day) and an area of 13,135,496 ft^2 yields an average gradient of 0.0004 ft/ft upward.

Finally, vertical recharge through precipitation into the refuse unit can be approximated by dividing the net total flux into the refuse unit, 41,179 ft^3/day (derived by summing the outward lateral and vertical fluxes), by its total surface area, 13,135,496 ft^2, to yield a recharge rate of 13.73 inches per year.

6.2.2 Numerical Modeling

Given the structure provided by initial conceptual model development, numerical analysis is then applied to evaluate selected features of the geologic and hydrologic system through construction of mathematical models that solve the equations of groundwater flow and solute transport. These models allow for hypothesis testing through the variation of field measured input parameters, and act to complete the conceptual model development process. In order to better define the detailed characteristics of the flow system at each individual landfill section, two dimensional (cross-sectional) flow and solute transport models were developed that provided the basis for ultimate construction of an areal three dimensional representation of the flow system for the entire landfill complex (Section 6.6). Details regarding the cross-sectional numerical analysis performed at Landfill Section 6/7 are provided here. Cross-sectional numerical analysis was performed using the geologic and hydrologic database available during preparation of the Draft Final Hydrogeological Report (IT Corporation, Wehran Envirotech, and O'Brien & Gere, 1993a). While some of these data may vary from those presented in this report (e.g., recharge rate, lithologic unit correlation) they do not substantively affect the findings of the numerical analysis, as the cross-sectional flow and solute transport simulations were performed primarily within the context of sensitivity analysis.

The overall objective of the cross-sectional modeling performed for Landfill Section 6/7 was to gain a better understanding of the vertical flow system, and to generally quantify the flow system at the specific cross-section location. Specific objectives for the cross-sectional modeling included:

- Examination of the potential for leachate migration to the underlying bedrock unit.
- Sensitivity analysis to determine the potential vertical migration of leachate based on the variation of permeability and thickness of sand, silt/clay and till sub-hydrostratigraphic units that underlie Landfill Section 6/7.

- Evaluation of the layering requirements for subsequent regional three-dimensional model development.

- Development of a tool for the evaluation of various remedial alternatives during the leachate mitigation design process.

6.2.2.1 Model Selection

To satisfy the general and specific objectives of the cross-sectional model analysis, a numerical model code was selected that computes both groundwater flow and solute transport. The model code selected to perform the cross-sectional analysis is a public domain code developed by the U.S. Geological Survey known by the acronym HST3D: A Computer Code for Simulation of Heat and Solute Transport in Three-Dimensional Ground-Water Flow Systems (Kipp, 1987).

HST3D was selected because of its versatility and ability to solve the groundwater flow equation for both variable viscosity and density flow systems. In addition, it has the capability to solve the thermal transport equation for portions of the flow system which may be non-isothermal. The three governing equations of flow, solute and energy transport are coupled through the interstitial pore velocity, the dependence of the fluid density on pressure, temperature, and solute-mass fraction, and the dependence of the fluid viscosity on temperature and solute mass-fraction. The solute-transport equation is only for a single solute species with possible linear-equilibrium sorption and linear decay. Finite-difference techniques are used to discretize the governing equations using a point distributed grid. The flow-, heat-, and solute-transport equations are solved, in turn, after a partial Gauss-reduction scheme is used to modify them.

Boundary-condition types may be specified pressure, specified flux, an approximate free-surface, leakage and two types of aquifer influence functions. All boundary conditions may be a function of time. A complete description of the HST3D code is contained in Attachment 13.

6.2.2.2 Areal Extent

The basic assumption in the development of a two-dimensional cross-sectional model is for the cross-section being simulated to be located along a groundwater flow path. This allows for the three-dimensional system to be reduced to a two-dimensional system described as length and elevation along the flow path. The selection of the flow path for the cross-sectional model was based on water-level data collected during the period November 3 through 10, 1991. Water level data for the period were averaged and planimetric contour water level elevation maps were prepared for water in the refuse and bedrock hydrostratigraphic units. Water level elevation maps for the period November 3-10, 1991 are provided in Attachment 37. Similar maps were constructed with water level data from the 30-day period June 17 through July 17, 1992 for comparison with the data used in the original cross-section selection. Time-averaged head data for the refuse and bedrock hydrostratigraphic units across the June - July 1992 period are shown on Sheets 6.32 and 6.40, respectively. Very little difference was observed between the two sets of respective water level elevation contour maps, and the originally selected cross-section location was determined to be representative of flow along an areal flow path. The cross-section selected which most closely corresponds to a flow path for both the refuse and bedrock units is indicated on Sheet 6.43 as section line 6/7 MCS-6/7 MCS. The cross-section selected trends on an east-west line, and follows a flow path that runs from the Main Creek on the west, to the landfill property boundary on the east. Based on the water-level data shown on Sheets 6.32 and 6.40, several other flow paths could have been selected for modeling purposes. This particular flow path was selected because it contains the majority of the hydrogeologic conditions encountered at the site, and is a good representation of general flow conditions beneath the landfill. The cross-section location also contains the major hydrostratigraphic units to be examined, as determined by the specific modeling objectives for Landfill Section 6/7 noted previously.

6.2.2.3 Discretization

Model discretization describes how the area to be simulated is divided into discrete unit locations for the purposes of model data input and output, and to support internal data processing performed by the model computer code. The extent of model discretization is dependent on several factors that influence the final model grid design. Factors considered in the Landfill Section 6/7 discretization for the two-dimensional numerical model included:

- The location of model internal/external boundary conditions
- The irregularity of model internal/external boundary conditions
- The numerical method of solution
- The location of any specialized source/sink areas
- Specific modeling objectives (Section 6.2.2)

The Landfill Section 6/7 cross-sectional model discretization is shown on Sheet 6.44. The modeled area was discretized vertically into 42 total node locations with a uniform spacing between the node locations of 2.5 ft, except for the uppermost node which has a separation distance of 10.0 ft. The upper variation in spacing was selected to represent the upper saturated portion of the landfill. The total vertical distance discretized was 110 ft and represents a range in local elevation from 10.0 to -100.0 ft.

Horizontally, the model was discretized into 33 total node locations with a uniform spacing between nodes of 100 ft except between node locations 1 to 2 and 2 to 3, where the spacing was extended to 200 ft. Node spacings were increased at these two locations because they do not represent area below the landfill. They were included to extend the model boundary beyond Main Creek to determine the potential effect of Main Creek on groundwater flow moving beneath Landfill Section 6/7.

In addition to the node locations shown on Sheet 6.44, the model area was divided into 139 zones. Hydraulic model input data is defined by these zones, and individual properties can vary independently on a zone-by-zone basis. The zonation was selected to correspond to the hydrostratigraphic units and to allow for the variation of properties within an individual unit for purposes of sensitivity analysis. Zone locations shown on Sheet 6.44 are further defined in the calibrated model data input files provided in Attachment 19.

6.2.2.4 Hydraulic Input Properties

Hydraulic input properties for the Landfill Section 6/7 cross-sectional model were obtained from information obtained from the center boring program, the Phase I and Phase II well installation program, and the Hydrogeological Literature Review (IT Corporation and Wehran EnviroTech, 1991a; Attachment 44). All data collected as part of this program have been described previously, and are briefly summarized in Table 6.9, which indicates the hydraulic input data for

the calibrated cross-sectional model in terms of the hydrostratigraphic units. The mean hydraulic conductivity data in this table correspond to the adjusted values which produced the best calibration for the cross-sectional model. Differences in the calibrated parameter values and those contained in Table 6.3 are not significant. It should be noted that porosity data indicated on Table 6.9 represents effective, and not total, porosity. This distinction is most significant relative to the clay units, where total porosity is reported in the range of 40-60 percent (Freeze and Cherry, 1979). The effective porosity is based on specific yield values reported by Morris and Johnson (1967); specific yield is more representative of the interconnection of pores within a material through its measurement of free, drainable water within a unit. All model hydraulic input properties by zones are provided in the data input files contained in Attachment 19.

6.2.2.5 Boundary Conditions

In general, numerical model boundary conditions describe how water enters and leaves the model flow system. Boundary conditions can describe recharge through precipitation that enters the system vertically, or flow to/from rivers and streams at the model edges. Boundary conditions also are used to describe the horizontal flow of groundwater across a vertical face at the lateral model boundary. The selection of a model boundary condition depends on the availability of data to describe the boundary, and how important the boundary is to determining flow conditions within the modeled area.

Three types of boundary conditions were used to describe groundwater flow in and out of the cross-sectional numerical model. A constant flux of water into the model at the upper model layer was used to represent recharge due to precipitation. A constant rate equal to 13.92 inches per year (rate determined from preliminary analytical flux analysis) was uniformly applied to the upper model surface for final, transient model simulations.

Head-dependent flux boundary conditions were used to simulate groundwater moving across the models vertical edge boundaries. Groundwater is able to move explicitly across this type of boundary as a function of the hydraulic conductivity of the hydrostratigraphic unit, a set water level on the outside of the model boundary, and the model computed water level on the inside of the model boundary. The set water levels at the model boundaries were determined from field collected water level data and extrapolated both horizontally and vertically. The hydraulic

conductivity values used at the boundaries correspond to the appropriate horizontal value for the hydrostratigraphic unit present at the boundary.

The third type of boundary condition used in the cross-sectional model is the river leakage condition that was used to simulate flow into the Main Creek on the western side of the modeled cross-section and the unnamed tributary stream on the eastern side of the modeled cross-section. The river stage in Main Creek was assumed to equal an elevation of -2.38 feet as determined from field data collected from tidal gauge C (location indicated on Figure 4.33), and an elevation of 1.0 foot in the eastern tributary stream, based on topographic data. The bottom thickness for both Main Creek and the tributary stream were assumed to be 1.0 foot. The hydraulic conductivity of the bottom material for Main Creek was assumed to be 4.5 x 10 -5 cm/sec, and for the tributary stream 1.8 x 10 -5 cm/sec. These estimates were derived from review of channel bed grain size data obtained through performance of the Consent Order Appendix A-7 Surface Water and Sediment Investigation (IT Corporation, 1992). Both surface water channels were assumed to contain fine sand to silt bottom material.

The final type of boundary condition simulated by the model was a no-flow boundary beneath the lower model layer in the bedrock hydrostratigraphic unit. All model input data for boundary conditions is contained in Attachment 19.

6.2.2.6 Calibration

Calibration of the transient two-dimensional model consisted of comparing water level data collected in the field with model computed water level data at known locations. The transient model simulation was run for a period of 25 years roughly corresponding to the period of refuse disposal at Landfill Section 6/7 based on review of historical aerial photography contained in the Hydrogeological Literature Review (IT Corporation and Wehran EnviroTech, 1991a; Attachment 44).

Table 6.10 summarizes the field observed versus the model-computed water levels at known observation points for the calibrated two-dimensional cross-sectional model. Field data for each of the monitoring well locations shown on Table 6.10 represent manual or time averaged water levels for the period June 17 through July 17, 1992.

Comparison of field-averaged versus model-computed water levels suggests a fair calibration with a root mean square (RMS) error of +/- 1.46 ft. Based on the two-dimensional modeling objectives and the availability of field measured water level data along the cross-section, no attempt was made to further refine the model calibration. The poorest calibration was at location 6W91:IT162I. The location of this point near the Fresh Kills suggests that the regional effect of the river on the flow of groundwater actually extends beneath the landfill to a greater extent than predicted by the model.

The final calibration for the Landfill Section 6/7 cross-sectional model is considered a transient calibration due to the fact that groundwater storage terms are taken into consideration over the period of simulation. For the HST3D code, storage is calculated as a function of porosity, density, and compressibility of water and the aquifer material (Table 6.9). The inclusion of the compressibility term into the groundwater flow equation allows for the simulation of any additional vertical pressure changes that may occur to the underlying units due to the added weight of the saturated refuse. This added pressure is the result of an increasing saturated refuse mound thickness that is developed over the operational period of the landfill.

Sheet 6.45 shows the model computed water level elevation contours for the cross-sectional model calibration. These data, along with the direction and calculated mean velocity of groundwater flow, are also portrayed in a more convenient format on Figure 6.50. Average linear velocity estimates were calculated through the relationship:

$$V = \frac{Q}{n_e A} = - \frac{Kdh}{n_e dl} \quad (Fetter, 1988)$$

Where K = hydraulic conductivity (cm/sec)
dh/dl = hydraulic gradient (ft/ft)
n_e = effective porosity

Hydraulic conductivity and effective porosity were derived from the data indicated on Table 6.9. Hydraulic gradient data were derived from the head equipotential contours indicated on Sheet

6.45, applied across a specified distance (calculated as the length of the hypotenuse across a defined right angle within each hydrostratigraphic unit).

Model results suggest that flow within the refuse unit is generally horizontal with the majority of flow toward Main Creek to the west and the tributary stream to the east. A groundwater mound is developed within the central portions of the landfill, creating a groundwater divide between flow to the two surface water bodies. Beneath the groundwater mound, a vertical downward gradient is evident into the underlying unconsolidated unit.

Flow in the unconsolidated overburden unit appears to be local to the landfill in nature, with the major source of discharge being Main Creek on the western side of the landfill. A lesser component of shallow discharge is evidenced to the tributary stream on the eastern landfill boundary. Except for those areas directly beneath the landfill mound, flow within the unconsolidated unit is generally horizontal. Beneath the landfill mound, a vertical downward gradient is evident within the upper portion of the unconsolidated unit. The magnitude of the gradient decreases with depth but extends to the bedrock unit. This raises the possibility of downward flux from the landfill, through the overburden, and into the bedrock. This would be consistent with the thinner, more permeable overburden soils in the eastern portion of Landfill Section 6/7. An alternative possibility is that the heads in the bedrock are higher as a result of the lithostatic pressure-effect discussed earlier.

Flow within the bedrock unit appears to be generally horizontal and regional in nature. Although higher heads beneath the landfill are indicated, they are generally local in nature and do not appear to affect flow either at the model boundaries or beneath Main Creek. In general, flow within the bedrock unit discharges toward the Main Creek.

Figure 6.21 schematically summarizes the flow rates at the recharge, surface water, and lateral model boundaries in units of cubic feet per day (ft ^{3}/day). Positive rates refer to groundwater entering the flow system and negative rates refer to groundwater leaving the flow system. Examination of Figure 6.21 indicates that the majority of groundwater moving in and out of the flow system takes place within the upper model layers representing the refuse. Summing the discharge from the refuse to the Main Creek and the tributary stream, (14.40 ft ^{3}/day) and subtracting the total rate of recharge to the refuse layer (14.56 ft ^{3}/day), yields a net rate of groundwater flow leaving the refuse layer to the underlying units. Based on the data shown on

Figure 6.21, this rate equals 0.16 ft ^{3}/day, and corresponds to approximately 1 percent of the recharge entering the refuse through precipitation (infiltration).

Further examination of Figure 6.21 indicates that there is a net outflow of groundwater across both lateral model boundaries for the deeper units. The majority of flow from the bedrock unit is along the eastern model boundary. Summing the flow into the upper weathered bedrock unit (+0.19 ft^3/day) with that out of the more competent lower bedrock (-0.35 ft^3/day) yields a total flow from the bedrock of 0.16 ft^3/day, which is equal to the total vertical leakage (approximately 1 percent of the total recharge) out the base of the landfill, as discussed above. Examination of Sheet 6.46 indicates that there is a potential for leachate to migrate into the upper portion of the bedrock unit on the eastern model boundary. In general, the rates of groundwater moving across the model area support the conceptual model for Landfill Section 6/7 of a small, localized flow system within the upper refuse and unconsolidated units discharging locally to Main and Richmond Creeks on the western, northern, and southern landfill boundaries, and to the tributary stream on the eastern landfill boundary. The computed rates of groundwater flow also suggest that the regional bedrock flow system can be locally affected by higher water levels in the refuse mound, but that discharge is nonetheless routed toward the surface water channels of Main and Richmond Creeks.

6.2.2.7 Sensitivity Analysis

Model sensitivity analysis simulations were conducted to meet the objectives of the numerical modeling program (Section 6.2.2). For the two-dimensional, cross-sectional model, this involved a determination of the sensitivity of model-computed values to changes in model input, or a focused sensitivity analysis.

Both the steady-state and transient models were used during sensitivity analysis. Steady-state simulations were used to establish the long-term sensitivity of the flow system to potential changes in hydraulic properties. Transient simulations were used to evaluate potential hydrogeologic changes specific to the refuse unit.

To evaluate the potential for leachate migration from the refuse unit to the underlying unconsolidated and bedrock units, the two-dimensional cross-sectional model was used to

simulate solute transport for steady-state conditions. Steady-state conditions were assumed for sensitivity analysis to enable the comparison of solute distribution between various simulations for the case where the model computed water levels are the most conservative for the particular hydraulic property changed. Steady-state simulations also remove absolute time as a controlling factor when comparing different model simulations.

In addition to the hydraulic data described earlier, the model requires information on the properties of the solute to be transported along with the effective porosity of the material the solute will move through. Appropriate input values applied to all hydrostratigraphic units (for this and all other landfill section sensitivity analyses) are summarized below:

Dispersivity: longitudinal = 100 ft, transverse = 10 ft (Lallemand - Barres and Peaudecrcf, 1978);

Molecular Diffusivity = 1 x 10^{-9} m^2/sec (Camp, 1963);

Density = 62.4 lb/ft^3 (Chemical Rubber Co., 1990); and

Viscosity = 1.0 centipoise (Chemical Rubber Co., 1990).

Sheet 6.46 shows the distribution of scaled mass-fraction of solute for the steady-state model run for a transport period of 20 years (the results of this simulation are not significantly different from the final transient simulation). The scaled mass-fraction is an option in the HST3D code that assumes a solute concentration from 0.0-1.0. Scaled mass-fractions are extremely useful during sensitivity analysis because they are easily related from one area in the model to another, and from one model simulation to another. Mass is entered into the flow system as a solute concentration of 1.0. The effects of advection, dispersion, and diffusion on solute concentration are evidenced in the resultant distribution of the mass fraction (e.g. a mass fraction of 0.05 is equivalent to a solute concentration 5 percent of the input (source) concentration). The solute transport analyses performed herein do not assume any constituent attenuation or retardation, and as such are extremely conservative. The steady-state model run (base simulation) indicated on Sheet 6.46 indicates limited opportunity for vertical solute transport, with the exception of the eastern model boundary area, where a thinning of overburden deposits coupled with a rising of the bedrock surface provides the potential for transport into the weathered bedrock.

A total of 17 sensitivity analysis simulations were selected for the preliminary modeling based on initial lithostratigraphic interpretations. Table 6.11 summarizes the model simulations and identifies the model input properties that were varied. Table 6.12 summarizes the distribution of lateral flux by lithologic unit and model boundary for the base (steady state) simulation and all sensitivity runs. In general, simulations 1-6 investigated the sensitivity of the refuse unit to changes in hydraulic conductivity and anisotropy, simulations 7-8 investigated the potential for a sand lens or layer directly beneath the landfill, simulations 9-11 investigated the potential for sand within the low permeability silt and clay units, simulations 12-15 investigated the variation of hydraulic conductivity in the till, glaciolacustrine clay, weathered bedrock and bedrock units, and simulations 16-17 investigated dispersivity and molecular diffusion. All simulations were run for a time period of 20 years to remain consistent with the calibrated steady state model simulation.

All steady state model output results are presented in Attachment 18, with input file data contained in Attachment 17. Each simulation output contains a plot of model-computed hydraulic head and scaled mass-fraction distribution, and summary mass balance calculations. Additionally, "difference" plots are presented which subtract the hydraulic head and scaled mass-fraction data associated with each individual sensitivity run from corresponding values computed for the calibrated base simulation. This type of plot allows for an easier comparison of the location and magnitude of changes in sensitivity analysis output relative to the base simulation. Comparison between various sensitivity simulations are also made easier with the difference plots.

The major results of the sensitivity analysis can be summarized as follows:

- Variations in hydraulic conductivity and ratios of vertical to horizontal K in the refuse unit generally only affect the flow within the refuse unit. Solute transport to the underlying units was not significantly affected in terms of the distribution of solute within the individual hydrostratigraphic units.

- The potential for high permeability sand lenses beneath the refuse can effect the distribution of solute with more direct solute discharge to the surface water and less to the underlying units.

- High permeability sand lenses beneath the refuse do not significantly alter the refuse head distributions or mass flux exiting/entering the landfill.

- High permeability sand lenses within the lower permeability silt and clay units can effect the distribution of head within the lower permeability unit, but do not significantly change the distribution of solute.

- Increases in the hydraulic conductivity of the till unit increase the potential for solute to migrate into the bedrock unit on the eastern model boundary.

Based on the results of initial cross-sectional model sensitivity analysis, the following recommendations were identified in the Interim Hydrogeological Report (IT Corporation, Wehran EnviroTech, and O'Brien & Gere, 1992a):

- Additional field data concerning the hydraulic conductivity, thickness, and elevation of the till underlying the northeastern portion of Landfill Section 6/7, should be collected.

- Shallow water-table piezometers should be installed on opposite sides of the unnamed stream to determine its potential to serve as a line sink on the eastern landfill boundary.

These recommendations were addressed with data collected during the Phase II well installation program in 1992 (Section 4.3.2). Additional hydraulic conductivity, water level (hydraulic head), and hydrostratigraphic unit elevation and thickness data collected during the Phase II investigation programs were incorporated into the final cross-sectional transient model simulation described in Section 6.2.2.6 and the regional three dimensional model (Section 6.6).

6.3 Landfill Section 1/9

6.3.1 Conceptual Model

The regional conceptual model illustrated the range of complexity within the Fresh Kills Landfill site. Each individual landfill section exhibits its own unique characteristics that set it apart somewhat from the other sections locally. For example, while Landfill Section 6/7 may be the least complex area in terms of hydrostratigraphic unit definition, it is distinguished by exhibiting the thinnest saturated unconsolidated unit between the base of the refuse and the top of the bedrock (eastern landfill border). Landfill Section 1/9 is distinguished in terms of its great complexity relative to hydrostratigraphic unit definition and the consequent dynamics of the groundwater flow system.

6.3.1.1 Hydrostratigraphic Units

The lithologic units identified beneath Landfill Section 1/9 can be grouped into the threefold regional hydrostratigraphy outlined in prior conceptual analysis, but with greater variation and subsequent subdivision of the unconsolidated deposit into hydrostratigraphic sub-units. As indicated in the regional discussion, the complex stratigraphy underlying Section 1/9 can be simplified by dividing the overburden deposits into two categories relative to their ability to transmit groundwater flow. The relatively high permeability coarse grained sand deposits are grouped into the transmissive hydrostratigraphic sub-unit category and the fine grained low permeability deposits are grouped into the restrictive hydrostratigraphic sub-unit category. Wherever transmissive units are in direct vertical and/or lateral connection, regardless of geologic unit (i.e., Recent, glacial, Cretaceous sands), they combine to form a single, correlative transmissive horizon in which preferential groundwater flow may occur. Similarly, wherever low permeability restrictive units are in direct contact, they combine to form a single correlative confining unit impeding groundwater flow, and in turn, contaminant migration. The hydrostratigraphy of Landfill Section 1/9 is best illustrated in profile on the north-south trending hydrostratigraphic cross-sections HA, HB and HC shown on Sheets 6.12 through 6.14, and the east-west trending cross-sections HI, HJ, HK, HL, HM, HQ and HR shown on Sheets 6.20 through 6.24 and 6.28 and 6.29, respectively.

The refuse/fill hydrostratigraphic unit covers the entire area of Landfill Section 1/9 (Sheet 5.30). This unit is bordered on three sides by surface waters: Arthur Kill to the west, Fresh Kills to the north, and Sleight Creek to the south. The eastern toe of slope is parallel to the Staten Island Expressway. An existing leachate collection system (Veterans Avenue Collection System) is located along the southeastern and eastern toe of slope and currently recirculates collected leachate back into the refuse. The refuse may directly overlie Recent deposits, glacial deposits or Cretaceous deposits depending on the specific area of the landfill (refer to Section 5.4.2). Of greater importance relative to hydrostratigraphy are the areas where refuse is in direct hydraulic communication with transmissive sand horizons, particularly those that can be correlated laterally to the rivers or vertically to deeper regional groundwater flow systems. Examination of the hydrostratigraphic cross-sections indicates that the refuse is in direct contact with Recent sands in the northern portion of the landfill, and extensively along the western portion of the landfill. Refuse is also in contact with underlying glacial and Cretaceous sands in the eastern and southern

portions of the section, respectively, but to a much lesser extent. These interconnections between hydrostratigraphic units (refuse/sands) represent areas of potential downward vertical migration of leachate into shallow unconsolidated overburden, and where the sands are vertically and/or laterally continuous, subsequent migration into deeper flow systems.

The unconsolidated overburden hydrostratigraphic unit beneath Landfill Section 1/9 can be characterized as consisting predominantly of fine grained low permeability deposits underlain with correlative coarse grained sand deposits in which preferential groundwater flow occurs. Restrictive low permeability hydrostratigraphic sub-units within the overburden sequence include, where present, Recent silt and clay, glacial silt and clay, glacial till, Cretaceous clay and residual clay. As noted earlier, due to the variation of the glacial till composition across the entire landfill site, the glacial till deposits are differentiated on the hydrostratigraphic cross-sections. As illustrated in the cross-section, these restrictive sub-units combine to form laterally and vertically continuous confining layers that act to restrict groundwater flow in both the horizontal and vertical direction. This is particularly important in considering vertical migration of contaminants from the refuse to the regionally extensive bedrock hydrostratigraphic unit. Virtually everywhere across Landfill Section 1/9, the bedrock unit is overlain by a confining unit sequence (predominantly residual clay) limiting the potential for direct hydraulic communication with the refuse or transmissive sand units above. A detailed discussion of the occurrence and spatial distributions of restrictive units identified beneath Section 1/9 is presented in Section 5.4.2.

Within the predominately fine grained restrictive overburden sequence, transmissive sand units occur as distinct correlative hydrostratigraphic sub-units in which preferential groundwater flow occurs within the overburden. Transmissive units identified beneath Section 1/9 include Recent, glacial and Cretaceous sands. The occurrence and interconnection of these sand horizons is best illustrated in the hydrostratigraphic cross-sections.

Recent sand deposits underlying Section 1/9 have been correlated to Recent sand Units 1, 2 and 3 (Sheets 5.36 and 5.37). Recent sand deposits occur extensively throughout the northern and western portions of Landfill Section 1/9. As previously discussed, Recent sand Unit 1 is the most areally extensive Recent sand unit, typically occurring at the base of the Recent silt and clay. These sands extend from the central area of Section 1/9 to the western boundary where they intersect with the Arthur Kill, and are present in the northern portion of the landfill between the Arthur Kill and Fresh Kills, extending into Section 2/8 (Sheet 5.36).

Recent sand Unit 2 is the uppermost sand unit occurring along the Section 1/9 western boundary, and is frequently in direct contact with the overlying refuse unit but separated from Recent sand Unit 1 by underlying Recent silt and clay deposits (Sheet 5.37). Recent sand Unit 3 occurs in the east central portion of Section 1/9 where a former tidal marsh was located, and occurs as a sand pocket of limited extent (Sheet 5.37).

Similar to Landfill Section 6/7, glacial sands occur scattered throughout Landfill Section 1/9. Nine separate glacial sand units were identified within the glacial sequence in Landfill Section 1/9 and include Units 6, 7, 8, 9, 13, 13A, 18, 23, and 25 (Sheets 5.49 and 5.50). The glacial sands identified in the eastern portion the section, where a former topographic high existed, occur interbedded with glacial till and is associated with a kame feature. The glacial sand units are generally of limited extent and not correlated as a continuous horizon beneath Section 1/9. However, where glacial sands are in direct contact with Recent sands and/or Cretaceous sands, they act as a composite transmissive unit that can be both laterally and vertically extensive.

Cretaceous sand deposits are present beneath most of Landfill Section 1/9 with the exception of the northeastern area. Cretaceous sand Unit 1 (Sheet 5.63) is the most areally extensive sand and occurs as the basal unit in the Cretaceous sequence. This unit can potentially be correlated to a regional Cretaceous sand sequence extending southward and westward into New Jersey. Cretaceous sand Unit 2 located in the northwest, and Unit 3 located in the southeast (Sheet 5.64), are sand deposits of limited areal extent that are separated from the basal sands by Cretaceous clay confining units.

As previously discussed, preferential groundwater flow in the overburden unit will occur within the transmissive sand hydrostratigraphic sub-units. Interconnection of these units both laterally and vertically provides for continuous transmissive horizons through a predominately fine grained sequence. For example, as illustrated in the hydrostratigraphic cross-section HJ, Recent, glacial and Cretaceous sands are in direct hydraulic connection and combine to act as a single transmissive hydrostratigraphic unit potentially transmitting groundwater flow across the entire width of Landfill Section 1/9. Whereas simple transmissive units alone may not present significant pathways for groundwater flow, transmissive units together can present continuous horizons of significant thickness.

The lateral interconnections of the various transmissive hydrostratigraphic sub-units are illustrated in the hydrostratigraphic cross-sections. These interconnections are most prevalent between Recent sand Unit 1, glacial sand units, and Cretaceous sand Unit 1 in the western and southern areas of the landfill. Similarly, vertical connections between the transmissive units are most prevalent along the western boundary and south central areas of Section 1/9, but occur as very localized areas or windows of interconnection (see Sheets 5.93, 5.94 and 5.95).

The bedrock hydrostratigraphic unit is comprised of siltstones, shales and sandstones of the Stockton Formation (Sheet 5.82). The bedrock surface in the northern portion of the site slopes relatively gently to the east and to the west. Within the central portion of the site, the bedrock slopes steeply to the south, flattens out, and then slopes steeply again to the south in the southernmost portion of the site. The upper surface of the bedrock is characterized as weathered bedrock across most of the site (Sheet 5.71), with the exception of a small area in the southeast. Residual clay covers the bedrock everywhere across Section 1/9 (Sheet 5.68), and serves as the lowermost confining unit above the transmissive bedrock hydrostratigraphic unit.

6.3.1.2 *Hydraulic Conductivity Distribution*

Available hydraulic conductivity data for Landfill Section 1/9 are summarized in Tables 6.1, 6.2 and 6.3. Figure 6.22 presents the distribution of hydraulic conductivity versus stratigraphic unit for Landfill Section 1/9. Refuse hydraulic conductivity values range from 5.1×10^{-7} cm/sec at 1P91:IT515S to 4.2×10^{-1} cm/sec at 1P89:XP2. The geometric mean of refuse hydraulic conductivity data at Landfill Section 1/9 is 2.3×10^{-3} cm/sec. The refuse hydraulic conductivity values for Landfill Section 1/9 tend to cluster in the 10^{-3} to 10^{-2} cm/sec range (Figure 6.22). The spatial distribution of refuse in situ hydrauic conductivity data is shown on Sheet 6.2.

The overburden lithologic units beneath Landfill Section 1/9 exhibit great variability. Whereas substantial thicknesses of low permeability, fine-grained material (silts and clays) are extensive, the overburden is multilayered with sand lenses, most notably Recent and Cretaceous sand, the latter of which is continuous southward and eastward in association with a more regional deposit. Sheets 6.3 through 6.9 present the areal distributions of available in situ K data for transmissive units within the overburden sequence underlying Landfill Section 1/9. The distinction between restrictive and transmissive units is important in this area, as these hydrostratigraphic sub-units

have a major effect on the flow system beneath the landfill. The following table summarizes the hydraulic conductivity distribution found within sub-units of the Landfill Section 1/9 overburden (refer to Tables 6.1, 6.2 and 6.3):

Restrictive Units	Kv	
	Range	Geometric Mean [a]
Recent Silt & Clay	10^{-7} to 10^{-8} cm/sec	9.2×10^{-8} cm/sec
Glacial Clay	10^{-7} to 10^{-8} cm/sec	9.1×10^{-8} cm/sec
Glacial Till	10^{-6} to 10^{-8} cm/sec	4.6×10^{-8} cm/sec
Cretaceous Clay	10^{-7} to 10^{-8} cm/sec	8.3×10^{-8} cm/sec
Residual Clay	10^{-7} to 10^{-8} cm/sec	8.1×10^{-8} cm/sec

[a] Laboratory Kv data

Transmissive Units	Kh	
	Range	Geometric Mean
Recent Sand [b]	10^{-2} to 10^{-4} cm/sec	6.1×10^{-3} cm/sec
Glacial Sand [c]	10^{-2} to 10^{-5} cm/sec	1.2×10^{-3} cm/sec
Cretaceous Sand [b]	10^{-2} to 10^{-7} cm/sec	1.8×10^{-3} cm/sec

[b] In situ Kh data
[c] Hazen (1911) approximation data

Sheet 6.8 depicts the areal distribution of hydraulic conductivity for the regionally correlative basal Cretaceous sand Unit 1. No patterns are readily apparent; the varied hydraulic conductivity distribution supports the interpretation of a complex Cretaceous depositional environment.

Estimates of in situ hydraulic conductivity for undifferentiated bedrock, including weathered bedrock, range from 2.6×10^{-8}cm/sec at 1W91:IT006D to 1.2×10^{-4}cm/sec at 1W91:IT010D. The geometric mean value for all the bedrock hydraulic conductivity values is 4.2×10^{-6} cm/sec. The geometric mean value for bedrock hydraulic conductivity, excluding the weathered bedrock,

is 3.0 x 10^{-5} cm/sec; the geometric mean K of the weathered bedrock is 2.9 x 10^{-6} cm/sec. A review of the hydraulic conductivity data (Table 6.2) and distribution of bedrock hydraulic conductivity in Landfill Section 1/9 (Sheet 6.10) indicates a zone of very low permeability in the bedrock along the eastern boundary of Landfill Section 1/9, trending northeast - southwest, as noted in the regional conceptual analysis. Figure 6.2A indicates the bedrock hydraulic conductivity distribution by formation type and weathering characteristics for Landfill Section 1/9.

6.3.1.3 Thickness Distribution

The total thickness and saturated thickness of the refuse, and the thickness of the overburden hydrostratigraphic units, are shown in plan view on Sheets 5.30, 6.30, and 6.31, respectively. The thickness distribution of these units are also depicted in profile on the hydrostratigraphic cross-sections presented on Sheets 6.12 through 6.14 (north-south trending profiles) and Sheets 6.20 through 6.24 and 6.28, 6.29 (east-west trending profiles).

As can be seen in both plan and profile, Landfill Section 1/9 exhibits a substantial refuse mound reaching thicknesses of greater than 140 ft, and generally greater than 100 ft, throughout much of the fill area. Available data from shallow piezometers in the refuse mound indicate a substantial saturated refuse mound, reaching as much as 100 ft. It is important to note that limited information from a pair of shallow/deep refuse piezometers (1P92:ATW-Z, ATW-S) indicate that, similar to the observed condition at Section 6/7, the elevation of the leachate mound surface may be significantly lower (approximately 65 ft lower) than that indicated by the shallow refuse piezometer water level data.

The thickness of the overburden unit is substantial everywhere beneath Landfill Section 1/9. This unit is typically greater than 50 ft thick, and thickens seaward to greater than 140 ft as the depth to bedrock increases southward (Sheet 6.31).

The Recent sand hydrostratigraphic sub-units beneath Section 1/9 range in thickness from less than 1 foot to greater than 40 ft thick (Sheet 5.38). The uppermost sand unit along the western boundary of Section 1/9 (Unit 2) averages approximately 10 ft in thickness. The lowermost and areally extensive Recent sand Unit 1 ranges from 20 to 40 ft thick along the western portion of

the landfill and averages about 15 ft thick in the northern section. The glacial sands identified beneath Section 1/9 range in thickness from 2 to 21 ft and are typically less than 10 ft thick (Sheet 5.55). The Cretaceous sand hydrostratigraphic sub-units are thin in the northern areas of Section 1/9, and thicker to the south and southeast (Sheet 5.65). In the south central portion of the landfill, the Cretaceous sand (Unit 1) is very thick, with the thickest accumulations being in the east-central area of the landfill. Thickness of the areally extensive basal sand (Unit 1) ranges from several feet to over 80 ft (Sheet 5.66). The hydrostratigraphic cross-sections provide in profile a more detailed presentation of the spatial variations in thickness and correlation of the transmissive hydrostratigraphic sub-units as well as the restrictive confining units within the overburden sequence.

6.3.1.4 Boundary Conditions

Similar to Landfill Section 6/7, the major conceptual model boundary conditions for Landfill Section 1/9 consist of recharge through precipitation as the upper boundary, the bedrock unit as the lower boundary, and the Arthur Kill, Fresh Kills and Sleight Creek as lateral flow boundaries to the west, north and south, respectively for the refuse unit and shallow, unconsolidated overburden units. Horizontal flux across lateral boundaries as a function of the regional gradient is also a boundary condition for the deeper unconsolidated overburden units and the bedrock flow system.

Another boundary condition, which is internal to the unconsolidated units and most prevalent beneath Landfill Section 1/9, is the density boundary created by saltwater intrusion. At Landfill Section 1/9, the effects of saltwater intrusion are observed within the Cretaceous sand unit, primarily to the west and south. Density data collected from monitoring wells completed within this unit exhibits density variation from 1.002 to 1.017. Theoretically, salt water intrusion is defined as a wedge shape, with the point of the wedge at the bottom of the aquifer unit. The wedge is formed due to the fact that the saltwater is denser than the fresher groundwater and so it tends to sink. The locally discharging freshwater then flows over the top of this wedge and is either forced to discharge upward to a shallow sink, or moves along the top of denser saltwater until it discharges into the ocean. Ideally, the effects of saltwater intrusion act as a potential barrier to flow of freshwater and ultimately to the downward vertical advective migration of leachate. As discussed in Sections 4.1.2 and 6.6.2.2, however, if the presence of seawater in

Cretaceous sands is the result of induced recharge caused by deep pumpage, then an extensive mixing zone rather than a classical salt water wedge would have developed in these transmissive deposits under Section 1/9, complicating the evaluation of vertical leachate migration relative to density effects.

6.3.1.5 Conceptual Model of Groundwater Flow

The contoured horizontal head distributions used for the development of the conceptual flow model for the refuse, Recent sand Unit 1, Cretaceous sand Unit 1, and bedrock units at Landfill Section 1/9 are identified on Sheets 6.32, 6.38, and 6.40, respectively. The contours shown on these maps represent water levels averaged for the period June 17 through July 17, 1992. All water levels have been corrected to represent freshwater levels as described in Section 6.1.3.3 and tabulated in Tables 6.5 and 6.6.

6.3.1.5.1 Plan View

Analysis of the water level contours for the refuse unit shown on Sheet 6.32 for Landfill Section 1/9 indicates the presence of two mounds, which develop radial flow patterns towards the landfill boundaries. Based on available data, the peak of the primary mound is located within the southern third of the landfill section and extends well up into its central area. The second mound is located within the northern third of the landfill section and is approximately one-fourth the magnitude of the primary mound. Horizontal gradients vary across the site from 0.08 ft/ft on the east side of the landfill to 0.005 ft/ft on the northern side of the landfill.

Horizontal flow within the refuse discharges to the west toward the Arthur Kill, toward the north to the Fresh Kills, toward the east to Landfill Section 2/8, and toward the south to Sleight Creek. A portion of the shallow lateral flow within the refuse unit is captured by a shallow subsurface drain, located near the toe of the landfill sideslope along the southern and eastern edges of the landfill, parallel to Route 440 (Veterans Avenue Leachate Collection System). Groundwater flow collected within this drain is recharged back into the landfill within the southern region of the primary landfill mound. Available data from this partial collection system is discussed in more detail in Section 6.3.1.5.4.

As noted earlier, the water level contours indicated on Sheet 6.32 represent the first water encountered during the shallow piezometer installation program. Similar to Landfill Section 6/7, a continuous boring through the refuse at location 1P92:ATW-D indicated the presence of unsaturated zones within the refuse column. Water levels obtained from a shallow/deep refuse piezometer pair installed at this location (1P92:ATW-Z, ATW-S) indicate a basal head 65 ft lower than that observed in the shallow saturated zone. Although only one location was available for examination relative to the presence of unsaturated zones and variation in vertical head, it is likely that other zones exist that affect the water levels indicated on Sheet 6.32 in terms of describing a fully saturated flow system. The potential effect these lower water levels can have on the flow system was previously discussed in Section 6.1.1.2. Therefore, the water level contours shown on Sheet 6.32 should be regarded as being conservative in terms of describing flow within the refuse unit, in that the use of these water levels for flow analysis will generally compute larger quantities of potential groundwater flow than may actually be occurring in the field.

Water level elevation data available for Section 1/9 transmissive overburden hydrostratigraphic sub-units are shown in plan view on Sheets 6.33 through 6.39. The first correlative sand unit in which head data could be contoured and flow components determined is Recent sand Unit 1. As shown in Sheet 6.33, the groundwater flows from beneath the central portions of Section 1/9 westward to the Arthur Kill in Recent sand Unit 1. In the northern portion of the landfill, groundwater moves laterally southwest to the Arthur Kill and northeast to the Fresh Kills from a groundwater high in the central portion of the Recent sand channel deposits (Sheet 6.33). Horizontal gradients in the sand range from about 0.012 ft/ft to 0.0017 ft/ft. Relatively low gradients are observed along the western boundary from central portions of the landfill to the Arthur Kill, where areally extensive deposits of Recent sand occur (Sheet 6.33). Conversely, in the northern portion of Section 1/9 where the sands are less extensive and perhaps representative of a distinct channel deposit, the hydraulic gradients are much steeper and increase down gradient toward the surface water discharge areas.

The primary transmissive unit within the unconsolidated overburden at Landfill Section 1/9 for which water level data can be meaningfully contoured is the Cretaceous sand. Sheet 6.38 indicates the distribution of water levels within Cretaceous sand Unit 1, which is the thickest and most areally extensive deposit. Groundwater flow beneath Landfill Section 1/9 in this sand is primarily from the northwest and northeast (where the Cretaceous sand pinches out) toward the

south. Hydraulic gradients within this unit range from 0.001 ft/ft in the northeast to 0.0002 ft/ft along the southern landfill boundary. The small groundwater divide within the Cretaceous sand unit may be the result of the Cretaceous unit rising as it moves toward the northwest and potentially coming into close contact with the Arthur Kill channel or a Recent or glacial sand unit, which itself is in hydraulic communication with the Arthur Kill. (The surface of the Cretaceous sand unit at monitoring well location 1W91:IT001D is at an approximate elevation of -37 ft). Additional analysis of transient water-level data presented in Section 6.3.1.5.3 will further discuss the potential for a hydraulic connection between the Cretaceous sand unit and the Arthur Kill. It is important to note that, although limited information is available within the central portion of Landfill Section 1/9, potential mounding due to vertical leakage from the upper refuse unit is not observed within the Cretaceous unit beneath the landfill where reliable data are available.

The only monitoring location where hydraulic evidence for vertical leakage into the Cretaceous sand from the refuse unit was potentially observed was at piezometer IT504I, located in the north-central portion of Landfill Section 1/9. Water levels in this piezometer are considered suspect due to their sporadic behavior (varying from no measurable water elevation to an elevation of approximately 55 feet RHW). Several water levels were manually recorded in the range of 10 to 14 feet RHW for a time period of approximately two months from August through September of 1992. As a result of the above, this data point was not included in water level data set shown on Sheet 6.38. This specific piezometer location is discussed further in Section 6.3.2.6, relative to calibration of the two dimensional cross-sectional numerical model.

The horizontal component of groundwater flow in the bedrock hydrostratigraphic unit is shown on Sheet 6.40. Available water-level data for the bedrock unit indicates the presence of two groundwater mounds; one beneath the northeast portion of the landfill and one beneath the southwest portion of the landfill. The presence of these two mounds creates a groundwater divide with the majority of flow moving either to the southeast or west. Horizontal hydraulic gradients within the bedrock unit are fairly uniform and range approximately from 0.006 ft/ft beneath the southwest area of the landfill to 0.003 ft/ft beneath the northern area of the landfill.

The explanation for the mounding in the bedrock may be the result of two different physical processes: direct hydraulic flux of groundwater from the overlying unconsolidated overburden unit or lithostatic pressure. In order for the mounds in the bedrock to be a function of direct flux

from the overlying sediments, the hydraulic heads within the different hydrostratigraphic units above the bedrock would all have to be higher than those in the bedrock. Examination of the water level elevation contours for the overlying Cretaceous sand unit indicates that heads within this unit are all lower than the heads in the bedrock, implying an upward vertical flux from the bedrock unit to the Cretaceous sand.

The apparent mounding within the bedrock unit is likely the result of lithostatic pressure changes that are occurring at depth due to the increase in total weight the landfills are placing above the unconsolidated and bedrock surfaces. As the height of the landfill increases, the weight of the landfill (refuse plus leachate) also increases. This weight increase, in turn, applies a vertical pressure which is transmitted downward to the underlying units. Depending on the compressibility of the underlying units, the response to this increased vertical pressure will be a combination of increased pore pressures and compression of the underlying unit. For materials with low compressibility factors, the increase in vertical pressure is distributed more into the compression of the matrix of the unit and less into pore pressures. For materials with higher compressibility factors, the increase in vertical pressure is distributed more as a pore pressure and less into the compression of the matrix. Freeze and Cherry (1979) provide representative ranges of values of compressibility for various earth materials and show that the compressibility of sands can be one to three orders of magnitude less than fractured rock. Therefore, it is possible for water levels in the bedrock to be higher than those in the Cretaceous sand due to the fact that the sand unit is distributing the vertical pressure from the added weight of the landfill within its matrix while the lower bedrock units show the added weight by increased pore pressures, which would cause increases in hydraulic heads, as measured within the monitoring wells.

Collection of the detailed compressibility, viscosity, density and porosity data that would be required to perform an in-depth analysis of aquifer compressibility is beyond the scope of this investigation. However, this phenomenon has been evaluated analytically in this investigation and within the context of sensitivity analysis (Section 6.1.4.1, Attachment 40, and subsequent two dimensional cross-sectional numerical analyses).

6.3.1.5.2 Profile View

The vertical distribution of water levels and the general flow of groundwater at Landfill Section 1/9 is shown in an east-west profile on hydrostratigraphic cross-section HK (Sheet 6.22) and in a north-south profile on hydrostratigraphic cross-section HB (Sheet 6.13). Similar to the profile analysis of the other landfill sections, the hydrostratigraphic cross-sections are not necessarily located along a horizontal flow path (with the vertical head distribution therefore potentially affected by horizontal flow components). Regardless, they are useful to describe the general vertical flow components and to draw conclusions relative to the flux distribution. The vertical water levels for the east-west profile shown on Sheet 6.22 suggest a complicated flow system within the unconsolidated unit. Similar to Landfill Section 2/8, the Cretaceous sand units act as a major sink, or receptor of flow from the upper unconsolidated overburden unit and the lower bedrock. Significant vertical head losses occur within the refuse and upper unconsolidated overburden units where a groundwater mound is evident. Flow in the bedrock is generally vertically upward, with a horizontal component toward the Arthur Kill.

Similar vertical flow conditions are evident on the north-south profile shown on Sheet 6.13. Significant head losses occur beneath the landfill toward the Cretaceous sand unit, where it is present beneath the southern two-thirds of the landfill. Discharge in the northern area of the landfill is predominantly toward the Fresh Kills in the shallow flow system.

Within the bedrock, a horizontal component flowing from the north of the Fresh Kills indicates potential upward discharge into the Fresh Kills from the shallow bedrock, with flow beneath the Fresh Kills towards Landfill Section 1/9 in the deeper bedrock.

A mound is evident in the bedrock unit beneath the southern portion of the landfill which creates vertical components upward toward the overlying Cretaceous unit. This mound also creates horizontal flow in the bedrock unit to both the north and south.

In addition to the piezometric profiles, vertical flow conditions can be assessed by examining the vertical distribution of hydraulic head depicted in profile or the hydrostratigraphic cross-sections without contained equipotentials. The general hydraulic relationships between the three major hydrostratigraphic units are defined by the distribution of heads in profile. These vertical flow conditions are summarized in a simplistic manner by the distribution of vertical gradients shown

in plan view on Sheets 6.41 and 6.42. As illustrated on Sheet 6.41, positive or downward vertical gradients between the refuse and first confined underlying transmissive unit occur throughout Section 1/9.

As shown on Sheet 6.42, negative or upward vertical gradients between the bedrock and first overlying transmissive unit occur across the entire Landfill Section 1/9. It should be noted that the distributions of vertical gradients depicted on Sheets 6.41 and 6.42 represent only the potential for vertical flow between major hydrostratigraphic units based on head distribution and that flux determinations need to take into account the controlling permeability of hydrostratigraphic units across which flow will occur.

6.3.1.5.3 Temporal Head Variations

Tidal influences were observed in Landfill Section 1/9 monitoring wells and piezometers (Table 6.8). Similar to Landfill Section 6/7, tidal effects in shallow/refuse wells are negligible with the exception of wells screened in either landfill basal sands or surficial sands exterior to the filled areas. Figure 6.23 presents a composite hydrograph for Landfill Section 1/9 wells screened in refuse/fill. Whereas tidal effects are absent in the refuse, tidal influences can be seen throughout the landfill in wells screening the overburden and bedrock hydrostratigraphic units. Tidal effects are more pronounced (higher amplitude in the tidal cycle) in perimeter wells in close proximity to tidal surface waters. Figures 6.24 through 6.28 and Figures 6.29, 6.30 present composite hydrographs of Cretaceous sand and bedrock wells, respectively.

Similar to Landfill Section 6/7, water level changes within the refuse unit at Landfill Section 1/9 show the effects of barometric pressure change. These effects are best observed in observation wells 1W91:IT001S, 002S, 003S, 004S and 007S. Unlike Landfill Section 6/7, the effects of potential recharge from precipitation are not directly observable within the refuse unit at Landfill Section 1/9. Recharge may be evident in monitoring well 1W91:IT001S on days 4 and 23 of the record.

As with Landfill Section 6/7, the bedrock tidal fluctuations are most likely pressure-induced, whereas fluctuations in the overburden (intermediate depth) wells are probably a combination of both pressure-induced and flux-induced changes, if in direct hydraulic connection. Despite the

temporal variations in head, the hydraulic relationships established under steady-state analyses are consistent under transient conditions. This is illustrated by Figure 6.31, a representative well cluster hydrograph, as well as the full suite of composite hydrographs for the landfill section (Appendix J). In addition, long term water level data for well cluster IT001 are presented in Appendix J on Sheet J.1. In general, these long term data support the interpreation that Section 1/9 groundwater flow conditions are generally under steady-state with minor changes over time.

Section 6.3.1.5.1, describing the horizontal flow of groundwater, suggested that the Cretaceous sand unit in the vicinity of monitoring well location 001 may be in hydraulic connection with the Arthur Kill. Comparison of the transient water-level data for the Cretaceous sand at this monitoring location (1W91:IT001I) with data from other monitoring wells completed in the Cretaceous sand (Appendix J) indicates that the water-level changes observed within the Cretaceous unit at this location show the largest amplitude and shortest lag time, supporting the hypothesis that the Cretaceous sand unit may be hydraulically connected or in close contact to the base of the Arthur Kill channel in this area.

6.3.1.5.4 Groundwater Fluxes

Groundwater fluxes were computed for the Landfill Section 1/9 circumferential areal boundary which corresponds to the geologic perimeter cross-section shown on Sheet 5.5, and encompasses an area of 20,194,301 ft^2. Similar to Landfill Section 6/7, flux calculations were performed for the three major hydrostratigraphic units of refuse, unconsolidated overburden, and bedrock. Vertical fluxes were calculated between each major hydrostratigraphic unit within the circumferential area shown on Sheet 5.5. Horizontal fluxes were computed for individual segments along the circumferential perimeter hydrostratigraphic cross section. Attachment 31 summarizes the individual horizontal flux calculations for each segment number shown on Sheet 5.5, and provides similar detail for the vertical flux analysis.

Figure 6.32 graphically indicates the total horizontal and vertical flux components for each of the major hydrostratigraphic units. Similar to the analysis that was performed for Landfill Section 6/7, the recharge available through precipitation to the refuse unit was calculated as the sum of groundwater leaving the system as both horizontal and vertical flux, or 78,822 ft^3/day (589,590 gal/day). The total vertical flux of groundwater that leaves the base of the refuse unit is

estimated to be 10,828 ft^3/day (80,990 gal/day), or approximately 14 percent of the total leaving the refuse unit.

Groundwater enters the unconsolidated overburden hydrostratigraphic unit from both the refuse and bedrock units at estimated net rates of 10,821 ft^3/day (80,940 gal/day) and 801 ft^3/day (5,990 gal/day), respectively. Groundwater leaves the unconsolidated unit with a total estimated horizontal flux of 11,622 ft^3/day (86,930 gal/day).

Groundwater leaves the bedrock hydrostratigraphic unit vertically to the unconsolidated unit and laterally at flux rates of 817 ft^3/day (6,110 gal/day) and 814 ft^3/day (6,090 gal/day), respectively. Assuming very little contribution from storage within the cross-sectional area of the bedrock, the sum of the two flux rates would equal the approximate flux of groundwater upward from the deeper bedrock flow system, and also suggests an upward component of flow within the bedrock unit. It should be noted that the analytical fluxes shown on Figure 6.32 have been rounded to obtain a mass balance. Due to the analytical nature of the calculations and the average of calculated flux numbers for individual horizontal segments, a mass balance error of 2 - 3 percent is possible within the detailed calculations.

An approximate average vertical gradient within the bedrock can be computed by rearranging Darcy's Law to solve for the gradient, as described in Report Section 6.2.1. Using the total surface area of 20,194,301 ft^2 for the area inside the circumferential boundary indicated on Sheet 5.5 for Landfill Section 1/9, a bedrock geometric mean hydraulic conductivity (Table 6.3) for Section 1/9 of 4.2×10^{-6} cm/sec (0.0119 ft/day) and the total flux of water moving upward into the bedrock of 1,615 ft^3/day and solving Darcy's Law for the gradient yields an average upward gradient in the bedrock of 0.007 ft/ft. Water-level data collected at monitoring wells 1W91:IT013D and 1P91:IT013Z, with screened intervals completed within the shallow and deep bedrock, respectively, indicate an upward vertical flow within the bedrock, and an upward hydraulic gradient of 0.02 ft/ft.

A recharge rate into the refuse unit in inches per year can be calculated for Landfill Section 1/9 by dividing the individual fluxes leaving the refuse unit by the total surface area enclosed by the circumferential areal boundary. Dividing the total flux rate of 78,822 ft^3/day by the area given above and converting units, yields a recharge rate to the refuse unit of 17.10 inches per year.

Several additional methods for calculating the potential recharge to the refuse unit at Landfill Section 1/9 were also performed. The results of hydrologic evaluation of landfill performance (HELP) model analysis performed by Ahmed and Khanbilvardi (1989) suggest an average annual recharge rate of 15.7 in./year.

Approximations of recharge using the Veteran's Avenue recirculation system were made by dividing the average daily volume of leachate collected in the system plus estimated underflow by the surface area that the system drains (Attachment 30). The recharge rate calculated for the Veteran's Avenue system by this method is 11.9 in./year. Additionally, a range of recharge was estimated using the SCS runoff curve number method (Lu, 1985). This method provided a range of recharge from 10.4 to 31.9 in. per year, the higher value being considered unrepresentative due to lack of accurate minimum runoff data (Appendix 30).

6.3.2 Numerical Modeling

Numerical modeling for Landfill Section 1/9 consisted of the construction of a two-dimensional, cross-sectional, groundwater flow and solute transport model. Cross-sectional numerical analysis was performed using the geologic and hydrologic database available during preparation of the Draft Final Hydrogeological Report (IT Corporation, Wehran Envirotech, and O'Brien & Gere, 1993a). While some of these data may vary from those presented in this report (e.g., recharge rate, lithologic unit correlation) they do not substantively affect the findings of the numerical analysis, as the cross-sectional flow and solute transport simulations were performed primarily within the context of sensitivity analysis.

The primary objective of the cross-sectional analysis was to gain a better understanding of the vertical flow system at Landfill Section 1/9, and to generally quantify the flow system along a particular flowpath. Specific objectives for the modeling included:

- Examination of the potential for leachate migration to the underlying unconsolidated overburden and bedrock units.
- Sensitivity analysis to determine the potential vertical migration of leachate based on the variation of permeability and thickness of Cretaceous sand, Recent sand, glacial sand, silt/clay and bedrock hydrostratigraphic units that underlie Landfill Section 1/9.

- Evaluation of the layering requirements for subsequent regional three-dimensional numerical model development.

- Preliminary development of a tool for the evaluation of various remedial alternatives during the leachate mitigation design process.

6.3.2.1 Model Selection

To satisfy the general and specific objectives of the preliminary cross-sectional model, a numerical model code was selected that computes both groundwater flow and solute transport. As noted in Section 6.2.2.1, this code is represented by the HST3D model (Kipp, 1987) for this investigation (Attachment 13).

6.3.2.2 Areal Extent

As noted earlier, the basic assumption in the development of a two-dimensional cross-sectional model is for the cross-section being simulated to be located along an areal flow path. This allows for the three-dimensional system to be reduced to a two-dimensional system described as length and elevation along the flow path. The selection of the flow path for the preliminary cross-sectional model was based on water level data collected during the period January 6 through January 13, 1992; data from June 17 through July 17,1992 was used for final model calibration. Water level data for the periods were time-averaged and planimetric contours were prepared for head in the refuse, Cretaceous sand Unit 1, and bedrock hydrostratigraphic units. Contoured equipotential data for these three hydrostratigraphic units are shown on Sheets 6.32, 6.38, and 6.40, respectively, for the time period June 17 through July 17, 1992. The cross-section selected that most closely corresponds to a flow path for both the refuse and bedrock hydrostratigraphic units is shown on Sheet 6.43, as section line 1/9 MCS-1/9 MCS. The cross-section selected trends on an approximate north-south line and follows a flow path that runs from monitoring well 1W91:IT008 on the southwest corner of the landfill to monitoring well 1W91:IT001 on the northwest side of the landfill. Based on the water-level data indicated on Sheets 6.32, 6.38, and 6.40, several other flow paths could have been selected for modeling purposes. This particular flow path was selected because it contains the majority of the hydrogeologic conditions encountered at the site and is a good representation of flow in general

beneath the landfill. The section also contains the major hydrostratigraphic units to be examined by the specific modeling objectives for Landfill Section 1/9.

6.3.2.3 Discretization

Model discretization describes how the modeled area to be simulated was divided into discrete unit locations for the purposes of model data input and output, and to support internal data processing performed by the model code. The extent of model discretization is dependent on several factors that influence the final model grid design. Factors considered in the Landfill Section 1/9 discretization included:

- The location of model internal/external boundary conditions
- The irregularity of model internal/external boundary conditions
- The numerical method of solution
- The location of any specialized source/sink areas
- Specific modeling objectives (Section 6.3.2)
- The location of the Cretaceous sand unit

The Landfill Section 1/9 cross-sectional model discretization is illustrated on Sheet 6.47. The modeled area was discretized vertically into 61 total node locations with a non-uniform spacing between the node locations. Node spacing varied between individual node location 1 to 2 at 30 ft, from node location 2 to 5 at 10 ft spacings, from node location 5 to 53 at 2.5 ft spacings, and from node locations 53 to 61 at 10 ft spacings. The smaller nodal spacings from nodes 5 to 53 represent the majority of the unconsolidated hydrostratigraphic unit between the refuse and bedrock. The total vertical distance discretized was 260 ft and represents a range in local elevation from 80.0 to -180.0 ft. Horizontally, the model was discretized into 35 total node locations with a uniform spacing between nodes of 200 ft.

In addition to the node discretization, the model area has been divided into 253 zones. Hydraulic model input data is defined by these zones, and individual properties can vary independently on a zone-by-zone basis. The zonation was selected to correspond to the hydrostratigraphic units and to allow for the variation of properties within an individual unit for purposes of sensitivity

analysis. Zone locations are also shown on Sheet 6.47 and are further defined in the calibrated model data input file provided in Attachment 23.

6.3.2.4 Hydraulic Input Properties

Hydraulic input properties for the modeling at Landfill Section 1/9 were obtained from information obtained during the center boring and Phase I and II well installation programs, and from the Hydrogeologic Literature Review (IT Corporation and Wehran EnviroTech, 1991a; Attachment 44). All data collected as part of this program have been described previously, and are briefly summarized in Table 6.13, which identifies the hydraulic input data for the cross-sectional model in terms of the hydrostratigraphic units. All model hydraulic input properties are provided in the model input file contained in Attachment 23.

6.3.2.5 Boundary Conditions

In general, numerical model boundary conditions describe how water enters and leaves the model flow system. Boundary conditions can describe recharge through precipitation that enters the system vertically or flow to/from rivers and streams at the model edges. Boundary conditions also are used to describe the horizontal flow of groundwater across a vertical face at the model lateral boundary. The selection of a model boundary condition depends on the availability of data to describe the boundary, and how important the boundary is to determining flow conditions within the modeled area.

Three types of boundary conditions were used to describe groundwater flow in and out of the cross-sectional numerical model. A constant flux of water into the model at the upper model layer was used to represent recharge due to precipitation. Based on the results of preliminary analytical flux analyses, a constant rate equal to 15.24 inches per year was uniformly applied to the upper model surface.

Head-dependent flux boundary conditions were used to simulate groundwater moving across the model vertical edge boundaries. Groundwater is able to move explicitly across this type of boundary as a function of the hydraulic conductivity of the hydrostratigraphic unit, a set water

level on the outside of the model boundary, and the model computed water level on the inside of the model boundary. The set water levels at the model boundaries were determined from field collected water level data and extrapolated both horizontally and vertically. The hydraulic conductivity values used at the boundaries correspond to the appropriate horizontal value for the hydrostratigraphic unit present at the boundary.

The third type of boundary condition simulated by the model was a no-flow boundary beneath the lower model layer in the bedrock hydrostratigraphic unit. All model input data for boundary conditions is contained in Attachment 23.

6.3.2.6 Calibration

Similar to the analysis performed at Landfill Section 6/7, calibration of the Landfill Section 1/9 two-dimensional model consisted of comparing water level data collected in the field with model computed water level data at known locations. The model simulates a period of 30 years, roughly corresponding to the period of refuse disposal at Section 1/9 based on review of historical aerial photography contained in the Hydrogeological Literature Review (IT Corporation and Wehran EnviroTech, 1991a; Attachment 44).

Table 6.14 summarizes the field observed versus the model-computed water levels at known observation points for the calibrated two-dimensional cross-sectional model. Field data for each of the monitoring well locations shown on Table 6.14 represents manual or time averaged water levels for the period June 17 through July 17, 1992.

The final calibration for the Landfill Section 1/9 cross-sectional model is considered a transient calibration due to the fact that groundwater storage terms are taken into consideration over the period of simulation. For the HST3D code, storage is calculated as a function of porosity, density, and compressibility of water and the aquifer material (Table 6.13). The inclusion of the compressibility term into the groundwater flow equation allows for the simulation of any additional vertical pressure changes that may occur to the underlying units due to the added weight of the saturated refuse. This added pressure is the result of an increasing saturated refuse mound thickness that is developed over the operational period of the landfill.

Comparison of field-averaged versus model-computed water levels suggests a fair calibration with a root mean square (RMS) error of +/-1.6 feet. Based on the two-dimensional modeling objectives and the availability of water level data along the cross-section, no attempt was made to further refine the model calibration.

Sheet 6.48 shows the model computed water level contours for the cross-sectional model calibration. These data, along with the direction and calculated mean velocity of groundwater flow, are also portrayed in a more convenient format on Figure 6.48. Average linear velocity estimates were calculated through the relationship:

$$V = \frac{Q}{n_e A} = -\frac{Kdh}{n_e dl} \quad (Fetter, 1988)$$

Where K = hydraulic conductivity (cm/sec)
dh/dl = hydraulic gradient (ft/ft)
n_e = effective porosity

Hydraulic conductivity and effective porosity were derived from the data indicated on Table 6.13. Hydraulic gradient data were derived from the head equipotential contours indicated on Sheet 6.48, applied across a specified distance (calculated as the length of the hypotenuse across a defined right angle within each hydrostratigraphic unit).

Model results suggest that flow within the refuse unit is generally horizontal with the majority of flow toward the lateral boundaries on the north and south. A vertical component of flow is obvious in the center of the landfill. A groundwater mound is developed within the central portions of the landfill creating a groundwater divide for flow within the refuse. Beneath the groundwater mound, a significant vertical downward gradient is evident into the underlying unconsolidated unit.

Model results suggest that considerable vertical head loss occurs within the low permeability hydrostratigraphic units comprised of the glacial till, glacial clay, Recent silt and clay, and Cretaceous clay. Model results also indicate that higher permeability sand units can affect both

the vertical and horizontal flow systems, consistent with prior discussions relative to the conceptual model, and sensitivity analysis performed on the Landfill Section 6/7 model.

The effects of mounding of the groundwater within the refuse is also observed within the Cretaceous clay, residual clay, and bedrock hydrostratigraphic units. What is interesting to note is that within the Cretaceous sand unit, flow is generally horizontal and toward the model lateral boundary. Therefore, although a potentially significant vertical head loss is computed for the low permeability materials directly beneath the landfill, horizontal flow is still maintained within the deeper, higher permeability units.

The effect the higher permeability units have on defining flow within the lower units is also illustrated by noting the difference in computed water levels in the vicinity of the large shallow, Recent sand deposit toward the southern end of the landfill cross-section. A considerable loss in hydraulic head is computed between the base of the landfill and top of the Recent sand deposit. Model-computed heads extend around the deposit and continue to exhibit a vertical gradient until contact with the Cretaceous sand, where the flow orientation essentially changes to the horizontal. Results also suggest that the presence of higher permeability units can effect the flow in the deeper units.

It should be noted that model computed water levels within the Cretaceous sand unit at piezometer IT504I are near those recorded in the field during July 1992 (Table 6.6). While water levels from this piezometer have varied widely over the period of record and may be spurious, the correlation noted above indicates the potential for higher water levels to be recorded within the Cretaceous sand units directly beneath the refuse unit in areas of leachate mounding. Model results suggest that such higher water levels in the Cretaceous unit would be due to vertical head losses from the base of the refuse being dissipated into the relatively thin sands at this location.

Figure 6.33 schematically summarizes the flow rates at the recharge and lateral model boundaries in units of cubic feet per day (ft^3/day). Positive rates refer to groundwater entering the flow system and negative rates refer to groundwater leaving the flow system. Examination of Figure 6.33 indicates that, unlike the model result for Landfill Section 6/7, the potential for significant groundwater flux occurs within both the refuse and unconsolidated overburden model layers. Summing the horizontal discharge from the refuse and Recent/glacial sand unit in contact with refuse (-5.15, -2.32, -4.42) and subtracting this discharge from the total rate of recharge to the

refuse layer (+18.8 ft^3/day), provides an estimate of the net rate of vertical groundwater flow leaving the refuse layer to the underlying units (6.91 ft^3/day). This value corresponds to approximately 37 percent of the infiltration entering the refuse through precipitation.

Further examination of Figure 6.33 indicates that there is a net outflow of groundwater across both lateral model boundaries. More water leaves the flow system below the refuse on the southern boundary than the northern, which is due to the fact that a significantly thicker unit of higher permeability Cretaceous sand occurs at that boundary. Calibration results (Sheet 6.48) suggest therefore, that the Cretaceous sand sub-unit within the unconsolidated overburden hydrostratigraphic unit plays a significant role in defining the hydraulic flow conditions beneath Landfill Section 1/9.

Sheet 6.49 shows contours of the model computed distribution of scaled mass-fraction at the end of the 30 year simulation period. The distribution of scaled mass-fraction suggests that the potential for vertical migration is more prevalent in the western and southwestern portions of Landfill Section 1/9 where thick sequences of Recent sands are present. The potential for horizontal and vertical migration of leachate is described in more detail within the context of the regional three-dimensional areal model in Section 6.6.2.

6.3.2.7 *Sensitivity Analysis*

Sensitivity analysis for the numerical model was performed subsequent to numerical model calibration. Data collected during the Phase II drilling program, and ongoing slope stability investigations (Report Section 4.5.2.1 and Attachment 29) suggest the potential for low permeability layers ($\leq 1 \times 10^{-5}$ cm/sec) to be present at the base of the landfill refuse mounds. The potential for these low permeability layers to effect the water levels in the landfill, and also to act as a barrier to potential vertical leachate migration to lower hydrostratigraphic units, was one focus of the two-dimensional model sensitivity analysis. The results of this specific sensitivity analysis were then used to evaluate refuse unit model layering requirements for the three-dimensional regional model.

Additional objectives of the sensitivity analysis for the Landfill Section 1/9 two-dimensional model included:

- Evaluation of the effects of horizontal to vertical anisotropy in the refuse unit.
- Evaluation of the effects of high permeability units within a low permeability matrix in the unconsolidated overburden unit underlying the base of the refuse.
- Evaluation of the potential for Recent sand lenses near the periphery of the refuse unit to act as migration pathways for leachate to the Cretaceous sand unit.
- Evaluation of the need for additional model layering to describe the refuse unit in the three-dimensional numerical model.

Sensitivity analysis results were evaluated similar to those described for the two-dimensional analyses of Landfill Section 6/7. The distribution of model-computed water levels and scaled-mass fractions for each sensitivity simulation were compared to those calculated in a base simulation (represented under transient conditions on Sheets 6.48 and 6.49). The comparison consisted of subtracting corresponding node computed values. These difference values were then contoured to obtain a visual depiction of the magnitude and location where the individual sensitivity analysis had the greatest impact on the model-computed values. Steady state input file data for the sensitivity analyses is provided in Attachment 21. The steady-state base simulation used for sensitivity analysis comparisons is similar to the calibrated (transient) model for Landfill Section 1/9, except the groundwater recharge rate was reduced to a value of 13.0 inches per year (to be consistent with preliminary sensitivity analyses performed at Landfill Section 6/7). Sensitivity run output files and associated graphics are presented in Attachment 22.

Table 6.15 describes the property changes implemented for each of the 15 sensitivity analyses performed at Landfill Section 1/9. Table 6.16 summarizes the distribution of lateral flux by lithologic unit and model boundary for the base simulation and all sensitivity runs.

Similar to determining the sensitivity of the flux of groundwater through the flow system by examining the flow mass balance, the same type of analysis can be performed for the distribution

of solute within the flow system. This is best described by determining the relative percentage of solute present within each of the hydrostratigraphic units at the end of the simulation period and comparing these percentage values with sensitivity simulations of similar duration. For the purposes of sensitivity analysis, all simulations assume a steady-state flow condition for a 20-year simulation period. Table 6.17 summarizes the percentage distribution of solute for each of the sensitivity analysis simulations.

Simulations 1-7 investigated hydraulic property changes in terms of horizontal to vertical hydraulic conductivity variations for the refuse unit as a whole, or on a layer-by-layer basis; Simulations 8-15 investigated the potential for low permeability zones within the refuse; Simulation 16 investigated the effects on the flow system when higher permeability sands are present directly beneath the landfill. Simulations 17-21 investigated changes to hydraulic properties in the underlying hydrostratigraphic units and recharge. Sensitivity analysis simulations 22-24 investigated the potential for unsaturated zones to exist within the refuse unit and their potential impact on flow within the refuse and to the underlying hydrostratigraphic units. Finally, sensitivity analysis run 25 evaluated the effect of the orientation of the cross-sectional model alignment (expressed as a change in head gradient) on flux to and within the Cretaceous sand unit.

Sensitivity results for Simulations 1-7 suggest that model-computed water levels within the refuse unit are most sensitive to uniform changes in permeability. This effect is best observed by sensitivity analysis run 3 where an order of magnitude overall decrease in permeability of the refuse unit increased heads by as much as 60 feet above the base water levels, which are approximately 30 feet above any field observed water levels within the refuse unit.

Simulations 1, 2, and 4 through 7 suggest that if lower permeability units do exist within the refuse they can effect the model-computed water levels to elevations approaching water levels observed in the field. Little effect was observed on the distribution of leachate flux. In order to evaluate the potential for significantly lower permeability zones within the refuse, the Landfill Section 1/9 cross-sectional model was rezoned to incorporate smaller zone areas within the refuse unit to allow for better control over the areas within the refuse to be examined. Sensitivity Analysis Run 8 is the base model simulation for the rezoned model grid.

Sensitivity Analysis Runs 9-15 evaluated the potential for significantly lower (2 to 3 orders of magnitude) values of permeability to effect model-computed water levels and solute transport.

Examination of model results indicates that significantly lower permeability zones within the refuse unit generally tend to enhance the horizontal flow components within the upper portion of the landfill, above the low permeability zone. Lower permeability zones also allow for additional head loss to occur vertically in the refuse, which in turn distributes less head to the lower hydrostratigraphic units. Not surprisingly, the potential vertical migration of leachate is also decreased when low permeability layers are simulated within the refuse.

In order to evaluate the effect that large discontinuous sand lenses below Landfill Section 1/9 may have on the distribution of model-computed water levels and potential leachate distribution, the large Recent sand lens which is simulated as below the southern third of the cross-sectioned model area was simulated as having hydraulic characteristics similar to the surrounding glacial till/Cretaceous clay hydrostratigraphic unit. Model results indicate that water levels within the refuse unit increased by as much as 14.0 feet. Again, similar to the low permeability units simulated in the refuse unit, head drops within the region of the Recent sand deposits are more uniform across the glacial till/Cretaceous clay hydrostratigraphic unit. Correspondingly, less leachate is computed as moving vertically downward, with approximately 89 percent of the solute distributed within the refuse unit (Table 6.17, runs 9-15).

Sensitivity Analysis Runs 17-21 examine the potential for leachate to move vertically downward near the northern model boundary where Recent and Cretaceous sand units may be in contact, or separated by thin units of the glacial till/Cretaceous clay hydrostratigraphic unit.

Sensitivity Analysis Run 17 simulates a direct connection between the shallow Recent sand and deeper Cretaceous sand hydrostratigraphic units. Simulations 18-21 then progressively add a 5.0-foot thick unit of lower permeability glacial till/Cretaceous clay between the two sand units, starting at the top of Cretaceous sand. Therefore, Run 21 represents a glacial till/Cretaceous clay hydrostratigraphic unit thickness of 20 feet between the two sand units.

Sensitivity analysis results suggest that a glacial till/Cretaceous clay unit of greater than 15.0 feet can significantly reduce the potential vertical migration of leachate for model simulation areas where a Recent sand unit is present above a shallow Cretaceous sand unit. Model results also

suggest that any leachate that does migrate to the Cretaceous sand unit does not appear to migrate significantly (approximately 2.5 feet) below the sand unit. This is probably because model results suggest that flow through the Cretaceous sand unit is generally horizontal, so that any leachate entering this unit through a vertical flow component will then and migrate laterally within the sands. Consequently, model results suggest that the potential for leachate leaving the shallow flow system within the Cretaceous sand unit can be controlled by controlling the horizontal flow regime within this specific unit.

During installation of monitoring wells as part of the Phase II drilling program, continuous core samples obtained through the refuse at each of the landfill sections indicated that unsaturated zones were present within and below saturated portions of the refuse, with thickness from approximately 2 to 20 feet. These unsaturated zones may represent a potential internal boundary condition to leachate flow within the refuse unit. Sensitivity analysis simulations 22-24 investigated the potential for these unsaturated zones to affect model-computed water levels and leachate distribution. To simulate the unsaturated flow conditions, the permeability of selected zones within the refuse unit were lowered approximately 5 orders of magnitude. This low permeability value essentially represents an approximate no-flow boundary condition, but still allows leachate to migrate through the zone, as could be occurring if the zones were partially saturated.

Model results suggest that these unsaturated zones can act to reduce the potential for leachate to migrate vertically downward within the refuse unit and to underlying hydrostratigraphic units. The potential no flow boundaries within the refuse also increase model-computed water levels within the refuse unit and tend to decrease water levels at the base of the refuse, below the simulated unsaturated zones. Computed water level changes ranged from a lowering of head by approximately 2 to 5 ft below the unsaturated zone, to an increase of head by approximately 2 to 7 ft above the unsaturated zone. Transient analysis of this scenario is discussed in Section 7.4, with model results contained in Attachment 35. Section 7.4 also provides the results of additional transient solute transport analysis considering vertical interconnection of Recent and Cretaceous sand units at Section 1/9 (Figure 7.595, Attachment 24).

Sensitivity analysis simulation 25 investigated the effect of a higher degree of correlation between the cross-sectional model alignment and the orientation of the groundwater flow gradient in the Cretaceous sand unit (e.g., a steeper hydraulic gradient was simulated across the sand unit). As

indicated in Table 6.17, no significant variation in solute distribution was observed under this condition. This finding suggests that, for deep units within the model cross-section, full correlation between the model cross-sectional alignment and the flow regime is not essential for the evaluation of solute flux.

Finally, the two-dimensional cross-sectional groundwater flow and solute transport model was used to examine the potential for downward vertical flux of groundwater within the northern portion of Landfill Section 1/9, where extensive glacial kame deposits are present. To determine the potential for vertical flux from the upper units to affect model computed heads in the bedrock unit, model computed water levels were compared for equal simulation periods of 30 years for cases assuming the bedrock to be compressible and incompressible.

Attachment 40.1 shows model computed water levels assuming the bedrock is compressible. It is interesting to note that a groundwater mound does occur beneath the northern portion of the cross-sectional model in areas where the Recent silts and clays, glacial tills and residual clays are thin. This is also an area where the bedrock surface rises upward. No mound is evident directly beneath the central portion of the landfill.

Attachment 40.2 shows the difference between model computed heads assuming incompressible versus compressible conditions in the bedrock. Positive numbers indicate higher model computed heads for the case where the bedrock is assumed compressible. This plot shows that a bedrock mound is developed below the main portion of the landfill by a magnitude of as much as 10 feet. No change is observed beneath the northern portion of Section 1/9.

Model results suggest that both vertical flux and increased pore pressures due to the loading of refuse, as described in 6.1.4.1 for the Terizaghi theory of consolidation, can increase model computed water levels within the bedrock.

6.4 Landfill Sections 2/8 and 3/4

Landfill Sections 2/8 and 3/4 are combined within this section of the report for presentation purposes relative to ultimate numerical analysis. Individual conceptual models are developed for each section prior to a discussion of the combined two-dimensional numerical analysis results.

6.4.1 Landfill Section 2/8 Conceptual Model

6.4.1.1 Hydrostratigraphic Units

The stratigraphy and hydrostratigraphy encountered beneath Landfill Section 2/8 is similar to that identified previously for Landfill Section 1/9. The chief differences between the two sections relates to the thickness and proportions of the units and their internal materials. As elsewhere defined for the project area, the general hydrostratigraphic units for Landfill Section 2/8 consist of refuse, overburden, and bedrock with subdivision of the overburden into sub-hydrostratigraphic units.

Consistent with the regional and individual landfill section conceptual model development, the stratigraphy beneath Landfill Section 2/8 can be simplified by grouping the various overburden units into transmissive and restrictive units based on the ability of the materials to transmit groundwater. Individual transmissive sand units that are vertically and/or laterally interconnected combine to act as correlative hydrostratigraphic sub-units in which preferential groundwater flow can occur. Likewise, restrictive fine-grained units that are interconnected combine to from correlative hydrostratigraphic sub-units that restrict groundwater flow and impede vertical contaminant migration. The hydrostratigraphy of Landfill Section 2/8 is best illustrated in profile on the north-south trending hydrostratigraphic cross-sections HD, HE, HF and HG shown on Sheets 6.15 through 6.18, respectively; and on the east-west trending cross-sections HI, HJ, HK, HL and HM shown on Sheets 6.20 through 6.24, respectively.

Unlike Landfill Sections 1/9 and 6/7, extensive filling at Section 2/8 has been limited to only a portion of the total landfill property area, roughly the northern third (refer to Sheet 5.30). The landfill section is bounded on the west by the Staten Island Expressway and Section 1/9. The north, northeast and eastern boundaries border the Fresh Kill and Richmond Creek. The southern limits of the refuse are bordered by two small streams (Richmond Creek Tributaries 1 and 2); Tributary 1 also runs across the northern third of the landfill, discharging into Richmond Creek. The refuse/fill unit is almost entirely underlain by fine grained restrictive unconsolidated units beneath Section 2/8. Recent silt, clay or peat is found below the refuse/fill in the northern and far southeastern portion of the section. In the central and southern portions of the landfill, glaciolacustrine silt and clay, glacial till, or Cretaceous clay underlie the refuse/fill. Isolated

areas of discontinuous sand units occur beneath the refuse, but are typically separated from other transmissive units by sequences of low permeability materials.

An exception to the above occurs in the area of 1W91:IT301, where Recent sand is in direct contact with the base of the refuse and can be correlated across Richmond Creek to Section 6/7 (refer to Sheet 6.24). It should be noted that shallow sand units separated from the refuse by thin layers of low permeability material, which may or may not be correlated as continuous beneath the fill, have the potential to vertically route leachate through interconnected transmissive pathways to more continuous units (i.e., 2P91:IT806, Ks; Sheet 6.22).

Similar to Sections 6/7 and 1/9, the unconsolidated overburden hydrostratigraphic unit can be described as existing primarily of fine grained low permeability materials interlayered with correlative and noncorrelative deposits of coarse-grained high permeability material. The restrictive hydrostratigraphic sub-units include Recent silt and clay, glaciolacustrine silt and clay, glacial till, Cretaceous clay and residual clay, where present. Where these restrictive sub-units are vertically and/or laterally interconnected, they act to restrict groundwater flow and impede potential contaminant migration between transmissive units (refuse, sands, bedrock). A more detailed discussion and presentation of the occurrence and spatial distribution of the restrictive units identified beneath Section 2/8 is provided in Section 5.4.3.

Within the predominately fine grained matrix of the overburden unit, transmissive sand units occur as distinct correlative hydrostratigraphic sub-units in which preferential groundwater flow will occur. Recent, glacial, and Cretaceous sand units represent the transmissive hydrostratigraphic sub-unit underlying Section 2/8. The occurrence, spatial distribution and correlative of these transmissive horizons are best illustrated in the above-noted hydrostratigraphic cross-sections.

Recent sand deposits underlying Landfill Section 2/8 have been correlated to Recent sand Units 1, 3, 4 and 5. The Recent sand deposits are primarily scattered occurrences, found in the northern and eastern portions of the landfill in previous marsh areas that were present prior to placement of the fill (Sheets 5.36 and 5.37). Only Recent sand Unit 1, occurring in the northern portion of Section 2/8 is areally extensive, and can be considered correlative across adjacent landfill sections (Sheet 5.36). The other Recent sand units are of limited extent, although Unit

6 appears to be in direct contact with Richmond Creek in the easternmost area of Section 2/8 (Sheet 5.37).

Glacial sands occur throughout Section 2/8. The greatest concentration of these sand deposits occurs along an east-west band that trends through the center of the Section and is associated with the kame feature identified in Landfill Section 1/9. Nine glacial sand units were identified within the glacial sequence beneath Section 2/8, and include Units 8, 9, 10, 14, 15, 17, 23, 24, and 25. Glacial sands occur within and/or below the glaciolacustrine silt and clay deposits, and within, above, and below the glacial till units.

Cretaceous sand deposits occur extensively beneath the southern two thirds of Landfill Section 2/8. Cretaceous sand Unit 1, the basal and areally extensive sand unit, is present within the entire Cretaceous sequence underlying Section 2/8 (Sheet 5.63). This sand unit can be correlated across to Section 1/9, and potentially in a southerly and westerly direction to a regional Cretaceous sequence. Sand Units 3, 4, 5, and 6 (Sheet 5.64) occur in the upper portions of the Cretaceous sequence, are typically interbedded with Cretaceous silt and clay, and are discontinuous deposits of limited areal extent.

Preferential groundwater flow will occur in the overburden within the above-noted transmissive hydrostratigraphic sub-units. The interconnectedness of these units is limited beneath Section 2/8 (refer to hydrostratigraphic cross-sections and Sheets 5.93, 5.94 and 5.95). However, both Recent sand Unit 1 and Cretaceous sand Unit 1 represent section-wide correlative sand units in which groundwater can readily move laterally beyond section boundaries; and in the case of the Cretaceous sand, vertically into deeper flow systems.

The bedrock unit is comprised of the Stockton Formation in the north and west, and serpentinite and schist in the south and east (Sheet 5.82). The bedrock surface has a relatively flat surface generally sloping to the southeast (Sheet 5.74). The upper surface of the bedrock is characterized as weathered bedrock across the entire site (Sheet 5.71).

The majority of the bedrock unit is overlain by low permeability residual clay, Cretaceous clay, or glacial till. However, beneath the central portions of the landfill where residual clay is absent (sheet 5.68), there are areas where Cretaceous sand is in direct contact with the underlying bedrock unit (refer to Sheets 6.16, 6.21, 6.22, and 6.23). The areas where these sands directly

overlie the bedrock represent potential migration pathways to the deep flow system from the correlative basal Cretaceous sand unit.

6.4.1.2 Hydraulic Conductivity Distribution

Available hydraulic conductivity data for Landfill Section 2/8 hydrostratigraphic units are summarized in Tables 6.1, 6.2 and 6.3. Figure 6.34 illustrates the distribution of hydraulic conductivity by stratigraphic unit for Landfill Section 2/8. The refuse hydraulic conductivity values from in-situ testing range from 3.0×10^{-7} cm/sec to 1.6×10^{-1} cm/sec. The distribution of refuse hydraulic conductivity values for Landfill Section 2/8 is shown on Sheet 6.2. The geometric mean hydraulic conductivity is 2.1×10^{-3} cm/sec as calculated from 19 in situ tests. As indicated on Figure 6.34, refuse hydraulic conductivity values tend to cluster in the range of 10^{-3} cm/sec. The horizontal distribution of hydraulic conductivity values for the refuse is indicated on Sheet 6.2.

Due to the diversity of the lithology at Section 2/8, the overburden unit exhibits significant variation in hydraulic conductivity distribution, as summarized below:

Restrictive Units	Kv	
	Range	**Geometric Mean [a]**
Recent Silt & Clay	ND[b]	ND
Glacial Clay	10^{-7} to 10^{-8} cm/sec	9.9×10^{-8} cm/sec
Glacial Till	10^{-7} to 10^{-8} cm/sec	1.4×10^{-7} cm/sec
Cretaceous Clay	10^{-7} to 10^{-8} cm/sec	7.9×10^{-8} cm/sec
Residual Clay	ND	ND

[a] Laboratory Kv data
[b] Data not available

	Kh	
Transmissive Units	**Range**	**Geometric Mean [c]**
Recent Sand	ND	ND
Glacial Sand	10^{-2} cm/sec	1.4 x 10^{-2} cm/sec
Cretaceous Sand	10^{-2} to 10^{-6} cm/sec	3.0 x 10^{-4} cm/sec

[c] In situ Kh data

In-situ hydraulic conductivity data for Recent silt and clay, Recent sand, and residual clay are not available within Landfill Section 2/8; data from only one in situ test is available for the glacial sand. Grouping of these units is based on lithologic descriptions of the material and correlation with hydraulic conductivity values for these units across the site (Figure 6.2). Sheets 6.3 through 6.9 illustrate the areal distributions of in situ hydraulic conductivity data for the various transmissive hydrostratigraphic sub-units within the overburden beneath Landfill Section 2/8.

In-situ hydraulic conductivity estimates for the undifferentiated bedrock (including weathered bedrock) range from 1.5 x 10^{-2} cm/sec to 7.2 x 10^{-8} cm/sec. The geometric mean K estimate for all undifferentiated bedrock is 1.7 x 10^{-5} cm/sec (Table 6.3) based on 14 tests. The geometric mean value for bedrock, excluding the weathered rock, is 2.6 x 10^{-6} cm/sec. The geometric mean value for wells screened in weathered bedrock is 2.0 x 10^{-5} cm/sec. The order of magnitude increase in weathered bedrock hydraulic conductivity may reflect the characteristics of the serpentinite bedrock, which does not exhibit a residual clay mantle, and the presence of a pitted or vuggy zone observed in the weathered horizon of this unit. Figure 6.2A indicates the bedrock hydraulic conductivity distribution by formation type and weathering characteristics for Landfill Section 2/8. Sheet 6.10 depicts the areal distribution of available in situ hydraulic conductivity data for Landfill Section 2/8 bedrock hydrostratigraphic unit.

6.4.1.3 Thickness Distribution

Plan view thickness distributions for refuse (total and saturated), are illustrated on Sheets 5.30 and 6.30, respectively. As indicated, Landfill Section 2/8 exhibits distinctive refuse and leachate

mounds. The thicknesses of refuse, saturated refuse, and comparisons with Landfill Section 1/9, can also be seen in profile on Sheets 6.22 and 6.23. As noted in earlier discussions, the elevation and saturated thickness of the leachate mound as depicted on Sheets 6.32 and 6.30 is believed to conservative (high) due to basal mound water level data (2P92:IT806Z, Table 6.5; and Attachment 29), and the identification of thick unsaturated zones within the refuse documented during the drilling of test well 2P92:ATW-D.

Overburden unit thickness for Landfill Section 2/8 is shown in plan view on Sheet 6.31, and in profile on Sheets 6.13 through 6.18 (north-south) and 6.20 through 6.23 (east-west). The general thickness of overburden ranges from approximately 60 ft to greater than 120 ft, generally increasing southward in conjunction with a deepening bedrock surface and thickening Cretaceous sequence. Recent sand unit thicknesses range from less than 1 foot (Unit 1) to greater than 14 ft (Unit 5). The thickness of Recent sand Unit 1 is generally less than 5 ft beneath Landfill Section 2/8, with thicknesses of 5 ft or more identified in Units 3, 4, and 5 (Sheets 5.39 and 5.40). Glacial sand units identified beneath Section 2/8 range in thickness from 1 foot to 15 ft and are typically less than 5 ft thick (Sheet 5.55). The Cretaceous sands beneath this section tend to be thinner than those observed in Landfill Section 1/9, rarely exceeding 20 ft in thickness (Sheet 5.65, 5.66 and 5.67). The most extensive Cretaceous sand, Unit 1, ranges in thickness from as little as 1 foot in the eastern portion of Landfill Section 2/8 to greater than 50 ft in the southwestern tip of Landfill Section 2/8 (Sheet 5.66). The hydrostratigraphic cross-sections (Sheets 6.12 through 6.29) provide in profile a more detailed presentation of the spatial variations in thickness and correlation of the various transmissive hydrostratigraphic sub-units, as well as the fine grained restrictive confining units within the overburden sequence.

6.4.1.4 Boundary Conditions

The primary boundary conditions for Landfill Section 2/8 include recharge through precipitation, discharge to surface water, bedrock base, and horizontal flux. Lateral boundary conditions for the shallow unconsolidated overburden flow system include Richmond Creek to the east, Fresh Kills to the north, and Richmond Creek Tributaries 1 and 2 to the west and south. Lateral boundary conditions for the deeper unconsolidated and bedrock flow systems are defined by the regional flow system previously described.

6.4.1.5 Conceptual Model of Groundwater Flow

6.4.1.5.1 Plan View

Refuse head distributions are shown on Sheet 6.32. As noted earlier, the water level distribution in Landfill Section 2/8 is based on measurements obtained during June 17 through July 17, 1992. These data indicate a distinct groundwater/leachate mound indicative of radial flow with discharge to local surface waters. Horizontal gradients in the refuse unit range from 0.1 ft/ft within the central refuse mound to 0.009 ft/ft at the landfill periphery. As noted in earlier discussions, the leachate mound elevation indicated on Sheet 6.32 is likely representative of perched conditions. Evidence for this assessment at Section 2/8 is provided by water level data from piezometer 2P92:IT806Z, basal refuse piezometer data obtained by Woodward Clyde in support of Consent Order Appendix A-10 Slope Stability Investigations (Attachment 24) and boring log data derived from deep test well 2P92:ATW-D.

Sheets 6.33 through 6.39 illustrate the spatial distributions of available water level data for the unconsolidated sand units beneath Landfill Section 2/8. Due to limitations in available data, the head distribution for the overburden unit as a whole is generally not amenable to plan view equipotential delineation, as noted earlier in the regional discussion. However, based on the limited amount of head data available and knowledge of local flow conditions at neighboring landfill sections, it is not unreasonable to assume that within the shallow sand units, preferential groundwater flow will be horizontal toward local surface water discharge areas (i.e., Fresh Kills, Richmond Creek, Richmond Creek tributaries). The elevation of hydraulic head in these units above that of the Fresh Kills and Richmond Creek support this assumption. Head distributions for Cretaceous sand Unit 1 (Sheet 6.38), indicate a gradient to the southwest converging with the south-southeast gradient exhibited under Section 1/9. The horizontal gradient in the Cretaceous unit ranges from 0.005 ft/ft beneath the landfill to 0.001 ft/ft at the southern landfill boundary.

Groundwater mounds in the bedrock unit similar to those observed in Landfill Sections 1/9 and 3/4 are not evident beneath Section 2/8. In general, flow in the bedrock is generally to the south, with heads being controlled by a mound present beneath Section 1/9 which extends into Section 2/8. This mounding in 1/9 creates an apparent horizontal component toward the northeast in the northern section of the landfill which meets with flow from beneath Sections 3/4 and 6/7.

Horizontal gradients in bedrock range from approximately 0.004 ft/ft beneath the southern portion of the landfill to approximately 0.00002 ft/ft beneath the southeastern portion of the landfill.

6.4.1.5.2 Profile View

The vertical distribution of water levels and the general flow of groundwater at Landfill Section 2/8 is shown in an east-west profile on hydrostratigraphic cross-sections HK and HL (Sheets 6.22 and 6.23) and in a north-south profile on hydrostratigraphic cross-sections HE and HG (Sheets 6.16 and 6.18). Similar to the analysis at other landfill sections, the water levels shown on the hydrostratigraphic profiles are not fully representative of a horizontal flow path, and in some hydrostratigraphic units the direction of flow may be perpendicular to the cross-section. Regardless, the profiles represent general vertical flow conditions at the landfill section from which representative conclusions can be drawn.

Vertical water levels depected in profile along an east-west direction in section HK suggest that the Cretaceous sand units, which are fairly continuous along the cross-section, serve as a sink for groundwater from the upper unconsolidated overburden units and the lower bedrock. Flow in the bedrock unit is generally horizontal with potential upward discharge toward Richmond Creek. Flow in the refuse mounds show steep vertical gradients toward Richmond Creek and shallower gradients toward Landfill Section 1/9. Vertical water level distributions depicted in a north-south direction along section HG suggests a significant gradient toward the Richmond Creek from both the landfill and the deeper bedrock system.

Vertical flow conditions are summarized in general by the distribution of observed vertical gradients (Table 6.7) shown in plan view on Sheets 6.41 and 6.42. As illustrated on Sheet 6.41, positive or downward vertical gradients between the refuse and first confined underlying transmissive unit occur over the majority of the fill area in Section 2/8, covering the central portion and extending westward across to Section 1/9. Negative or upward gradients to the refuse are observed only along the Section 2/8 periphery in the north, south and east. As shown in Sheet 6.42, positive (downward) gradients between the bedrock and first overlying transmissive unit are prevalent beneath the landfill mound and west central area extending into Section 1/9. Negative (upward) gradients from the bedrock occur over half of the landfill section, primarily in the northern half and southwestern portions of the landfill.

6.4.1.5.3 Temporal Head Variations

Temporal head variations observed in Landfill Section 2/8 are consistent with those observed in Landfill Sections 6/7 and 1/9. Generally, tidal effects are negligible in the refuse unit (Table 6.8), as illustrated in the composite hydrograph on Figure 6.35. However, within the bedrock and overburden units, tidal influences are evident at perimeter well locations along the eastern and northern borders of the landfill, in close proximity to tidal streams. Downgradient western and southern well locations show little or no tidal effects. Figure 6.36 and 6.37 present composite hydrographs of Landfill Section 2/8 intermediate and bedrock wells, respectively, to illustrate this point. The tidal effects on bedrock wells is most likely a pressure-induced fluctuation as opposed to direct tidal flux, likely due to the separation of the bedrock unit from surface waters by significant thicknesses of low permeability, unconsolidated material. However, intermediate wells screen sand units of varying continuity that may or may not be in direct hydraulic connection with surface waters. Despite the temporal variations in head, hydraulic relationships between and within hydrostratigraphic units remain consistent with the steady-state analysis of groundwater flow. This is illustrated by Figure 6.38, a representative well cluster hydrograph, as well as the full suite of composite hydrographs for the landfill section (Appendix J 30 day hydrographs, and long term hydrograph Sheet J.3).

Similar to the shallow refuse wells in Landfill Sections 1/9 and 6/7, barometric pressure changes are observed in refuse monitoring wells 2W91:IT302S and 306S. Recharge through precipitation was not readily observed at either of the well locations. Barometric effects were also observed in intermediate well 2W91:IT305I and possibly in 306I1, although the record for the latter well is not complete. Bedrock well 2W91:IT305D also exhibits barometric effects.

Tidal effects were observed only in bedrock wells 2W91:IT303D and 304D, both of which are located along the Richmond Creek. It is interesting to note that bedrock well 2W91:IT302D exhibited no tidal effects, although it is also located along Richmond Creek.

6.4.1.5.4 *Groundwater Fluxes*

Groundwater flux calculations were analytically determined for the three major hydrostratigraphic units of refuse, unconsolidated material and bedrock with methods similar to that described for the regional conceptual model. The region encompassed by the analytical analysis is shown on Sheet 5.5, and represents an area of 9,977,608 ft^2. Details regarding the horizontal flux calculations for each of the hydrostratigraphic units, as well as vertical flux analysis, are contained in Attachment 31.3.

Figure 6.39 schematically summarizes the net horizontal and vertical fluxes for each major hydrostratigraphic unit, and indicates that the majority (approximately 96 percent) of recharge that enters the refuse unit through precipitation, leaves as horizontal flux at the landfill periphery. The remaining groundwater moves vertically downward into the unconsolidated unit where it leaves as horizontal flux, as the net flux from the bedrock unit is also into the unconsolidated unit.

The net flux of water estimated for the bedrock unit indicates water leaving both horizontally and vertically upward. This suggests that in order to balance the flux equation, a net upward vertical gradient would be required within the bedrock unit. An approximate net vertical gradient can be calculated for the bedrock unit by rearranging terms in Darcy's Law (as detailed previously in Section 6.2.1.5.4) inputting the net total flux into the bedrock of 541 ft^3/day (4,045 gal/day), the geometric mean hydraulic conductivity for the bedrock unit beneath Section 2/8 (1.7 x 10^{-5} cm/sec), and the total area over which the leakage occurs (9,977,608 ft^2), yields an average site-wide upward gradient of 0.001 ft/ft. It should be noted that the analytical fluxes shown on Figure 6.39 have been rounded to obtain a mass balance. Due to the analytical nature of the calculations and the average of calculated flux numbers for individual horizontal segments, a mass balance error of 2 - 3 percent is possible within the detailed calculations.

Finally, the total recharge to the refuse unit can be approximated in units of inches per year by dividing the total flux into the refuse unit of 37,065 ft^3/day by the total area (9,977,608 ft^2), yielding a recharge rate of 16.27 inches per year.

6.4.2 Landfill Section 3/4 Conceptual Model

6.4.2.1 Hydrostratigraphic Units

The hydrostratigraphy underlying Landfill Section 3/4 is unique in that almost the entire section is underlain by a significant thickness of Recent deposits including peat, silt/clay and sand attributed to an extensive tidal marsh depositional environment present prior to landfill development. Whereas the geologic depositional model would suggest a dominant distribution of silt and clay with lenses or channels of Recent sand, stratigraphic data identify a broad areally extensive and laterally continuous deposit of Recent sand beneath the majority of the site. This deposit was also identified beneath the PASNY site west of Section 3/4 (Wehran, 1991) and has been correlated across Fresh Kills and Main Creek to Landfill Sections 1/9, 2/8 and 6/7 (Sheet 5.36). Boring logs from Section 3/4 indicate that the Recent sand directly underlies refuse/fill in the western and northern portions of the landfill, and occurs beneath silt/clay and peat elsewhere in Section 3/4. Beneath the Recent deposits are glacialacustrine silts and clays which, in turn, are underlain by glacial till and residual clay that overlie the bedrock, a distribution consistent with the stratigraphy identified in the north-west portions of Section 6/7. A glacial kame deposit occurs in the east central area of the landfill that is potentially correlative to the south and east.

In keeping with the hydrostratigraphy of neighboring sections and the regional conceptual model, the primary hydrostratigraphic units include refuse, overburden and bedrock. Similar to conceptual model development for other landfill sections, Section 3/4 stratigraphy can be simplified by grouping the overburden deposits into transmissive and restrictive units. Preferential groundwater flow will occur within the transmissive hydrostratigraphic sub-units underlying Section 3/4 predominantly where the sands are interconnected and exhibit lateral continuity. Conversely, groundwater flow will be restricted or impeded by the low permeability fine grained restrictive units that have been identified as both laterally and vertically continuous beneath the extensive shallow Recent sand deposits. The hydrostratigraphy of Landfill Section 3/4 is best illustrated in profile by the north-south trending hydrostratigraphic cross-sections HC, HD, HE shown on Sheet 6.14 through 6.16 and on the east-west trending cross-sections HN, HO, HP shown on Sheets 6.25 through 6.27, respectively.

The refuse/fill hydrostratigraphic unit covers the entire area of Landfill Section 3/4 (Sheet 5.30). The primary refuse mound is limited to the southern two thirds of the total property area. Section 3/4 refuse/fill is bordered on three sides by surface waters represented by Fresh Kills to the south, Main Creek to the east, and tributaries to Main Creek and Fresh Kills in the north and northwest. The PASNY site lies to the west of Section 3/4 separated by Route 440 (Staten Island Expressway). As previously indicated, the refuse unit is directly underlain by Recent sand deposits in the western and northern portions of the landfill that extend beneath the western edges of the landfill mound. These areas are of particular significance as they represent potential windows where contaminants can migrate vertically downward into the overburden, and in turn be transmitted laterally across landfill boundaries via interconnected transmissive horizons. Elsewhere, the refuse is underlain by low permeability Recent silt/clay, and glacialacustrine silts and clays. The glacial kame deposit is of potential significance as a vertical leachate conduit.

Aside from the areally extensive shallow Recent sand deposits identified earlier, the overburden hydrostratigraphic unit beneath Section 3/4 consists predominantly of fine grained low permeability materials interlayered with discontinuous sand units of limited extent. Restrictive low permeability hydrostratigraphic sub-units within the overburden sequence include Recent peat, silts and clays, glaciolacustrine silts and clays, glacial till and residual clay. As previously indicated, due to the heterogeniety of the glacial till composition across the entire Fresh Kills project area, the glacial till deposits are differentiated from the other restrictive units on the hydrostratigraphic cross-sections. As illustrated on these cross-sections, these restrictive sub-units combine to form laterally and vertically continuous confining units that act to limit groundwater flow in both the horizontal and vertical direction. This is of importance in considering the vertical migration of contaminants from the refuse to the bedrock hydrostratigraphic unit. Across all of Section 3/4, the bedrock unit is marked by a laterally continuous sequence of low permeability confining units (primarily residual clay at the base) thus limiting the potential for direct hydraulic communication with the refuse or transmissive sand deposits above. A more detailed discussion of the occurrence and extent of the low permeability materials which are grouped into restrictive sub-hydrostratigraphic units is provided in Section 5.4.4.

As previously discussed, the primary transmissive units within the predominantly fine grained overburden sequence are the shallow Recent sand deposits underlying almost the entire section. The only portions of Section 3/4 where Recent sands were not encountered are in the east central portion of the landfill where a glacial kame deposit occurs. These Recent sand deposits are

correlated to the areally extensive Recent sand Unit 1 identified site wide (Sheet 5.36). Of lesser importance with regard to site hydrostratigraphy are glacial sands, which occur within the overburden sequence as scattered deposits of limited lateral and vertical extent. These sands occur interbedded and interfingered with glacialacustrine sediments and non-lodgement glacial till. The glacial sands have been correlated to three glacial units including Unit 1, 5, and 20. Units 1 and 5 are somewhat extensive in that they can be correlated beneath Main Creek to glacial deposits underlying Section 6/7. As noted previously, sands associated with the glacial kame deposit may act to allow for leachate migration to depth; however, residual clay overlying the bedrock limits flux potential to that unit.

The bedrock hydrostratigraphic unit underlying Section 3/4 is comprised of the Triassic Stockton Formation in the southeast, and the Lockatong Formation in the northwest (Sheet 5.82). This hydrostratigraphic unit includes weathered bedrock throughout most of the section where it overlies the move competent bedrock (Sheet 5.71). The surface of the bedrock beneath Section 3/4 (Sheet 5.74) shows a general trend to the south, although a bedrock high exists in the southeast corner of the section that may have influenced the sinuous path of Main Creek near its confluence with Fresh Kills.

6.4.2.2 *Hydraulic Conductivity Distribution*

Figure 6.40 illustrates the distribution of hydraulic conductivity by stratigraphic unit for Landfill Section 3/4. The range of in-situ hydraulic conductivity data for the refuse is 6.0×10^{-7} cm/sec to 1.1×10^{-1} cm/sec, with a geometric mean of 2.8×10^{-3} cm/sec (Table 6.3). Refuse K values tend to cluster in the range of 10^{-1} cm/sec to 10^{-3} cm/sec. The horizontal distribution of hydraulic conductivity for the refuse is illustrated on Sheet 6.2. As indicated, no spatial pattern in the refuse hydraulic conductivity distribution is apparent. Consistent with the descriptions presented earlier, the overburden can be differentiated into restrictive and transmissive units, as follows:

Restrictive Units	Kv	
	Range	Geometric Mean [a]
Recent Silt & Clay	10^{-8} cm/sec	6.4×10^{-8} cm/sec
Glacial Clay	10^{-6} to 10^{-8} cm/sec	2.0×10^{-7} cm/sec
Glacial Till	10^{-7} cm/sec	1.2×10^{-7} cm/sec
Residual Clay	10^{-7} to 10^{-8} cm/sec	1.5×10^{-7} cm/sec

[a] Laboratory Kv data

Transmissive Units	Kh	
	Range	Geometric Mean [b]
Recent Sand	10^{-3} to 10^{-7} cm/sec	1.8×10^{-5} cm/sec
Glacial Sand	10^{-3} cm/sec	8.7×10^{-3} cm/sec

[b] In situ Kh data

Sheets 6.3 through 6.7 illustrate the horizontal distribution of available in situ hydraulic conductivity data for the various transmissive hydrostratigraphic sub-units in the overburden beneath Landfill Section 3/4. Only limited data (one sample) are available in Section 3/4 for the Recent silt and clay and the glacial sand. The hydraulic conductivity distribution for the Recent sand at Section 3/4 is skewed by several atypically low values, resulting in a mean K approximately one order of magnitude lower than that exhibited by the regional database. As noted subsequently through reference to Table 6.18, final numerical model calibrated K for this unit is on the order of 2×10^{-3} cm/sec, or one order of magnitude higher than the mean K exhibited by the regional database.

In-situ hydraulic conductivity estimates for undifferentiated bedrock (including weathered bedrock) range from 7.0×10^{-3} cm/sec to 1.7×10^{-6} cm/sec, with a geometric mean hydraulic conductivity of 4.9×10^{-5} cm/sec (Table 6.3). The geometric mean for bedrock, excluding weathered bedrock is 2.7×10^{-4} cm/sec, and for weathered bedrock is 1.9×10^{-5} cm/sec. The apparent lower permeability of the weathered bedrock may be a reflection of the clay matrix developed from the parent shale material. Figure 6.2A indicates the bedrock hydraulic

conductivity distribution by formation type and weathering characteristics for Landfill Section 3/4. Sheet 6.10 shows the horizontal distribution of in situ hydraulic conductivity data available for the undifferentiated bedrock underlying Landfill Section 3/4.

6.4.2.3 Thickness Distribution

The thickness of the refuse, saturated thickness of the refuse, and overburden thickness are shown in plan view on Sheets 5.30, 6.30, and 6.31, respectively. Hydrostratigraphic thickness distributions for the section, from a profile perspective, are presented on Sheets 6.14 through 6.16 (north-south) and 6.25 to 6.27 (east-west). As indicated, maximum refuse thicknesses are in excess of 120 ft and a pronounced groundwater mound with substantial thicknesses is evidenced (albeit, based on limited data). Overburden thicknesses are on the order of 80 to 100 ft, with a slight increase from east to west. The Recent sand sub-hydrostratigraphic unit beneath Landfill Section 3/4 ranges in thickness from 1 foot to more than 25 ft (Sheet 5.38). The thickest deposit of Recent sands occur in the northwest-central portions of the landfill, reaching thicknesses of 15 to 20 ft or more. The remainder of the Recent sand deposit averages about 10 ft thick and decreases to 5 ft or less toward the southern and eastern boundaries (Sheet 5.34). The glacial sands identified beneath Section 3/4 range in thickness from 1 foot in Unit 20 to greater than 50 ft in Unit 1. The thickness distributions for glacial sand Units 1, 3, and 5 are shown on Sheets 5.53 and 5.54, respectively. A more detailed presentation of the spatial variations in thickness and correlation of the transmissive as well as restrictive sub-units within the overburden are provided on the hydrostratigraphic cross-sections.

6.4.2.4 Boundary Conditions

The boundary conditions for Landfill Section 3/4 include many of the same elements as with other landfill sections, predominately:

- Surface waters
- Infiltration
- Bedrock base
- Regional gradient

The surface water boundaries for the refuse/fill and upper overburden hydrostratigraphic sub-units include Fresh Kills to the south, Main Creek to the east, and tributaries to Main Creek (Travis Creek) and the Fresh Kills to the north and northwest.

6.4.2.5 Groundwater Flow

6.4.2.5.1 Plan View

Horizontal head distributions are presented on Sheets 6.32, 6.33 and 6.40 for the refuse, Recent sand Unit 1 and bedrock units, respectively. In addition, available water level elevation data for the glacial sand units identified beneath Landfill Section 3/4 are illustrated on Sheets 6.35 through 6.36. The highest recorded water level in a refuse unit at the landfill is within Landfill Section 3/4, with an elevation of 122.31 feet for piezometer 3P92:IT431Z. This high water level creates an elevated mound within the central portion of Section 3/4, and a horizontal gradient of approximately 0.10 ft/ft. The horizontal gradient is significantly less in the northern area of the landfill, with a value of approximately 0.002 ft/ft. As noted in previous discussions, the leachate mound elevation indicated on Sheet 6.32 is likely representative of perched conditions. Evidence for this assessment at Section 3/4 is provided by boring log data derived from deep test well 3P92:ATW-D and deep basal refuse piezometer data (Attachment 29). Based on the water-level contours shown on Sheet 6.32, the horizontal flow of groundwater for the refuse unit discharges radially from the mound nearly equal in all directions.

The distribution of water level elevation data collected from Recent sand Unit 1 wells suggest that lateral flow within these shallow overburden hydrostratigraphic units is controlled by local discharge to nearby surface waters. As shown on Sheet 6.33, contoured head data indicate radial flow from beneath central portions of the landfill toward local surface water discharge areas. Within the Recent sand deposits underlying Section 3/4, a water level mounding condition is observed in the central portions of the landfill. This mounding condition is attributable to the refuse water level mounding above, which particularly influences the underlying sand heads to the north and west central areas of the landfill where Recent sand is in direct hydraulic communication with the overlying refuse. Based on this observed mounding condition in the Recent sands, horizontal groundwater flow moves radially from the central portions of Section 3/4 and discharges southward to Fresh Kills, eastward to Main Creek, northward to Travis Creek,

and westward to the PASNY site and the Fresh Kills tributary stream. Horizontal gradients in the Recent sand range from about 0.015 ft/ft to about 0.002 ft/ft beneath Section 3/4. As indicated on Sheet 6.33, the gradients tend to steepen toward discharge boundaries and are generally lower beneath the center of the landfill.

Although head data are not available to assess horizontal groundwater gradients for the remaining overburden units beneath Section 3/4, it would not be unrealistic to assume that similar flow patterns exist for these unconsolidated sub-units, but at significantly lower and varying horizontal gradients, dependent on the vertical head loss that occurs at depth as a result of intervening low permeability units. The vertical distributions of head illustrated on the hydrostratigraphic cross-sections discussed subsequently provide insight into general horizontal vertical groundwater flow patterns in the overburden.

As shown on Sheet 6.40, horizontal groundwater flow in the bedrock unit is similarly characterized by a radial flow pattern, which appears to be a subdued image of the overlying refuse mound. Data are not available in the bedrock for the highest refuse water-level location (3P92:IT431Z) so the actual shape of the mound may be shifted somewhat southerly. Regardless, water levels exhibited in the bedrock unit indicate a horizontal flow with a maximum gradient of approximately 0.01 ft/ft toward the southern landfill boundary and a minimum value of approximately 0.001 ft/ft toward the northern landfill boundary. As was discussed in Section 6.3.1.5.2, the hydraulic head in the bedrock unit is believed to be a function of hydrostatic overburden pressure from the landfill, with a potential component of downward vertical flux.

6.4.2.5.2 Profile View

The vertical distribution of water levels and the general flow of groundwater at Landfill Section 3/4 is shown in an east-west piezometric profile on hydrostratigraphic cross-section HO (Sheet 6.26). As noted earlier, the piezometric profile is not fully representative of a horizontal flow path, so the water levels shown do not necessarily represent simple vertical flow components; groundwater flow into or out of the plane of the cross-sectional may occur. Regardless, the profile serves as a means to generally evaluate vertical flow components beneath the landfill section.

The vertical water levels indicated on Sheet 6.26 suggest that a small groundwater mound is present within the bedrock unit beneath the landfill section, as noted in the plan view analysis. Groundwater flow away from the mound in the bedrock is generally horizontal with an upward discharge component toward Fresh Kills and Main Creek to the east, and toward the Arthur Kill to the west.

Vertical flow within the unconsolidated overburden units reflects the head loss that occurs between the refuse and bedrock units. The effect of the higher permeability glacial and Recent sand lenses can be seen in the profile beneath the western edge of the refuse mound, as water levels within this unit indicate a strong horizontal flow component with lateral discharge toward nearby surface waters.

The vertical flow conditions observed in profile on the hydrostratigraphic cross-sections can also be summarized by the distribution of observed vertical gradients (Table 6.7) shown in plan view on Sheets 6.41 and 6.42. As illustrated on Sheet 6.41, positive or downward vertical gradients between the refuse and first confined underlying transmissive unit occur throughout most of Section 3/4, with the exception of the northern and southernmost areas where groundwater mounding in the refuse is absent. Similarly, negative or upward gradients between the bedrock and first overlying transmissive unit occur across nearly the entire landfill section except in the northwest and southwest corners (Sheet 6.42). Vertical flow components from both the refuse and bedrock are controlled by the hydraulic mounding conditions previously discussed for these units.

6.4.2.5.3 Temporal Head Variations

Tidal influences are evident in several of the Landfill Section 3/4 monitoring wells (Table 6.8). Generally, tidal effects are negligible in the refuse unit, as illustrated in the composite hydrograph on Figure 6.41 for the period June 17 through July 17, 1992. However, within the bedrock and overburden units, minor tidal influences are evident at perimeter well locations along the eastern and southern borders of the landfill, in proximity to tidal streams. This is illustrated on Figures 6.42 and 6.43, which present composite hydrographs of Section 3/4 intermediate and bedrock wells, respectively. The tidal effects on the bedrock wells are most likely a pressure-induced fluctuation as opposed to direct tidal flux, due to the separation of the bedrock

from surface waters by significant thicknesses of low permeability material. However, intermediate wells screen sand units that may or may not be in direct hydraulic connection with surface waters. Despite the temporal variations in head, hydraulic relationships between and within hydrostratigraphic units remain consistent with the steady-state analysis of groundwater flow. This is illustrated by Figure 6.44, a representative well cluster hydrograph, as well as the full suite of composite hydrographs for the landfill section (Appendix J 30 day hydrographs and long term hydrograph for well cluster 3W91:IT405).

Barometric pressure effects are not as readily apparent in the refuse wells, but may be observed in well 3W91:IT406S. Recharge to the refuse through precipitation can be observed on the hydrograph for monitoring well 3W91:IT404S. This well is located at the toe-of-slope of the landfill on its eastern margin, near the Main Creek. Figure 6.45 shows the comparison of the water level hydrograph for monitoring well 404S with the quarter-hourly precipitation data recorded at the landfill site. No significant lag time between the precipitation events and the rise in water levels is observed, suggesting that the water-level changes are a local effect and not representative of a recharge response for the entire landfill. This is also supported by the fact that no other refuse monitoring well shows similar responses to the precipitation events.

6.4.2.5.4 Groundwater Fluxes

Horizontal and vertical groundwater flux estimates were calculated for Landfill Section 3/4 through analytical methods similar to those described for the regional conceptual model. The areal boundary used in the calculations is indicated on Sheet 5.5, encompassing an area of 7,866,495 ft^2. Details regarding the horizontal flux calculations for each of the hydrostratigraphic units, as well as the vertical flux analysis, are contained in Attachment 31.

Figure 6.46 summarizes the net horizontal and vertical fluxes for the three major hydrostratigraphic units of refuse, unconsolidated overburden and bedrock. Similar to the other individual landfill sections, the majority of groundwater leaving the refuse unit (approximately 89 percent), is through horizontal flow. The remainder of the flux leaves vertically through the base of the landfill to the underlying consolidated unit. Net flux out of the unconsolidated overburden unit is lateral to surface waters; this lateral component includes a small net upward flux from the bedrock unit.

The net flux of water estimated for the bedrock unit indicates water leaving both horizontally and vertically upward, with the majority as lateral flux. Solving Darcy's Law for a net gradient and using a net flux of 1,580 ft^3/day, a geometric mean hydraulic conductivity for the bedrock at Landfill Section 3/4 of 4.9 x 10^{-5} cm/sec, and an area of 7,866,495 ft^2 yields an upward gradient of 0.0015 ft/ft within the bedrock. It should be noted that the analytical valves shown on Figure 6.32 have been rounded to obtain a mass balance. Due to the analytical nature of the calculations and the average of calculated flux numbers for individual horizontal segments a mass balance error of 2 - 3 percent is possible for detailed calculations.

Finally, the average annual recharge to the refuse unit can be calculated from the total net flux into the refuse (32,777 ft^3/day) divided by the total area, equivalent to 18.25 inches per year. This number is the highest for any of the landfill sections, and reflects the very steep hydraulic gradients developed between the center of the leachate mound and Main Creek, resulting from the use of shallow refuse piezometer water level data to define the leachate mound elevation. As noted earlier, these data likely represent perched conditions; lower head in the refuse mound would result in reduced gradients and discharge and a decrease in the recharge estimate.

6.4.3 Numerical Modeling

Numerical modeling for Landfill Sections 2/8 and 3/4 consisted of the construction of a two-dimensional, cross-sectional, groundwater flow and solute transport model. Cross-sectional numerical analysis was performed using the geologic and hydrologic database available during preparation of the Draft Final Hydrogeological Report (IT Corporation, Wehran Envirotech, and O'Brien & Gere, 1993a). While some of these data may vary from those presented in this report (e.g., recharge rate, lithologic unit correlation) they do not substantively affect the findings of the numerical analysis, as the cross-sectional flow and solute transport simulations were performed primarily within the context of sensitivity analysis.

The objective for the cross-sectional modeling was to gain a better conceptual understanding of the vertical flow systems at Landfill Sections 2/8 and 3/4, and to generally quantify the flow system. Specific objectives for the cross-sectional modeling included:

- Examination of flow to adjacent surface water channels.
- Examination of the potential for leachate migration to the underlying unconsolidated overburden and bedrock hydrostratigraphic units.
- Sensitivity analysis to determine the potential for vertical migration of leachate based on the variation in hydraulic conductivity and thickness of sand, silt/clay and till hydrostratigraphic units that underlie Landfill Sections 2/8 and 3/4.
- Aid in the determination of layering requirements for the three-dimensional regional model.

6.4.3.1 Model Selection

To satisfy the general and specific objectives of the cross-sectional model, a numerical model code was selected that computes both groundwater flow and solute transport. As noted previously, this code is represented by the HST3D model (Kipp, 1987) for this investigation (Attachment 13).

6.4.3.2 Areal Extent

The basic assumption in the development of a two-dimensional cross-sectional model, as previously discussed, is for the cross-section being simulated to be located along an areal flow path. This allows for the three-dimensional system to be reduced to a two-dimensional system described as length and elevation along that path. The selection of the flow path across Landfill Sections 2/8 and 3/4 for the cross-sectional model was based on water level data collected during the period June 17 through July 17, 1992. Water level data for the period were averaged and planimetric contours were developed for the refuse, Cretaceous sand Unit 1, and bedrock hydrostratigraphic units. Contoured data for these units are indicated on Sheets 6.32, 6.38, and 6.40, respectively. The cross-section selected that most closely corresponds to a flow path for

both the refuse and bedrock units is shown on Sheet 6.43 as section line 3/4 and 2/8 MCS. The cross-section selected trends on an north-south line through Section 3/4 into Section 2/8, and then to the southeast, and follows a flow path that runs from well 2W91:IT309 on the southeastern side of Landfill Section 2/8, to well 3W91:IT401 on the north side of Landfill Section 3/4. Based on the water-level data shown on Sheets 6.32, 6.38, and 6.40, several other flow paths could have been selected for modeling purposes. This particular flow path was selected because it contains the majority of the hydrogeologic conditions encountered at the site and is a good representation of flow in general beneath both the landfills. The section also contains the major hydrostratigraphic units to be examined by the specific modeling objectives for these landfill sections.

6.4.3.3 Discretization

As noted previously, model discretization describes how the modeled area to be simulated was divided into discrete unit locations for purposes of model data input and output and internal data processing performed by the model code. The extent of model discretization is dependent on several factors that influence the final model grid design. Factors considered in the discretization for the two-dimensional numerical models for Landfill Sections 2/8 and 3/4 included:

- The location of model internal/external boundary conditions
- The irregularity of model internal/external boundary conditions
- The numerical method of solution
- The location of any specialized source/sink areas (i.e., wells)
- Specific modeling objectives (Section 6.4.3)

The Landfill Sections 2/8 and 3/4 cross-sectional model discretization is shown on Sheet 6.50. The modeled area was discretized vertically into 49 total node locations with node location 1 through 2 having a 20 ft separation, nodes 2 through 4 and 42 through 49 having a 10 ft separation, nodes 4 and 5 having a 50 ft separation, and all the remaining nodes having a 2.5 ft separation. The upper variation in spacing was selected to represent the upper saturated portion of the landfill. The total vertical distance discretized was 210 feet, and represents a range in local elevation from 70.0 to -140.0 feet. Horizontally, the model is discretized into 50 total node

locations with a uniform spacing between nodes of 200 feet for a total linear distance of 10,000 feet.

In addition to the node locations shown on Sheet 6.50, the model area was divided into 319 zones. Hydraulic model input data is defined by these zones, and individual properties can vary independently on a zone-by-zone basis. The zonation was selected to correspond to the hydrostratigraphic units and to allow for the variation of properties within an individual unit for purposes of sensitivity analysis. Zone locations are defined on sheet 6.50 and in the calibrated model data input file provided in Attachment 27.

6.4.3.4 Hydraulic Input Properties

Hydraulic input properties for the cross-sectional modeling performed at Landfill Sections 2/8 and 3/4 were obtained from data collected during the center boring and Phase I and II well installation programs, as well as the Hydrogeological Literature Review (IT Corporation and Wehran EnviroTech, 1991a; Attachment 44). All data collected as part of this program have been described previously, and are briefly summarized in Table 6.18, which identifies the hydraulic input data for the cross-sectional model in terms of the hydrostratigraphic units. Several of the geometric mean K values in this table do not correspond exactly to the values contained in Table 6.3. These differences are due mainly to the calibration process, where whole property values were adjusted to obtain the best model calibrations with field data. Differences in the estimated parameter values between the two data sets are not significant. All model hydraulic input properties for the individual zones are given in the data input file in Attachment 27.

6.4.3.5 Boundary Conditions

In general, numerical model boundary conditions describe how water enters and leaves the model flow system. Boundary conditions can describe recharge through precipitation that enters the system vertically or flow to/from rivers and streams at the model edges. Boundary conditions also are used to describe the horizontal flow of groundwater across a model vertical face at a lateral edge boundary. The selection of a model boundary condition depends on the availability

of data to describe the boundary and how important the boundary is to determining flow conditions within the modeled area.

Four types of boundary conditions were used to describe groundwater flow in and out of the cross-sectional numerical model. A constant flux of water into the model at the upper model layer was used to represent recharge due to precipitation. Two uniform rates were applied to the upper model surface based on the results of preliminary analytical flux calculations. Landfill Section 2/8 received a total of 11.22 inches per year, and Landfill Section 3/4 received 18.11 inches per year.

Head-dependent flux boundary conditions were used to simulate groundwater moving across the model vertical edge boundaries. Groundwater is able to move explicitly across this type of boundary as a function of the hydraulic conductivity of the hydrostratigraphic unit, a set water level on the outside of the model boundary and the model computed water level on the inside of the model boundary. The set water levels at the model boundaries were determined from field collected water-level data extrapolated both horizontally and vertically. The hydraulic conductivity values used at the boundaries correspond to the appropriate horizontal value for the hydrostratigraphic unit present at the boundary.

The third type of boundary condition used in the cross-sectional model is the river leakage condition, which was used to simulate flow into Fresh Kills, which separates Landfill Sections 2/8 and 3/4. The river stage in the Fresh Kills was assumed to equal -2.38 feet as determined from field data collected from tidal gauges B and C (Figure 4.29). The bottom thickness for the Fresh Kills was assumed to be 1.0 foot of fine sand to silt bottom material. The permeability of the bottom material for the Fresh Kills was assumed to be 4.5×10^{-5} cm/sec (based on review of channel bed grain size distribution data [IT Corporation, 1992]).

The final type of boundary condition simulated by the model was a no-flow boundary beneath the lower model layer in the bedrock hydrostratigraphic unit. The no-flow boundary condition was deemed appropriate due to the low net vertical hydraulic gradient obtained from the analytical flux analysis. All model input data for boundary conditions are contained in Attachment 27.

6.4.3.6 *Calibration*

Similar to the cross-sectional models for Landfill Section 6/7 and 1/9, calibration of the transient two-dimensional model for Sections 2/8 and 3/4 consisted of comparing water level data collected in the field with model computed water level data at known locations. Time averaged water levels from the period June 17 through July 17, 1992 were utilized for this purpose.

Table 6.19 summarizes the field observed versus the model computed water levels at known observation points for the two-dimensional cross-sectional model. Comparison of these data suggests an excellent calibration, with a root mean square (RMS) error of +/- 0.67 ft, the lowest obtained from all cross-sectional model simulations.

The final calibration for the Landfill Sections 2/8 - 3/4 cross-sectional model is considered a transient calibration due to the fact that groundwater storage terms are taken into consideration over the period of simulation. For the HST3D code, storage is calculated as a function of porosity, density, and compressibility of water and the aquifer material (Table 6.18). The inclusion of the compressibility term into the groundwater flow equation allows for the simulation of any additional vertical pressure changes that may occur to the underlying units due to the added weight of the saturated refuse. This added pressure is the result of an increasing saturated refuse mound thickness that is developed over the operational period of the landfill.

Sheet 6.51 shows the model computed water-level contours for the calibrated cross-sectional model. These data, along with the direction and calculated mean velocity of groundwater flow, are also portrayed in a more convenient format on Figure 6.49. Average linear velocity estimates were calculated through the relationship:

$$V = \frac{Q}{n_e A} = -\frac{Kdh}{n_e dl} \quad (Fetter, 1988)$$

Where K = hydraulic conductivity (cm/sec)
dh/dl = hydraulic gradient (ft/ft)
n_e = effective porosity

Hydraulic conductivity and effective porosity were derived from the data indicated on Table 6.18. Hydraulic gradient data were derived from the head equipotential contours indicated on Sheet 6.51, applied across a specified distance (calculated as the length of the hypotenuse across a defined right angle within each hydrostratigraphic unit).

Model results suggest that flow within the refuse unit for both landfill sections is generally horizontal with the significant flow toward the Fresh Kills and the model lateral boundary to the north of Section 3/4. A groundwater mound is developed within the central portions of each of the landfills creating a groundwater divide between flow to the Fresh Kills and model lateral boundaries to the north and south. Beneath the groundwater mound in the refuse, a vertical downward gradient is evident into the underlying unconsolidated unit.

Flow in the unconsolidated unit beneath both landfill sections appears to be local to the landfill in nature with the major source of discharge being the Fresh Kills and lateral boundary. The vertical distribution of water levels beneath each landfill section indicates a local downward vertical gradient with a larger downward vertical potential below Landfill Section 3/4, which is consistent with the net analytical vertical flux calculations.

The pressure head beneath Landfill Section 3/4 appears to effect the flow within the bedrock unit under this Section. This same effect is noted at Section 2/8, although it is less in nature due to the lower hydrostatic pressure exerted from the lower apparent mound in Section 2/8. Flow within the bedrock is generally horizontal with a discharge toward the model lateral boundaries.

One interesting feature in terms of vertical flow is an apparent higher water-level zone lying directly beneath the Fresh Kills and the smaller refuse mound at Landfill Section 2/8. These higher water levels are probably a combination of the higher vertical head losses which take place beneath each of the landfill mounds, coupled with the potential for lower heads to be controlled by the river. This higher head zone essentially serves as a hydraulic boundary and divides flow from the shallow and deeper systems, with the majority of the shallow flow discharging toward the river.

Figure 6.47 schematically summarizes the flow rates at the recharge, surface water, and lateral model boundaries in units of cubic feet per day (ft^3/day). Positive rates refer to groundwater entering the flow system and negative rates refer to groundwater leaving the flow system.

Examination of Figure 6.47 indicates that the majority of groundwater moving in and out of the flow system takes place within the upper model layers representing the refuse and shallow sand units. Summing the discharge from the refuse and shallow sand units to the Fresh Kills and lateral model boundaries, (20.59 ft^3/day) and subtracting the total rate of recharge to the refuse layer, (22.83 ft^3/day) yields a net rate of groundwater flow leaving the Landfill Section 2/8 and 3/4 refuse layers to the underlying units, equivalent to 2.25 ft^3/day. This value corresponds to approximately 10 percent of the groundwater entering the refuse through infiltration from precipitation.

Note that in review of Figure 6.47, the water balance must be evaluated across the entire cross-sectional area (both Landfill Sections 2/8 and 3/4), not within each landfill section individually. This is an important consideration in review of the data, notably at Section 2/8. For example, 1.23 ft^3/day of flux through the model southern boundary within the lower Cretaceous sand unit represents through-put across the entire model section, and not flow derived solely from the upper model layers (refuse); as noted above, most of the recharge from infiltration discharges through the refuse to the Fresh Kills.

Sheet 6.52 shows contours of model computed scaled mass-fractions at the end of the 40 year simulation period. It is interesting to note that a signficant concentration gradient is evident near each landfill section boundary with Main and Richmond Creeks, suggesting these surface water bodies act as discharge areas for leachate migrating away from the landfills. Scaled mass-fractions are also computed to migrate to the Cretaceous sand unit beneath Landfill Section 2/8 and the Recent and glacial sand units beneath Landfill Section 3/4. Solute migration to the bedrock is not indicated in either landfill. The potential for vertical and horizontal migration of leachate from both landfill sections is evaluated in more detail in Section 6.6.2.

6.4.3.7 Sensitivity Analysis

Similar to the sensitivity analysis performed for the cross-sectional numerical models for Landfill Sections 6/7 and 1/9, a focused sensitivity analysis was performed for the numerical cross-sectional model for Landfill Sections 2/8 and 3/4. Table 6.20 summarizes the various sensitivity simulations that were performed. All sensitivity model results corresponding to the Run Numbers listed on Table 6.20 are presented in Attachment 26. Table 6.21 summarizes the

distribution of lateral flux by lithologic unit and model boundary for the base (steady state) simulation and all sensitivity runs. The steady state input data file is contained in Attachment 25. As with the other landfill section numerical analyses, the distribution of model computed water levels and scaled mass fraction for each sensitivity simulation were compared to those calculated in a base simulation (represented under transient conditions on Sheets 6.51 and 6.52).

A review of the various sensitivity runs described in Table 6.20 in terms of parameter variation indicates that, in general, the sensitivity analysis concentrated on simulating maximum and minimum values of permeability for the various materials that comprise the refuse, unconsolidated and bedrock hydrostratigraphic units. In addition, sensitivity analysis was performed for maximum and minimum values of uniformly distributed recharge.

In general, maximum water level changes in the refuse units was obtained by decreasing the value for vertical permeability, or effectively increasing the horizontal to vertical anisotropy ratio. Variations in the permeability of the till, glacial clay and residual clay units also affected model computed heads in the refuse unit, with more computed changes within the Landfill Section 3/4 mound (approximately twice the water level change in value) than within the Section 2/8. This is probably due to the fact that the model simulates a thicker unit of low permeability tills, silts and clays directly beneath Section 3/4 than at Section 2/8, so any change in the hydraulic conductivity of these thicker units results in a more noticeable effect on the model computed water levels.

Changes in permeability of the underlying sand units (Recent sands, glacial sands, Cretaceous sands) had a significantly lower effect on water levels computed in the refuse, with the majority of the walter level change occurring near or around the individual sand body being simulated. The only exception was for the case where Recent sands in direct contact with the base of the landfill were simulated as lower permeability units. Model-computed water levels in the refuse unit for this sensitivity simulation tended to show increases similar to that observed through directly decreasing the vertical hydraulic conductivity of the refuse unit.

Finally, sensitivity analysis simulations relative to recharge rate indicate that variations in precipitation affect computed water levels within Landfill Section 3/4 to a greater degree than at Section 2/8.

6.5 Conceptual Model Summary and Conclusions

Before proceeding into the more comprehensive three-dimensional numerical model analysis, it is advantageous at this point to summarize the hydrogeology of the landfill based on the conceptual model analysis. As discussed in the regional and landfill section specific descriptions, the conceptual analysis (including both analytical and cross-sectional numerical flow solutions), plays an important role in forming the basis on which horizontal and vertical discretization and the distribution of hydraulic properties is made for the three dimensional numerical flow model.

Most of the pertinent hydraulic relationships derived through development of the landfill conceptual models are displayed graphically in profile on Figures 6.48 (north-south section through Landfill 1/9), 6.49 (north-south/southeast section through Sections 2/8 and 3/4), and 6.50 (east-west section through Landfill 6/7). These sections correspond to the two dimensional model cross-sections (as indicated on Sheet 6.43), and indicate water levels, head equipotential contours, and velocity vectors showing the direction and rate of groundwater flow based on the results of numerical analysis.

In summary, the geologic framework established for the Fresh Kills Landfill described in Section 5.0 was combined with information concerning the hydraulic properties of the geologic materials to describe the hydrogeology of the landfill site. Hydrogeological site characterization was identified to consist of a series of basic elements, including hydrostratigraphic units, hydraulic conductivity and thickness distributions, boundary conditions, hydraulic head distribution, temporal hydraulic head variations, and net groundwater flux determinations. These elements were used to construct a conceptual hydrogeological model of each individual landfill section as well as the entire landfill complex.

The site-wide conceptual model describes three major hydrostratigraphic units, comprised of an upper refuse unit, a central unconsolidated overburden unit, and a lower bedrock unit. In general, the majority of groundwater flow and potential leachate migration occurs in the upper refuse unit, due to its ability to receive direct recharge through precipitation (averaging 16.3 in./yr across the four landfill sections) and its relatively high hydraulic conductivity (10^{-2} to 10^{-4} cm/sec). The unconsolidated overburden unit is considered generally as a confining/semi-confining unit due to the nature of the low permeability, silt, clay, till, and materials of which it is mostly comprised (hydraulic conductivity ranges from 10^{-6} to 10^{-8} cm/sec). The presence of higher

permeability Recent, glacial and Cretaceous sand units within the unconsolidated overburden suggests potential migration pathways for leachate leaving through the bottom of the landfill. In most areas, sand units are not connected vertically through the overburden, and therefore, generally do not serve as direct hydraulic pathways from the refuse unit to the bedrock. Potential exceptions to this general model are indicated on Sheets 5.93-5.95. The transmissive units are further evaluated as to their hydraulic characteristics and their potential to serve as migration pathways for leachate in the three dimensional numerical analysis.

The bedrock hydrostratigraphic unit is comprised of both weathered and competent bedrock geologic units. The hydraulic conductivity distribution of the bedrock lies within a range from 10^{-7} to 10^{-4} cm/sec. The majority of groundwater flow within the bedrock is probably through joints and fractures within the upper bedrock surface. Net flux analysis for this unit shows the potential for both upward and downward gradients which are generally lower than the horizontal component within the bedrock.

Groundwater flow within the refuse is generally horizontal and radially outward from the leachate mounds that have developed within the central portions of the individual landfill sections. Groundwater mound heights differ for each section and do not appear to be directly correlated with the physical height of each refuse mound. Leachate mound elevations range from approximately 10 ft above the Richmond High Water vertical datum (RHW) at Landfill Section 6/7 to approximately 120 ft above RHW at Landfill Section 3/4. Additional water level data collected during the Phase II well installation program suggests that the presence of unsaturated zones in the refuse may be artificially raising (perching) the elevation of the groundwater mounds at each of the landfill sections and, therefore, the vertical driving force out of the base of the refuse may be considerably less than previously assumed.

The potential for leachate generation within each landfill section was evaluated analytically by calculating groundwater fluxes both horizontally and vertically for the refuse unit. The table below summarizes estimated rates for each landfill section, and indicates the corresponding landfill areas within which the estimates were derived.

Landfill Section	Leachate Generation		Area
	(ft^3/d)	(gal/d)	(ft^2)
1/9	78,822	589,590	20,194,301
6/7	41,179	308,025	13,135,496
2/8	37,065	277,250	9,977,608
3/4	32,777	245,170	7,866,495

Evaluation of groundwater flow within the unconsolidated overburden unit is complicated by the lack of head data within the lower permeability silt, clay, and till units. In general, there is a large potential for horizontal flow depending on the distribution and continuity of included sand lenses, layers or channels. The potential for horizontal flow within these units will be evaluated more extensively within the context of three-dimensional numerical analysis.

Groundwater flow within the bedrock unit is generally horizontal from the northeast to the south. Limited mounding appears to be present beneath the landfill leachate mounds within Landfill Sections 1/9 and 3/4. This phenomenon is believed to be the result of an increase in overburden pressure due to the additional weight of the landfill material; consequently, apparent mounding within the bedrock unit is considered to primarily represent a pressure induced rather than a flux induced head change.

Continuous water level measurements within monitoring wells in each of the hydrostratigraphic units indicates that tidal effects were observed within both the unconsolidated overburden and bedrock units but generally not within the refuse unit (Appendix J). Minor tidal fluctuations observed within shallow wells located along landfill margins where the wells screen refuse and/or Recent or glacial sands at elevations below sea level are considered negligible. This suggests that tidal effects may not be critical in evaluating remedial design alternatives for the refuse unit. Analysis of barometric pressure changes versus shallow refuse water levels suggests that water levels in the refuse respond in a manner similar to that exhibited by semi-confined or confined aquifers. This is probably due to the positive gas pressures within the refuse unsaturated zone.

Salt water intrusion within the Cretaceous sand unit beneath Landfill Section 1/9 and within areas of the bedrock underlying several landfill sections was observed from the analyses of both geophysical and inorganic chemical data. Water levels were corrected to freshwater with specific gravity data supplied from chemical analysis.

Cross-sectional numerical groundwater flow models were constructed for each of the landfill sections. The purpose for the models was to obtain a qualitative and, where data were sufficient, a quantitative analysis of groundwater flow and the potential for leachate migration.

Model results from the individual landfill section analyses indicate that the majority of leachate leaves the refuse unit as horizontal flow, with lesser quantities of flow (1-37 percent of total recharge) moving vertically downward to the underlying unconsolidated overburden or bedrock hydrostratigraphic units.

Sensitivity analysis on the two dimensional numerical models was focused to evaluate how potential variations in the hydraulic conductivity of the materials within the major hydrostratigraphic units can effect the model computed vertical head distribution and ultimately the potential for downward migration of leachate. Sensitivity analysis also focused on the presence and potential interconnectedness of high permeability sand lenses within the unconsolidated unit, and their ability to effect the vertical migration of leachate from the refuse to the underlying Cretaceous sands and/or bedrock.

Sensitivity analysis results generally indicate that sand lenses which may be in contact with the base of the landfill, and are areally continuous to the landfill edge will basically create a sink at the base of the refuse, and any potential leachate flow will move horizontally to a discharge point (usually one of the local surface water bodies). Sensitivity analyses also suggests that uniform variations in hydraulic properties do not, in general, significantly effect the vertical migration potential for leachate out the base of the landfill.

Finally, the sensitivity analyses indicate that simulation of potential continuous sand lenses beneath Landfill Sections 1/9, 2/8, and 3/4 needs to be incorporated into the three-dimensional numerical regional model.

6.6 Regional Numerical Modeling

The final phase in the description of the hydrogeology of the Fresh Kills Landfill site is the development of a numerical modeling tool through which the entire site can be evaluated in terms of groundwater flow. The specific objective of the numerical model is to confirm or refine

conclusions drawn by the conceptual models presented in Sections 6.1 through 6.5 concerning both regional and individual landfill section flow characteristics and their interrelationships, as well as providing a means to evaluate remediation options in accordance with the requirements of Consent Order Appendix A-4.

6.6.1 Groundwater Flow

A versatile three-dimensional code is required to satisfy the general and specific objectives of the numerical analysis of flow at Fresh Kills Landfill. The code should also be easily usable, or adaptable, for final numerical modeling or subsequent analysis related to the evaluation of remedial alternatives. One of the most versatile, well documented, and widely available codes is MODFLOW – "A Modular Three-Dimensional Finite-Difference Groundwater Flow Model" (McDonald and Harbaugh, 1984). This finite difference code was selected for application in this investigation (documentation contained in Attachment 12). In the formulation and development of this code, the governing groundwater flow equations are reduced to finite difference forms using the backward difference procedure. The ensuing solution procedure is iterative, based on either the strongly implicit procedure (SIP) or the Slice-Successive Over-Relaxation method (SOR). These solution techniques are very accurate, and have been documented in the literature (Remson et al., 1971). The MODFLOW code includes the ability to simulate multilayered, heterogenous, anisotropic aquifers subject to various hydrogeologic features such as rivers, drains, or wells penetrating several layers. The code also permits the use of several boundary conditions, including constant head, variable flux, and natural groundwater recharge.

6.6.1.2 Areal Extent

The areal extent of the regional Fresh Kills Landfill model was selected to encompass the full area of the Fresh Kills Landfill complex (approximately 3,000 acres). In general, the modeled area extends at least 150 feet beyond the edge of the landfill in any direction. The modeled area also includes portions of the Arthur Kill, Fresh Kills, Main Creek, and Richmond Creek surface waters. The width, length, and depth of these rivers were determined from topographic and bathymetric map surveys (U.S. Geology Survey, 1981; U.S. Department of Commerce, 1990).

Bathymetric data are graphically depicted on the hydrostratigraphic cross-sections HA-HA through HR-HR presented on Sheets 6.6 through 6.23, respectively.

6.6.1.3 Model Discretization

Model discretization describes how the modeled area is divided into discrete unit locations (grid points) for the purposes of model input data and mathematical calculations required in the numerical code. Model discretization has a strong influence on the computed distribution of simulated results, with more refined discretization enabling a better description of the distribution of computed results. However, refinement is subject to the limitation of software and hardware memory capacity and, more importantly, the associated run-time cost. Therefore, efficient selection of model grid size and design is very important. Generally, the grid size must be such that important minute details of the model, such as external/internal boundary conditions, can be incorporated in the model design. Above all, the discretization must preserve the accuracy of the method selected for the numerical solution.

For the Fresh Kills Landfill, the model area was discretized into 93 rows and 87 columns. A uniform grid size of 150 feet by 150 feet was used. A uniform grid spacing was selected since the interest in this model is to simulate regional groundwater flow. The square grid size of 150 feet is adequate even at the smallest observed river section widths. Sheet 6.53 indicates the regional model discretization and areas of active and inactive model cells. The model computes water level data only for cells which are designated as active.

Vertically, the model is discretized into 7 layers. These seven layers in total represent the three major hydrostratigraphic units of refuse, unconsolidated overburden, and bedrock. In general, Layers 1 and 2 represent the refuse unit, Layers 3 through 6 represent the unconsolidated overburden, and Layer 7 represents the bedrock. Sheets 6.55 through 6.59 show the distribution of high hydraulic conductivity sand units (transmissive units) within model Layers 2 through 6; no such zones were simulated in Layer 7 (bedrock). The identification and areal distribution of sands within each model layer was based on the distribution of correlative sand units described in Sections 5.2.4-5.2.6, and indicated on Sheets 5.35-5.40, 5.48-5.55, and 5.62-5.67. In general, sands within a layer were selected to be totally contained within that layer, corresponding to a defined range of top and bottom surface elevation. A particular sand unit may be present in more

than one layer in areas where the sand is known to be in vertical contact with another sand unit, or to have a considerable thickness. These multiple layer areas are identified on Sheets 6.55 through 6.58. Figure 6.51 lists the Recent, glacial, and Cretaceous sand units (by unit number) that are described on Sheets 5.36-5.40, 5.48-5.55, and 5.62-5.67, and indicated within each model layer on Sheets 6.55-6.59.

With the exception of some areas of Landfill Section 1/9, Layers 1 and 2 of the model represent the refuse unit. Sheet 6.55 indicates the areas in Landfill Section 1/9 where Recent sands known to be in contact with the refuse have been incorporated into model Layer 2 due to their shallow elevation. Recent sands may also be part of Layers 1 and 2 near the major surface water bodies where refuse or fill materials are not present. The thickness of each model layer varies as one-half the saturated thickness of the refuse at the particular node location. Therefore, the thickest refuse layers are approximately 60 ft in the central portions of landfill Sections 1/9 and 3/4, and thinnest at the individual landfill perimeter boundaries.

Model Layer 3 consists of high permeability Recent sands, glacial sands and Cretaceous sands, and low permeability Recent silt/clay, glacial clay and till. The distribution of high permeability sands is shown on Sheet 6.56. The thickness of the active cells in this unit varies from approximately 0.5 to 14.5 ft. The thickness of the layer was determined by the difference between the top and bottom elevations of the individual sand units, and is discussed in Section 6.6.1.4.

Model Layer 4 consists almost entirely of high permeability glacial sands, with some areas of Recent sand and low permeability glacial clays and till. The distribution of high permeability units is shown on Sheet 6.57. The thickness of active cells in this layer ranges from approximately 0.5 to 22.5 ft.

Model Layer 5 consists primarily mainly of high permeability glacial sands and shallow Cretaceous sands, and low permeability glacial clay, till and Cretaceous clay. The distribution of high permeability units in shown on Sheet 6.58. The thickness of the active cells in Layer 5 ranges from approximately 0.5 to 24.5 ft.

Model Layer 6 consists entirely of high permeability Unit 1 Cretaceous sand, and low permeability glacial clay and Cretaceous clay. Sheet 6.59 shows the distribution of the

Cretaceous sand unit. The thickness of the active cells in Layer 6 ranges from approximately 0.5 to 65.0 ft.

Model Layer 7 represents the bedrock unit, and no sand layers are simulated. The thickness of the bedrock unit is assumed to be 200 feet.

6.6.1.4 Hydraulic Input Properties

The input properties required by MODFLOW are dependent on the type of layer that is used to represent each hydrostratigraphic unit. Individual input properties are distributed into each active grid cell location for each layer. The respective distributed input data for the regional model were obtained from field data collected as part of the center boring and Phases I and II drilling programs. Hydraulic conductivity data obtained from these investigations and subsequent analysis were presented earlier in Tables 6.1 through 6.3, and described in detail for each landfill section. Distributed data entered as input to the modeling code were obtained from spatially interpolated field and/or laboratory test data. All model distributed input data is presented on a node by node basis in Attachment 14.

As described earlier, model Layers 1 and 2 represent the refuse hydrostratigraphic unit. These layers are subject to atmospheric conditions, and therefore are simulated as having unconfined flow conditions. The model input requirements for these two layers include the hydraulic conductivity and the bottom elevation of the refuse. The formation transmissivity which is internally estimated within the numerical code, varies as a function of each layer's distributed saturated thickness and the hydraulic conductivity. The distribution of the hydraulic conductivity data used for model Layers 1 and 2 input is shown on Sheet 6.2. Hydraulic conductivity data were refined based on the calculated relationship between hydraulic conductivity and depth indicated on Figure 6.2B. Similarly, the distribution of total saturated thickness for the refuse layers is indicated on Sheet 6.30. The respective data sets (for hydraulic conductivity and bottom elevation) used to generate these data inputs are contained in Tables 6.3 and 5.18, respectively.

To account for potential leakage effects from Layer 1 to Layer 2, a vertical conductance value is required by the model code to complete the input requirement of Layer 1. Distributed conductance values were computed from the distributed hydraulic conductivity and the saturated

thicknesses in the adjacent layers using the equivalent series conductance formula (McDonald and Harbaugh, 1984; Attachment 12); they are indicated on a model node by node basis on Attachment 14 Sheets A14.22 and A14.23 for Layers 1 and 2. The top and bottom elevations and thicknesses of model Layers 1 and 2 are indicated on a node by node basis on Sheets A14.1, A14.8, A14.28 and A14.2, A14.9, A14.29, respectively in Attachment 14. The input hydraulic conductivity distribution for each layer is similarly depicted on Attachment 14 Sheets A14.15 and A14.16.

As indicated on Sheet 6.56, model Layer 3 includes areas of Recent, glacial and Cretaceous sand units whose hydraulic conductivities range from 10^{-6} to 10^{-2} cm/sec. Distributed top and bottom elevation and thickness data for this model layer are contained on Attachment 14 Sheets A14.3, A14.10, and A14.30, respectively. Values of hydraulic conductivity were distributed on a node by node basis for areas described as high permeability sands, based on spatially interpolated hydraulic conductivity for each sand unit. The low permeability areas within a model layer were assigned a uniform value of 10^{-6} cm/sec, which is approximately equal to the geometric mean hydraulic conductivity of the low permeability silts, clays, and tills in the project area. Distributed values were not utilized for the low permeability units due to the small site-wide variation observed in laboratory determined hydraulic conductivity data, as compared to the higher permeability units (Figure 6.2). The rate of water movement through the low permeability units is significantly less than that associated with the more permeable units; therefore, distribution of values between 10^{-6} -10^{-8} cm/sec is not significant in the description of the overall groundwater flow system. Distributed input values of hydraulic conductivity are indicated on a node by node basis on Attachment 14 Sheet A14.17 for Layer 3.

Between the base of the refuse unit (Layer 2) and the top of Layer 3, a Recent silt/clay, glacial clay or till unit is present where these two layers are not in direct contact. As described earlier, these units are simulated as vertical conductance layers allowing for hydraulic communication between two adjacent model layers. The vertical conductance term between two model layers was varied on a node by node basis. Attachment 12 describes the method used to determine the vertical conductance term used by the model; in general, two formulas were applied. For cases where two model layers are in direct contact (i.e., bottom elevation of an upper layer equal to the top elevation of the next lower layer) the vertical conductance was computed at the node as the geometric mean hydraulic conductivity of the two individual layer hydraulic conductivities, divided by the distance between midpoint elevations of the two layers. This method allows for

groundwater to move freely between two high hydraulic conductivity units that may be in vertical connection across two layers. For node locations where layers are separated by a lower hydraulic conductivity unit, the equivalent series conductance formula was used to compute a nodal vertical conductance (Attachment 12). This method requires a thickness and hydraulic conductivity value for the material between the two layers. The thickness was determined by subtracting appropriate layer bottom and top elevations, and a hydraulic conductivity value of 10^{-6} cm/sec was assumed. This second method also allows for groundwater to move vertically between model layers, but as a function of the thickness and defined hydraulic conductivity of the vertical conductance unit. Distributed vertical conductance values for Layer 3 are indicated on Attachment 14 Sheet A14.24.

Model Layer 4 represents zones of Recent, glacial and Cretaceous sand; their areal distribution is shown on Sheet 6.43. The top and bottom elevations and thickness of this layer are indicated on a node by node basis on Attachment 14 Sheets A14.4, A14.11, and A14.31, respectively. Layer 4 hydraulic conductivity ranges from 10^{-6} to 10^{-2} cm/sec; distributed input data are indicated on Attachment 14 Sheet A14.18. Vertical conductance values were determined as previously described, and are indicated on Attachment 14 Sheet A14.25.

Model layer 5 represents the upper Cretaceous sand unit in the southern portion of the project area, and glacial sands to the north; their areal distribution is shown on Sheet 6.57. The top and bottom elevations and thickness of this layer are indicated on a node by node basis on Attachment 14 Sheets A14.5, A14.12, and A14.32, respectively. The hydraulic conductivity distribution varies from 10^{-6} to 10^{-2} cm/sec; distributed input data are indicated on Attachment 14 Sheet A14.19. Vertical conductance values were determined as previously described, and are indicated on Attachment 14 Sheet A14.26.

Layer 6 represents the lower Cretaceous sand unit (Unit 1); its areal distribution is shown on Sheet 6.59. The top and bottom elevations and thickness of this layer are indicated on a node by node basis on Attachment 14 Sheets A14.6, A.14.13 and A14.33, respectively. Hydraulic conductivity varies from 10^{-6} to 10^{-2} cm/sec; distributed input data are indicated on Attachment 14 Sheet A14.20. Vertical conductance values were determined as previously described, and are indicated on Attachment 14 Sheet A14.27.

Layer 7 represents the bedrock unit, which has previously been described as having an assumed thickness of 200 feet. The top and bottom elevations are indicated on Attachment 14 Sheets

A14.7 and A14.14. Distributed values of hydraulic conductivity range from 10^{-7} to 10^{-4} cm/sec; input data are indicated on Attachment 14 Sheet A14.21.

6.6.1.5 Boundary Conditions

Boundary conditions describe the flow of groundwater across the margins of the model area, both horizontally and vertically, thus essentially describing the water balance. Consequently, the assignment of the appropriate boundary conditions is a fundamental component of model design, but is subject to the availability of field data. MODFLOW allows the application of several types of boundary conditions. Those applied in this model include: 1) no flow boundary conditions; 2) constant flux boundary conditions; 3) head-dependent flux boundary conditions; and 4) river leakage boundary conditions.

Similar to the hydraulic properties which can be distributed on a node by node basis for individual model layers, model boundary conditions can also be distributed nodally by individual layer. As described in the individual landfill section conceptual model sections of this report, the upper model boundary for each section is defined as receiving recharge through precipitation. The landfill section analytical flux analyses suggest that recharge to the landfills can range from 13.73 to 18.25 inches per year. In order to maintain consistency with analytical results, recharge to the landfill was varied for each landfill section according to the values obtained from the analytical flux analysis. Recharge was simulated as a constant flux rate uniformly distributed throughout the period of simulation.

While recharge represents a source for groundwater at the site, other boundary conditions serve as discharge areas for groundwater, both locally and regionally. The major discharge boundaries, as described by the conceptual models, are the local surface waters: Arthur Kill, Fresh Kills, Richmond Creek, Main Creek and several small tributary streams along portions of the landfill boundaries. These boundaries are basically termed head-dependent, as the water level (stage) in them controls the direction of groundwater flow.

The majority of these rivers and streams are simulated as being present in Layer 1 and 2. In general, these rivers serve as constant sinks for discharge from the groundwater system, with the rate of discharge a function of the river stage, river bottom thickness, and hydraulic conductivity.

For modeling purposes, all river bottoms were assumed to have a thickness of 1 ft, and a bottom material consisting predominantly of fine sand to silt, with an approximate hydraulic conductivity of 4.5 x 10^{-5} cm/sec (based on review of channel bed grain size distribution data, IT Corporation, 1992). River stage elevation was derived from time averaged continuous water level data (Section 4.8.2, Table 6.5); river bottom elevation data was derived from bathymetric maps of the project area, as described previously in Section 6.1.2. The location of the river and stream boundaries is shown on Sheet 6.60. Attachment 14 presents in tabular model input form the node by node summary of the river bottom elevation, river stage elevation and river bottom conductance. The river bottom conductance term is a function of the length times the width times the hydraulic conductivity of the river bottom material divided by the thickness of the river bottom that is contained within an individual model node.

Another type of head-dependent boundary is simulated at the model's lateral boundaries. These boundaries can serve as both source or discharge areas for groundwater depending on the direction of groundwater flow at the boundary, and are distributed on a nodal basis for individual layers. Groundwater flows across the descritized boundary as a function of the hydraulic conductivity of the hydrostratigraphic unit, a source head outside the modeled area, and a model-computed water level at the boundary. The prescribed source heads were determined from time averaged groundwater elevation data that were extrapolated beyond the modeled area (Sheets 6.32 - 6.40). The head-dependent boundary condition was generally imposed on all external boundary grids in each layer where refuse or sand units were in contact with the boundary, except those adjacent to rivers in Layers 1 or 2. Where low hydraulic conductivity units were in contact with the boundary, a no-flow boundary was assumed. This assumption is based on the concept that the major direction of flow within the low permeability units is vertical, where as in high permeability units, flow is more likely to be horizontal. Attachment 14 presents the node by node summary of the model input data in tabular format.

The final type of head-dependent boundary simulated by the model is the Veterans Avenue leachate collection system within Landfill Section 1/9. For the simulation of this drain, groundwater is assumed to move into the drain only when the head in the collection system is lower than that of the surrounding groundwater. Sheet 6.60 shows the location of the leachate collection system drain. Attachment 14 presents the node by node summary of the model input data for this condition.

6.6.1.6 Model Simulation and Calibration

Calibration of the regional three-dimensional model consisted of comparing known average water levels recorded in the field for the period June 17 - July 17, 1992 with model computed values. The differences between the model computed water level and the field averaged water level, termed the residual, was squared and summed. The object during the calibration process was to minimize the sum of squares of the residuals. This method of calibration allows for tracking during the calibration process and allows the modeler to gauge if additional calibration simulations will significantly improve model results. The majority of data available for the regional model calibration are for the refuse unit (Layers 1 and 2), Cretaceous sand Unit 1 (Layer 6), and the bedrock (Layer 7). Limited water level data available for other shallow unconsolidated overburden units (Recent/glacial sands) were used for calibration in Layers 3, 4, and 5.

Tables 6.22 through 6.25 summarize the model computed water levels, field observed water levels, and residuals by well number for each model layer. Also shown on these tables is the sum of squares of the residuals, the standard deviation of the residuals, the root mean square error of the residuals and the simple mean of the residuals. When comparing model computed water levels to field observed values, it should be noted that exact correlation is rarely obtained. This is due to the fact that the field data represent a point measurement within a particular well, while the model computed value is an average over the entire model node, which for the three dimensional model represents an area of 22,500 ft^2.

Comparison of the statistics computed for the three hydrostratigraphic layers suggests that the best model calibration was obtained for Layer 6 (Cretaceous sand) with a root mean square error of 1.77 ft, a standard deviation of 1.57 ft, sum of squares error of 68.9 ft^2 and a simple mean of 0.87 ft. Not surprisingly, the least accurate calibration was obtained for the refuse layers, with a root mean square error of 6.30 ft, a standard deviation of 6.32 ft, a sum of squares error of 5,681 ft^2, and a simple mean of -0.25 ft.

Examination of Table 6.22 for the refuse unit suggests that the reason for the poorer calibration is due primarily to several well locations within the central portion of the landfill mounds where model computed water levels were computed lower by approximately 10 to 30 ft. This may be due to the fact that the water levels recorded within these refuse units are not representative of

the true water level surface, but represent perched conditions, as described previously within each of the landfill section specific discussions. Further examination of model computed water levels along the periphery of the landfill indicate a variance in predicted versus observed data of approximately 2 to 3 ft. Therefore, although the entire refuse unit would appear to have a poor calibration, removal of suspect water level data produces a good match, which is considered satisfactory for regional analysis.

Sheets 6.61 through 6.67 indicate contours of model computed water level elevations for model Layers 1 through 7, respectively. Computed head data are provided on a model node by node basis for each layer on Sheets A14.34 - A14.40 in Attachment 14. Comparison of model results for the refuse unit, Sheets 6.61 and 6.62, indicate that model computed water level elevations for the refuse unit (model Layers 1 and 2) show similar contour distributions to those for field data for the 30 day average shown of Sheet 6.32. Model computed water level elevations are similar for model Layers 1 and 2 in that, for purposes of this calibration, they are simulated as having equivalent hydraulic properties and thicknesses, with a high vertical conductance between the two layers. In general, the peaks for the model computed mounds within each of Landfill Section 1/9, 2/8, and 3/4 are shifted from those presented in the field contoured data. This is not surprising as the location of the peaks in the field contoured data is a function of the location of available data points, while the model computed values represent an actual water level calculation. No attempt was made to adjust the mound peaks within each landfill section, since insufficient data are available to justify such revisions. Model computed results for the refuse unit indicate horizontal discharge toward local surface waters, consistent with field observed data. The only location where model results suggest a different flow pattern than the field data is within the low area between Landfill Sections 1/9 and 2/8, where computed results suggest a larger component of flow from Section 1/9 toward Richmond Creek and Landfill Section 2/8.

Model computed water levels for unconsolidated overburden unit Layers 3 through 6 show similar trends to the two-dimensional cross-sectional model results discussed previously. In general, where low hydraulic conductivity values are present for a particular node within a layer, the model computed water level is similar to the node in the layer directly above, suggesting a predominant vertical flow component. Where a higher hydraulic conductivity sand is present within a layer, the model computed water levels are significantly reduced, suggesting a predominant horizontal flow component. These variations in computed water levels are transmitted vertically downward within each model layer. The effect of higher water levels

within the refuse mound are observed most noticeably within Landfill Sections 1/9 and 3/4, where vertically continuous low hydraulic conductivity units show the efffects of the refuse mounding as small mounds within each model layer down to model Layer 6.

Comparison of the contours of model computed water levels with those constructed from field data for the appropriate sand units for a particular layer (Sheets 6.63 - 6.66) with field data for the analogous sand units (Sheets 6.33 through 6.38) indicate similar gradients and directions of groundwater flow. In general the model computed water levels tend to be somewhat higher than those observed in the field, and the model computes less of a mounding effect in the higher hydraulic conductivity sand units. Again, no attempt was made to further calibrate the model in Layers 3-6, as areal data for the sand units in these layers are not sufficient to justify varying specific hydraulic properties.

A final note on model computed water levels within the unconsolidated overburden is that both the conceptual model and the results of the two-dimensional numerical analyses suggested that the major surface waters within the project area (Arthur Kill, Fresh Kills, Richmond Creek and Main Creek) appeared to act as both local and regional discharge areas for groundwater flow. Three-dimensional model results for the unconsolidated overburden unit are consistent with these findings, with groundwater flow patterns within the lower model layers (3 through 6) exhibiting a flow component toward the river channels simulated in Layers 1 and 2. Groundwater moving in the shallow refuse flow system discharges to the major surface waters and shallow local streams.

Finally, contours of model computed water level elevations for the bedrock unit (Layer 7), are shown on Sheet 6.67. Comparison of these data with the time averaged field data indicated on Sheet 6.40 indicates that the model computed values are more subdued, with a generally uniform gradient. Model computed values suggest that regional flow is from the northeast to the south and southwest, similar to the trend shown in the field data. The potential for mounding in the bedrock, as indicates in the field data, is not as evident in the model computed water levels. This may be due, in part, to the fact that the model represents steady-state conditions, suggesting that the potential mounding observed within the bedrock unit is a transient effect. The MODFLOW model code does not consider the effects of lithostratic pressure caused by the overlying refuse unit that can create a pressure induced mounding effect within the bedrock, as previously discussed.

Similar to the presentation of the results of the analytical flux analysis, horizontal and vertical fluxes can be calculated for each landfill section from the regional numerical model results, and Tables 6.26 summaries these fluxes for each landfill section by layer. Figures 6.52 through 6.55 illustrate net horizontal fluxes computed at model peripheral boundaries, and net vertical fluxes computed between the three major hydrostratigraphic units. In all cases, the areal boundaries within which these fluxes were computed are similar to those used for the analytical flux analysis.

On Figures 6.52-6.55, computed fluxes from model Layers 1 and 2 were combined to represent the refuse unit, computed flux results from model Layers 3 through 6 were combined to represent the unconsolidated overburden unit, and computed flux results from model Layer 7 represent the bedrock unit.

Model computed net fluxes at Section 6/7 (Figure 6.52) are comparable with the analytical data (Figure 6.20). Both the analytical and model computed results suggest small horizontal and vertical flux rates out of the base of the refuse and within the unconsolidated unit, consistent with the conceptual model. There is a noticeable difference between the net analytical flux and model computed net flux rates between the unconsolidated and bedrock units. The analytical results are approximately ten times those of the numerical model results (643 vs. 65 ft^3/day). Regardless, the difference represents less than two percent of the overall model water budgets for both methods of calculation. Both methods do suggest that water moving upward from the bedrock discharges laterally within the unconsolidated unit.

Figure 6.53 summarizes the model computed net horizontal and vertical fluxes for Landfill Section 1/9. The model computed net flux of recharge is very similar to that calculated through analytical methods. The model computed vertical net flux leaving the base of the refuse is approximately 14 percent, virtually the same as that computed by analytical methods. Model results also suggest that similar amounts of water leave the unconsolidated unit as horizontal flux. Table 6.26 indicates that approximately 75 percent of the water that leaves the base of the refuse exits Layer 3 as horizontal flux. This is not surprising, as Layer 3 is largely comprised of transmissive Recent sand units. Both the analytical and numerical model results indicate upward vertical discharge of groundwater from the bedrock into the unconsolidated overburden unit, and both results exhibit similar flux rates.

Figure 6.54 summarizes model computed net fluxes for Landfill Section 2/8. Model computed results suggest that approximately five percent of recharge moves vertically from the base of the refuse unit to the underlying unconsolidated unit, consistent with the results of the analytical analysis. Model results also suggest a net upward flux of groundwater from the bedrock unit into the unconsolidated overburden. Table 6.26 suggests that the majority of horizontal flux within the unconsolidated unit occurs within model Layer 6, representing the Cretaceous sand unit.

Finally, Figure 6.55 summarizes the model computed net groundwater fluxes for Landfill Section 3/4. These data indicate slightly lower but equivalent vertical fluxes out the base of the landfill relative to the analytical method. Both methods compute approximately 11 percent vertical leakage from the base of the refuse. Model computed vertical leakage between the unconsolidated overburden unit and the bedrock unit is the only simulated location where the model results compute a reversal in flux direction relative to the analytical analysis. Analytical results suggest upward flow from the bedrock unit to the unconsolidated unit, while numerical model results suggest a downward flux.

This reversal in the direction of vertical flux is probably due to the fact that the model does not simulate the mound in water levels observed within the bedrock unit directly beneath the landfill, therefore suggesting a downward flux from model Layer 6 to model Layer 7, (bedrock). This downward leakage rate represents less than approximately three percent of the total numerical model computed vertical leakage out the base of the refuse unit. Examination of Table 6.26 indicates that approximately 75 percent of the numerical model computed vertical leakage out the base of the refuse unit leaves as horizontal flux within model Layer 3, representative of Recent and glacial sands.

In summary, model computed results for both water levels and net horizontal and vertical fluxes are comparable to those obtained from the field, and calculated analytically. The major difference between field values and model values occurs in the lower model computed water levels for the central portions of the refuse mounds. As discussed, this may be due to the fact that the field reported water levels may not actually represent a true steady-state water level surface, but rather a perched zone created by low permeability unsaturated zones within the refuse units.

6.6.2 Solute Transport

To evaluate the potential for leachate to migrate from the refuse unit to deeper hydrostratigraphic units, a three-dimensional solute transport model was developed for the Fresh Kills landfill site. The computer program selected to provide the solute transport simulation is the Modular Three-Dimensional Transport Model (MT3D) capable of simulation of advection, dispersion, and sorption or retardation (chemical reactions of dissolved constituents in groundwater) developed for the United States Environmental Protection Agency (Zheng, 1990-1992). The model was developed to serve specifically as a post processor using the hydraulic flow output calculations from the MODFLOW model (MacDonald and Harbaugh, 1988) as input to the flow portion of solute transport, with the assumption that changes in the computed concentration field will not affect the hydraulic flow field.

MT3D was selected based on its ability to handle complex flow problems, and its direct relationship with the MODFLOW model used for simulating the regional flow system at the landfill site. The model uses a mixed Eulerian-Lagrangian approach to the solution of the three-dimensional advective-dispersive-reactive equation, with three basic methods of solution: The method of characteristics (MOC), the modified method of characteristics (MMOC), and the hybrid of these two methods (HMOC). The hybid method combines the strength of MOC for eliminating numerical dispersion, and the computational efficiency of MMOC. Finite-difference techniques are used for the spatial and temporal discretization of the equations. A complete description of each of the solution methods used by MT3D is provided in Attachment 12.

6.6.2.1 Input Properties

Since MT3D uses the hydraulic flow output from MODFLOW as input, the model discretization, hydraulic input properties, and boundary conditions described earlier for the flow model also apply to MT3D. Additional solute transport properties required by MT3D relate to porosity, dispersivity and sorption.

Based on the results of the two-dimensional cross-sectional modeling sensitivity analysis, model input values of effective porosity were identified separately for those model areas representative of the refuse, sand units, and silt/clay/till. The effective porosity of the refuse unit was assigned

a value of approximately 40 percent, the sand units were assigned a value of 25 percent and the silt/clay/till areas a value of 30 percent (Freeze and Cherry, 1979; Fetter, 1988). Values of dispersivity were input as 100 ft longitudinal and 10 ft transverse to the direction of groundwater flow. Sorption values are related to the bulk density of the porous media and the distribution coefficient of the particular chemical species of concern. The bulk density of the refuse material was assigned a value of 2.0 g/cm^3, similar to that of the sand units and silt/clay/till areas.

Similar to the two-dimensional, cross-sectional solute transport model simulations, an initial scaled mass-fraction value of 1.0 was input as a starting concentration. For all simulations, the initial concentration was equally distributed within the area of the refuse mounds in model Layers 1 and 2, and assumed to represent a constant source throughout the length of the simulation. All solute transport model input data is presented in Attachment 14.

6.6.2.2 Model Simulation

Very little data are available concerning the history and potential leachate distribution over time for the area beneath the landfill. Therefore, an attempt to simulate a know historical migration pattern is not feasible. Rather, the results of the solute transport simulation were used to observe potential migration pathways of leachate from the landfill mounds to and through underlying transmissive units. Such an analysis is useful for the integration of all components of the hydrogeological investigation (i.e., stratigraphic and hydrostratigraphic interpretations with observed water chemistry).

Two basic transport simulations were performed. The first simulation assumed that solute transport within the landfill was dominated solely by advection; therefore values of dispersivity and sorption were not input or calculated by the model. Solute transport of this type is extremely conservative, since virtually all chemical compounds and metals react with the aquifer matrix to some degree. The second simulation included dispersion and sorption, and is more representative of field conditions.

The period of simulation for both transport scenarios was 40 years, assuming a steady-state flow condition. (The hydraulic conditions for the entire simulation period are those of the steady-state, calibrated model shown for each model layer on Sheets 6.61 - 6.67.)

- ***Advective Flow***

Sheets 6.68 through 6.72 show the distribution of scaled mass-fraction for each model layer after 20, 25, 30 and 40 years of simulation time, respectively, for the case of advective transport only. Examination of Sheet 6.68 for model Layers 1 and 2 shows the distribution of scaled mass-fraction (held at a constant value of 1.0) for each landfill section, after a 20 year simulation period. The distribution of scaled mass-fraction in Layers 3 through 6 basically conform to the distribution of high hydraulic sand units shown on Sheets 6.55 through 6.59. Not surprisingly, the highest scaled mass-fractions are generally below areas with high model computed water levels, or generally the central portions of the landfill mounds. Trace concentrations of scaled mass-fraction (.05) are computed in model Layer 7 (bedrock) directly beneath the central portion of the landfill mound in Landfill Section 3/4, and along the southern boundary of Landfill Section 2/8.

It is also interesting to note that the migration and distribution of scaled mass-fraction within a particular model layer is a function of the hydraulic characteristics within that layer. An example of varying rates of migration is best observed on the western boundary of Landfill Section 1/9 between model Layers 4, 5, and 6. Vertical migration of scaled mass-fraction is apparent between the model layers, but the actual areal distribution varies as a function of the groundwater flow rate within a particular model layer. Therefore, although scaled mass-fractions move vertically between model Layers 5 and 6, the areal distribution in model Layer 6 is actually somewhat more extensive than in model Layer 5. This is probably because at this particular location, the hydraulic conductivity and thickness of model Layer 5 is less than that of model Layer 6 (Attachment 14), thus slowing the horizontal migration of the scaled mass fraction in model Layer 5 at this location.

In general, the distribution of scaled mass-fractions is similar for time periods of 25, 30 and 40 years for each of model layers 3 through 7, with generally increasing concentrations at any one node location. Layer 7 (bedrock) shows very little increase in scaled mass-faction, over the simulation time period with only one new area, along the northeast boundary of Landfill Section 1/9, showing trace levels after 40 years.

- ***Advective, Dispersive, and Sorption Flow***

Sheets 6.72 through 6.75 show the model computed scaled mass-fractions for model Layers 1 through 7 for times of 20, 25, 30 and 40 years, respectively, for the case where sorption is applied to the solute transport equation.

A linear sorption isotherm is used by the computer code to determine the value of the distribution coefficient, which, in turn, is used to calculate a retardation factor. The retardation factor is a measure of how fast a particular compound will move through the aquifer material. A chemical compound with a retardation factor of 1.0 is assumed to be non-retarded, i.e., the chemical compound moves by advection similar to the model computed distribution of scaled mass-fractions shown on Sheets 6.68 through 6.71.

The retardation factor is a function of the dry bulk mass density of the soil, volumetric moisture content of the soil (porosity for fully saturated flow systems such as the Fresh Kills three-dimensional model), and the distribution coefficient for the particular chemical compound of concern. Values of bulk density and porosity have been previously described.

The distribution coefficient for an organic compound is estimated through multiplication of the octonal-water partition coefficient (a measure of the ability of a compound to dissolve in water) with the total organic content of the soil. For the sorption characteristics at the Fresh Kills Landfill, a moderate mobility class octonal-water partition coefficient was obtained by averaging the values provided by Fetter (1988), to obtain a value of 305. Review of Table 4.6 indicates an average organic carbon content for glaciolacustrine and Recent clays of about 10 percent. For higher permeability units, Karickhoff, et.al (1979) suggests a value of between 0.1 to 3.3 percent. Since the sorption characteristics entered into the model are not variable on a node by node basis a value of 1 percent was assumed for both the high and low permeability units. This value was selected to be more representative of flow in the higher permeability units, where model simulations with advective transport only (Sheets 6.68 through 6.71) show the majority of the distribution of scaled mass-fraction concentration to occur.

Not surprisingly, the model simulations with retardation exhibit a pronounced decrease in the distribution of scaled mass-fraction within each model layer (except Layers 1 and 2 where the scaled mass-fraction value was maintained at a constant value of 1.0) for all time periods.

After 20 years of transport (Sheet 6.72) very little solute has migrated vertically beyond model Layer 3, representative primarily of Recent sand units. Trace levels of scaled mass-fractions are observed below Landfill Section 2/8, model Layer 5, representative of the upper Cretaceous sands, in areas where this unit is in contact with the overlying refuse or higher permeability sand units.

After 25 years (Sheet 6.73) trace levels of scaled mass-fractions are also observed in model Layer 5 below Landfill Section 1/9. No scaled scaled mass-fractions are observed in model Layers 6 or 7, except along the southern boundary of Landfill Section 2/8. Although scaled mass-fraction concentrations continue to increase in model Layers 3 through 5 for time periods of 30 (Sheet 6.74) and 40 years (Sheet 6.75) there is still very little movement vertically downward to model Layers 6 and 7, representative of the lower Cretaceous sands and bedrock.

- ***Pumpage Within Cretaceous Sand***

As discussed earlier in this report, the potential source of saline water observed within the Cretaceous sand unit in portions of Landfill Section 1/9 is not fully known, although the presence of a seawater influence is noted in the literature for Staten Island (Soren, 1988). Possible sources include: (1) residual (connate) seawater derived from the last eustatic high that has not yet been flushed from the sediments (Meisler, et al., 1984), migration through overlying Recent/glacial sediments in hydraulic communication with the Arthur Kill (possibly enhanced through channel dredging), (3) historic pumping activity in the bedrock or Cretaceous unit, resulting in localized areas of induced recharge from overlying sediments, or (4) a combination of the above.

The three-dimensional solute transport model was used to examine the potential for pumping from the Cretaceous sand unit to induce the migration of saline waters from river channels (e.g., Arthur Kill, Fresh Kills) to lower hydrogeologic units. A pumping well was simulated within the Cretaceous sand units represented by model Layers 5 and 6 within the southwestern corner of Landfill Section 1/9, at model row 85 and column 9 (Sheet 6.53). The well was pumped at 100 gallons per minute under steady-state conditions, and produced a maximum drawdown of approximately 12 feet. Attachment 39 shows contours of model computed water levels for model Layers 1 through 7.

A constant scaled mass-fraction value of 1.0 was assigned to each model river node and allowed to migrate by advection only for a period of five years. Attachment 39 contains a plot of time versus concentration for the pumping well. It can be seen that after approximately one year of pumping a breakthrough of scaled mass-fraction occurs, with concentrations increasing through the end of the simulation period. This simulation suggests that it is possible for saline water to migrate vertically to the lower hydrostratigraphic units as a function of local pumping. Such migration would result in seawater mixing within both shallow Recent sand and deep Cretaceous sand units, as observed in water quality data described in Report Sections 7.2.1 and 7.3.3.3.

6.6.3 Sensitivity Analysis

Focused sensitivity analysis was performed on the three-dimensional flow model to determine what effect changes to specific model input properties would have on the distribution of model computed water levels and scaled mass-fractions. Based on the results of two-dimensional cross-sectional flow and solute-transport analysis and regulatory agency comment, seven sensitivity analysis simulations were performed; as summarized in Table 6.27. In general, sensitivity analyses concentrated on river leakage, recharge, bedrock thickness, and the hydraulic conductivity of both the sand and silt/clay/till hydrostratigraphic sub-units.

Tables 6.28 through 6.31 summarize the total river flux and vertical flux components (up and down) for each model layer for Landfill Sections 6/7, 1/9, 2/8 and 3/4, respectively. All sensitivity analysis simulations were for steady-state flow conditions, with a solute transport period of 20 years. The model computed base conditions for computed water levels and scaled mass fraction are shown on Sheets 6.61 through 6.67 and 6.68, respectively. Contour plots of model computed water levels, difference in water levels from base conditions, scaled mass-fractions, and difference in scaled mass-fractions from base conditions are provided in Attachment 15 for each sensitivity run.

No surprisingly, comparison of the fluxes to the rivers and vertically between model layers indicates the largest change in flux components for sensitivity analysis run number 2, where recharge was uniformly increased to a maximum value of 18.25 inches. The least effect to the model computed flux components was for sensitivity analysis run number 4, where the bedrock thickness was increased to 300 feet.

While sensitivity analysis related to the hydraulic properties of the unconsolidated units had little affect on the discharge to rivers it did affect vertical flux between model layers. In general the largest magnitude of vertical flux change, both upward and downward, was observed between Layers 2, 3, 5 and 6. These changes are also seen in the model computed water level difference contours. In general, increases in hydraulic conductivity increase vertical fluxes and decreases water levels, with the opposite occurring for decreases in hydraulic conductivity.

In terms of comparing the sensitivity between landfill sections for fluxes and computed water levels, no one landfill section should more sensitive than another. However, each landfill section produced various changes in computed values that were dependent on the nature of the sensitivity run in each particular area. For example, changes in hydraulic conductivity for the sand units were more obvious in Layer 5 at Landfill Sections 1/9 and 3/4 than at 6/7 and 2/8, due primarily to the fact that the sand represented within Layer 5 is generally not present beneath Sections 6/7 and 3/4.

Similar to the sensitivity analysis for model computed water levels it is possible to compare changes of model computed scaled mass-fraction for individual sensitivity simulations to model computed base values. Attachment 15 provides contoured plots of both the model computed scaled mass-fraction and the difference in scaled mass-fraction between the model computed base simulation and individual sensitivity analysis simulations. Analysis of these data are useful in determining which model input properties can have the greatest impact on model computed distribution of scaled mass-fraction.

Sensitivity analysis variation in model computed scaled mass-fraction are best observed on the contoured plots of the scaled mass-fraction of the base values minus those of the individual sensitivity analysis simulation. Negative contoured difference values of scaled mass-fraction indicate a higher concentration was computed for the sensitivity simulation than for the base simulation. For sensitivity analysis run number 1, the largest difference was observed within the refuse unit, where concentrations decreased significantly along the river and stream channels. This is not surprising, as this sensitivity analysis simulation increased the river bottom conductance term by 25 percent, which allowed more simulated solute to discharge into the surface waters and away from the source (refuse mound) area.

Interestingly, increases and decreases of recharge to groundwater at the landfill (sensitivity analysis runs 2 and 3, respectively), have very little effect on the potential vertical migration of scaled mass-fraction from model Layers 1 and 2 (refuse) to the lower model layers. The same is true for sensitivity analysis run 4, representing an increase in bedrock thickness.

Order of magnitude increases and decreases in the hydraulic conductivity of the Recent, glacial and Cretaceous sand units (sensitivity analysis runs 5 and 6, respectively), show increases or decreases in scaled mass-fraction for some sand units below Landfill Sections 1/9 and 2/8.

The largest difference in model computed scaled mass-fraction is for sensitivity analysis run number 7, an increase in lodgement till hydraulic conductivity. Both increases and decreases in computed scaled mass-fraction are observed. Increases are observed below the central portion of Landfill Section 3/4 and the western boundary of Landfill Section 1/9 for model Layers 3 through 6. Decreases are observed below Landfill Section 6/7 and the peripheral area around Landfill Section 3/4. An increase in model computed scaled mass-fraction with depth is understandable in that an increase in hydraulic conductivity will allow for more water to move downward, due to an increase in the vertical flux. A decrease in model computed scaled mass-fraction for an increase in hydraulic conductivity suggests that these areas are controlled more by a horizontal flux component, and that by increasing the hydraulic conductivity, more water moves out of the flow system horizontally, decreasing the amount of scaled mass-fraction available to move vertically.

7.0 Water Chemistry

This section presents the analysis of groundwater chemistry data obtained through performance of quarterly groundwater sampling of monitoring wells at the Fresh Kills Landfill during 1991 and 1992. This analysis is prefaced by an initial discussion of the characteristics of landfill leachate, the results of prior investigations at the landfill, and sources of background or "natural" groundwater data for comparative analysis. The results of the current sampling program are then summarized in tabular and graphical form by landfill section and monitoring zone. These summaries allow for a comparison of chemistry data between and within monitoring zones, with background chemistry data (where available), and with water quality standards for an assessment of leachate migration. The water quality assessment is followed by a geochemical analysis of dissolved solutes and environmental isotopes that allows for an independent and more rigorous characterization of the sources and mixing characteristics of groundwaters underlying the landfill. Finally, the results of numerical groundwater flow and solute transport analyses are discussed relative to the findings of the water quality and geochemical investigations.

7.1 Introduction

Landfill leachate is formed when water, generally in the form of precipitation, infiltrates through a landfill, picking up organic and inorganic compounds by physical extraction, hydrolytic, and fermentive processes. The composition of leachate from a particular landfill will vary by location, season, and age of the landfill (Lema, et al., 1988). Although leachate composition varies spatially and temporally, leachate formation follows a typical sequence of microbially mediated redox processes in an increasingly anaerobic environment. These processes are no different from those which organic rich marine sediments undergo after burial (Baedecker and Back, 1979a, 1979b; Stumm and Morgan, 1981). The sequence of leachate formation processes allows for the identification of certain leachate indicator parameters that would be expected as typical constituents of municipal landfill leachate. NYSDEC (1988a,b) defines the following as being among leachate indicator parameters:

- TKN (Total Kjeldahl Nitrogen) Nitrogen-bearing wastes are typically found in municipal solid waste and TKN detects nitrogen in the form of ammonia and associated organic

forms. TKN measures the total reduced nitrogen, which is the sum of ammonia and organic nitrogen (Fetter, 1993).

- Ammonia, which is formed through the anaerobic processes of ammonification and nitrate reduction, is the most common nitrogen-bearing compound released from landfills and represents a useful leachate indicator.

- Nitrate is not a major component of landfill leachate, but is the only form of nitrogen regulated under New York State water quality standards.

- COD and BOD represent chemical and biochemical oxygen demand, respectively, and indicate the presence of organic matter. These tests are standard measures of how much oxygen would be required to remove all the organic material from a sample.

- Total Organic Carbon (TOC) provides a measure of the carbon-bearing organic acids and other organic compounds typically found in leachate (formed primarily by aerobic respiration) which are not tested during analyses for standard organic compounds.

- Total Dissolved Solids (TDS) is a standard measure of the filterable residue dissolved in water. Leachate samples typically have high TDS values and similarly elevated specific conductance measurements.

- Sulfate levels are commonly high in fresh leachates, but tend to decrease as sulfate is chemically reduced in older leachate samples.

- Dissolved carbonate hardness (a combination of dissolved calcium and magnesium) and dissolved carbonate alkalinity are usually higher in landfill leachate than in natural groundwater.

- Alkalinity represents the quantity and kinds of compounds present that collectively shift the pH to the alkaline side of neutrality. In the pH conditions typical of the landfill environment, bicarbonate (HCO_3^-) is the dominant constituent of alkalinity. Bicarbonate is formed during sulfate reduction, denitrification, iron and manganese reduction, ammonification, and fermentation when organic matter is present. Essentially, the production of bicarbonate is due to the presence of organic matter.

- Chloride concentrations are commonly elevated in leachate samples, derived from the natural salt content of food and wastes, as well as the biodegration of chlorinated hydrocarbons (household pesticides and plastics) and products such as bleach. Chloride is very mobile and not readily degraded or absorbed onto soil materials which generally makes it a useful leachate indicator.

- Dissolved sodium is common in leachate, and often is not readily removed by chemical reactions, except by ion exchange where mixed layered clays are present.

- Iron and Manganese are common leachate indicators that are elevated in reducing environments with an acidic pH. Other metals, such as sodium, calcium, and magnesium are also affected by Eh/pH conditions.

- Calcium concentrations in municipal waste leachate have been reported well above levels in most naturally occurring waters.

- Potassium is released from organic materials during the initial stages of refuse decomposition, making it an important parameter for tracing leachate migration with time.

- Magnesium contributes to the water's total hardness and is a common constituent of groundwater. Because major constituents have proven useful in determining the origin or groundwater and fingerprinting pollution sources, it has been included in the monitoring parameters.

Observed concentration ranges of selected leachate indicator parameters observed in landfills throughout the United States, experimental landfill cells, and landfills receiving municipal waste from a large urban area are shown in Table 7.1. This table also shows median values measured in the shallow/refuse groundwater monitoring zone at Sections 1/9, 2/8, 3/4, and 6/7 of the Fresh Kills Landfill. Because leachate composition in a landfill exhibits spatial and temporal variations (Lema, et al., 1988) and due to the limited amount of detailed data available regarding leachate composition, it is difficult to predict a precise range of concentrations for individual parameters within a typical landfill leachate. Nevertheless, data can be reviewed in a qualitative sense to predict a leachate composition. Examination of Table 7.1 indicates that the shallow/refuse monitoring zone at the Fresh Kills Landfill exhibits the presence of typical leachate indicator parameters at concentrations that generally fall within or below the ranges reported at other municipal refuse landfills throughout the United States.

As noted above, variability in leachate composition is a function of both spatial and temporal considerations, the former represented by the horizontal and vertical distribution of waste placement and content, and the latter represented by the continuum of chemical processes that occur within the landfill environment over time.

The chemical composition of leachate is controlled by the same set of processes that occur in organic-rich marine sediments (Baedecker and Back, 1979a,b). These processes result in the development of an anaerobic zone beneath a landfill (Figure 7.504). The processes, in order of

occurrence with decreasing Eh (oxidation-reduction potential), are defined by Stumm and Morgan (1981) as:

1. Aerobic reduction of organic matter
2. Denitrification
3. Manganese reduction
4. Nitrate reduction/ammonification
5. Iron reduction
6. Anaerobic reduction of organic matter
7. Sulfate reduction
8. Methane fermentation
9. Nitrogen fixation

These processes can be grouped together into an idealized five-phase waste-degradation sequence that applies specifically to sanitary landfills (Christensen and Kjeldsen, 1989). Phase I, which lasts only a few days, consists of the aerobic reduction of organic matter. Phase II, which is the first intermediate anaerobic phase, consists of denitrification, manganese reduction, ammonification, and further degradation of organic matter into volatile fatty acids. In this phase, the leachate contains high concentrations of calcium, iron, heavy metals, ammonium, and increasing bicarbonate concentrations. Phase III, the second intermediate anaerobic phase, consists of sulfate reduction and initial methane fermentation. In this phase, volatile fatty acids and sulfate concentrations decrease, and pH and alkalinity increase. The increase in pH reduces the solubility of metals. Iron and manganese likely precipitate as sulfide minerals. Ammonia concentrations continue to increase with the degradation of volatile fatty acids. Phase IV consists of methane fermentation, and correspondingly rapid production of methane. During Phase V, only refractory organic matter remains, and methane production decreases to very low levels. This sequence of waste degradation is idealized for a homogeneous landfill. The Fresh Kills landfill, which consists of four landfills of variable age and composition, likely exhibits the full spectrum of the waste degradation sequence.

The time frame for waste degradation is variable depending on abiotic parameters, such as the concentrations of oxygen, hydrogen, sulfate, nutrients, inhibitors, and water content, in addition to pH (Christensen and Kjeldsen, 1989). As noted above, the initial aerobic phase is very short, lasting only a few days (Christensen and Kjeldsen, 1989; Fetter, 1993). The time frame for each of the successive stages ranges from months to decades, dependent on the above parameters (Christensen and Kjeldsen, 1989). Also, the processes, although listed in order, have overlapping

ranges (Stumm and Morgan, 1981). As a result, several anaerobic processes may be ongoing in a landfill at the same time. In an experimental study of leachate quality, Ehrig (1989) showed that pH, BOD, COD, sulfate, calcium, magnesium, iron, manganese, zinc, and strontium concentrations evolve until methane fermentation is complete. Conversely, chloride, sodium, potassium, alkalinity, ammonium, organic nitrogen, nitrate, phosphorous, phenols, and heavy metals reach maximum concentrations relatively early during the evolution of the leachate, and methane fermentation does not affect their concentrations. Thus, leachate composition could evolve for decades after a landfill is closed, but the rate of evolution, and thus the actual composition of the leachate, is dependent on several parameters that can vary.

Given the above, it can be generally stated that leachate strength at Fresh Kills should be expected to decrease over time in the areas where active filling has been discontinued (i.e., Sections 2/8 and 3/4), and should be expected to maintain its current characteristics or increase in strength over time in the areas where active filling is scheduled to continue (i.e., Sections 1/9 and 6/7).

7.1.1 Previous Groundwater Quality Investigations

Two previous groundwater water quality investigations have been performed at the Fresh Kills Landfill site. Both investigations, although limited in scope, provide useful introductions to water quality at the site. An initial sampling and analysis program was performed for NYCDOS by Parsons Brinckerhoff-Cosulich during 1982, with results summarized by Wehran Engineering (Wehran Engineering, 1983). A more recent water quality investigation was conducted in April 1990 by Engineering-Science for the New York State Department of Environmental Conservation (NYSDEC) as a part of their groundwater contamination assessment program for selected landfills in New York state. The results of these investigations are presented qualitatively to provide a framework for subsequent discussion of the results of the ongoing, comprehensive sampling and analytical program.

- ***NYCDOS/Parsons Brinckerhoff-Cosulich/Wehran Engineering - 1982/83***

The Hydrogeological Investigation developed for the City of New York by Wehran Engineering included a qualitative review of groundwater quality data. The objective of this review was to

detect chemical data trends that would assist in delineation of the extent of landfill-derived groundwater and surface water contamination. Parsons-Brinckerhoff's data indicated that leachate contamination was present in the shallow, unconfined water bearing zones beneath the landfills as well as in the tidal streams between the landfill mounds. This contamination was manifested as elevated concentrations of biochemical oxygen demand (BOD), total kjeldahl nitrogen (TKN), total organic carbon (TOC), alkalinity, chemical oxygen demand (COD), ammonia, coliform, color, chloride, and low sulfate concentrations. Detailed data analyses were limited by Wehran Engineering to Sections 1/9 and 2/8 as the investigators felt that these sections represented the worst-case and best-case scenarios, respectively (significant refuse disposal had not occurred within Section 2/8 at that time).

Section 1/9 exhibited a higher degree of contamination in both the unconfined upper zone and within the semi-confined or confined Upper Cretaceous Sand, than did Section 2/8. Specifically, this was evidenced by elevated levels of BOD, TOC, COD, TKN, iron, lead, mercury, color, and chloride values. Low sulfate values in the confined Upper Cretaceous unit were presumed to be further indicative of groundwater contamination. Values for coliform, phenols, lead, manganese, and chloride were in excess of drinking water standards in the sand but were not felt to be indicative of gross groundwater contamination.

Within the deep water bearing zones (lower Cretaceous sand and bedrock), elevated levels of iron and manganese were thought to be due to the natural geochemistry of the formation material, rather than to leachate contamination. Concentrations of coliform, phenol, iron, lead, manganese, and chloride were generally lower by an order of magnitude in the confined zone than in the unconfined water-bearing zone. This difference was cited as evidence of the relative impermeability of the stratum separating the two zones, which was believed to result in an estimated net downward flow of less than ten percent of total flow. The investigators concluded that this small net downward flow, coupled with attenuation, chemical conversion, and biological degradation processes, results in insignificant leachate impact to the confined water bearing zones.

Appendix N contains a full compilation of the analytical data derived through the 1982 Parsons Brinckerhoff-Cosulich sampling effort. These data primarily represent filtered sample analysis, although unfiltered sample was collected for selected metals and indicator parameter analytes. Table 7.2 contains summary statistics for a subset of wells screened in the Cretaceous sand water

bearing unit (C8S, C8D, C9S, C9D, D11, D12, and D17). These wells, located along the southern perimeter of Landfill Section 2/8 and in the vicinity of the Brookfield Avenue Landfill, are believed to be representative of background water chemistry due to well location, lack of extensive refuse disposal prior to the time of sampling, and comparison with literature sources of background chemistry data. Where appropriate, these data have been incorporated into the assessment of current water quality data in Report Section 7.2, to assist in providing a baseline reference point for comparative analysis.

- ***NYSDEC - Site Contamination Assessment - April 1990.***

This water quality investigation, prepared by Engineering-Science for NYSDEC, included sampling of groundwater, groundwater surface seeps, and the groundwater/leachate collection system, and groundwater/leachate recirculation system seep at landfill Section 1/9. Samples were analyzed for Target Compound List (TCL) organic compounds, Target Analyte List (TAL) metals, and general chemistry parameters. Shallow groundwater samples were collected from ten monitoring wells installed in the refuse mound at Section 1/9. Fifteen TCL volatile organic compounds were detected in these samples. NY State Class GA groundwater standards and/or Maximum Contaminant Levels (MCLs) were exceeded for the following compounds: benzene, vinyl chloride, toluene, chlorobenzene, ethylbenzene, and total xylenes. Wells located along the eastern side of Section 1/9 exhibited the highest concentrations of volatile organic compounds. Thirteen TCL semivolatile organic compounds were also detected. NY State Class GA groundwater standard and/or MCLs were exceeded for 1,3-dichlorobenzene, phenol, 4-methylphenol, and 2,4-dimethylphenol. Generally, the highest semivolatile organic compounds were detected in wells located on the north and east sides of the landfill. Several TCL pesticide/PCB compounds were also detected at levels exceeding NY State Class GA groundwater standards as follows: endrin, 4,4-DDD, and Aroclor-1260. A total of sixteen metals plus boron were detected in groundwater samples from Section 1/9. Generally, the highest concentrations occurred along the north and east sides of the landfill. MCLs for arsenic, barium, total chromium, iron and lead were exceeded.

Shallow groundwater samples collected from ten monitoring wells in Section 6/7 were analyzed for TCL organic compounds, TAL metals, and general chemistry parameters. Ten TCL volatile organic compounds were detected in these samples. NY State Class GA groundwater standards and/or MCLs were exceeded for benzene, methylene chloride, acetone, 2-butanone, benzene,

toluene, chlorobenzene, ethylbenzene, and total xylenes. Eight TCL semivolatile organic compounds were detected in groundwater samples from Section 6/7. Class GA groundwater standards and/or MCLs were exceeded for naphthalene, 2-methylnapthalene, and bis(2-ethylhexyl) phthalate. Two TCL pesticide/PCB compounds were also detected; Aroclor-1254 and beta-BHC were detected at levels exceeding Class GA groundwater standards. A total of nineteen metals plus boron were also detected in these samples. Class GA groundwater standards were exceeded for iron, lead, barium, manganese, chromium, and silver. The highest concentrations of metals were detected in the northern area of the landfill.

The report concluded that the Fresh Kills Landfill is contaminating shallow groundwater within and beneath the refuse at concentrations exceeding standards contained in 6 NYCRR Part 703.5 and 10 NYCRR Part 5 regulations. Analytical data from this sampling event formed the basis for the identification of an initial critical parameter list by NYSDEC (Table 4.12) for the Consent Order Hydrogeological Investigation.

7.1.2 Relevant Literature Data

In the ensuing evaluation of water chemistry data derived from the current sampling program, several techniques are applied to evaluate the presence of leachate contamination in groundwater. In the shallow monitoring zone directly in contact with the refuse mounds, comparison of measured water quality with groundwater quality standards is generally sufficient for this purpose. If present in deeper monitoring zones, however, leachate concentrations would be expected to be much more dilute than within the refuse mound source areas. Consequently a comparative analysis of water quality between wells within a monitoring zone, and ideally between known background or "natural" water quality, is necessary to detect anomalous water chemistry at depth. In addition, geochemical analysis requires definition of the characteristics of various source groundwaters (i.e., leachate, seawater, and natural groundwater) to allow for an assessment of expected changes in chemistry resulting from the mixing of these discrete sources. Literature data defining background water quality is useful for this purpose either directly, or in terms of allowing for the identification of representative background water chemistry from selected onsite wells.

The availability of such background data within Staten Island is very limited, and consists primarily of general discussions of groundwater quality in Soren (1988) and Perlmutter and Arnow (1953). A much more extensive database is available for the Cretaceous sand aquifers of the New Jersey Coastal Plain, and to a lesser extent, the Newark group bedrock aquifers of central and western New Jersey. Appendix N contains a compilation of water quality analyses believed to be representative of the Cretaceous sand water bearing unit underlying the southern portion of Fresh Kills, derived from water supply wells screened in the middle aquifer unit of the Potomac-Raritan-Magothy aquifer system (Fusillo, et al., 1984). Available data from public water supply wells completed in the bedrock of the Newark Basin (Stockton and Lockatong Formations) is also provided in Appendix N (Vecchioli and Palmer, 1962; Kasabach, 1966; Barksdale, et al., 1958). Data from the bedrock units is much more limited than that available from the Coastal Plain sediments.

Table 7.2 contains summary statistics of the literature data contained in Appendix N. Of immediate significance in review of these data is the elevated concentration of several constituents in natural groundwaters; primarily iron, but also manganese, magnesium and sulfate. High iron content of groundwaters in the Cretaceous sands is widely reported in the literature (Soren, 1988; Anderson and Appel, 1969; Rush, 1968) and is believed to be the result of the residence time of the water in the deep flow system and the common occurrence of pyrite (iron sulfide) and iron oxides such as hematite and magnetite. Relative to the Newark Group bedrock aquifers, elevated groundwater concentrations of hardness forming constituents (primarily calcium and magnesium but also other polyvalent metals such as iron, aluminum and manganese) and sulfate (believed to be derived from the minerals glauberite and gypsum) are noted in mineralized to highly mineralized regions of the Stockton and Lockatong formations (Barksdale, et al., 1943; Kasabach, 1966; Gill and Vecchioli, 1965; Vecchioli and Palmer, 1962). These findings are directly relevant to the subsequent review of water chemistry data obtained from the current investigation, as the noted constituents routinely exceed water quality criteria in most intermediate depth and deep wells on-site, and should not be considered reflective of leachate migration.

Most of the data derived from these references represent filtered ("dissolved") sample analysis, and are not directly comparable with the majority of water quality analysis performed under the current investigation. However, where filtered data is available from the current sampling program in support of geochemical analysis, and where unfiltered data is available from the

literature, these data have been incorporated in the comparative water quality analyses presented subsequently in Section 7.2.

7.1.3 Considerations Regarding Filtered and Unfiltered Sample Analysis

Traditionally, the sampling protocol for laboratory analysis of metals and most indicator parameters in groundwater required filtration of the sample in the field to remove suspended material, thus providing analytical data representative of the dissolved concentration of solutes (Leighton; 1905, Rainwater and Thatcher, 1960; Barnett and Mallory, 1971; Puls and Barcelona, 1989). More specifically, as noted by Hem (1989) and discussed in report Section 7.3, sample filtration is necessary to remove the incidental effects of turbidity on the measurement of dissolved ions in support of geochemical characterization. The methods and standards for removal of suspended particulates from water samples have evolved over time; over the past several decades, 0.45 micron (um) filter material has represented the standard media for filtration.

Within the past five to ten years, the potential importance of colloidal transport of contaminants has been evaluated by the USEPA. Colloids consist of very small diameter particles that include: material formed by detachment from immobile soil and mineral matrices (e.g., clay platelets and silicate particles); particles formed in situ due to supersaturated mineral solutes (e.g., iron oxides); viruses and small bacteria; macromolecules (e.g., hydrophilic, humic, and fatty acids); and particles directly introduced by areal sources (e.g., landfill leachate) (Mills, et al., 1991).

The results of literature review (starting primarily with studies indicating the preferential adsorption of radionuclides onto clay particles), have shown that colloidal particles can move through the subsurface, thereby providing a mobile solid phase for contaminant migration. This assessment has led to the development of recommended sampling protocols by USEPA and many states (including New York) that require unfiltered (total) sample analysis for the assessment of groundwater quality.

In the subsequent analysis of water quality data relative to groundwater quality standards and criteria, the distinction between the dissolved (filtered) and total (unfiltered) concentration of metal ions in groundwater is significant. The effect of filtration is illustrated in Figures 7.1 through 7.10, where the results of total and dissolved analysis for a series of metals are compared

for each landfill monitoring zone at Fresh Kills (shallow/refuse, intermediate depth (confined sand), and deep (bedrock) water bearing zones). Sample data indicated on these plots is derived from all pairs of filtered and unfiltered data obtained as a result of the geochemical sampling program performed concurrently with Consent Order quarterly monitoring during July 1991, and January and July 1992 (Section 4.7). As indicated, the distribution of total concentration data is virtually always elevated relative to the dissolved data, and more frequently exhibits the presence of high (or "far") outliers[1]. The relevance of these data relative to the assessment of groundwater quality impact is discussed below, for general application to subsequent discussions of the water quality database generated during this investigation.

Some disagreement exists in the literature regarding the particle dimensions that pertain to colloids. In 1861, Graham (Ross and Morrison, 1988) coined the term colloid to represent particle sizes ranging between 0.001 um and 1 um. Thurman (1985) indicates a general colloid range of 0.002 um to 0.45 um (the latter equivalent to a molecular weight of 10^8). Glasstone and Lewis (1960) state that colloidal particles range in diameter from 0.005 um to about 0.2 um. Stumm (1977) considered that the range of colloid diameters extends to 10 um. Based on their literature review, Mills et al. (1991) indicated that the more widely accepted upper limit for colloidal size is 1 um.

Assuming an upper colloidal particle diameter in the 0.2 um to 1 um range, it is evident that the effect of sample filtration (with 0.45 um media) is not significant relative to the observed differences in the measured total and dissolved concentration of metals in groundwater. An assessment of the potential mobility of colloidal material in the higher range of particle size (i.e., 1 um to 10 um and above) is warranted, however, due to the significant effect of filtration on the presence of these particulates in the water sample. Mason et al. (1992) identify a means of providing such an assessment through reference to an empirical relationship used to estimate the migration of bentonite particles in grout through soil pores. For migration of a colloidal particle to occur in soil, the diameter of the migrating particle must be significantly smaller than the diameter of the soil pore; this relationship is defined as follows (Spooner et al., 1984):

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[1]An interpretive key for the "box" plots (also referred to as "box-and-whisker" plots [Tukey, 1977]) used to describe the distribution of analytical data is provided in Figure 7.11. These box plot presentations are used extensively in subsequent analyses of water quality data.

$$R = D_{15} / D_{85}$$

where D_{15} = diameter of the particles comprising the soil, where 15 percent of the soil mass is finer,

D_{85} = diameter of the migrating bentonite (or soil) particle, where 85 percent of the particles is finer, and

R = ratio which must be at least 19 and preferably greater than 24 to allow a bentonite (or soil) particle to penetrate soil pores.

If R is set to 24, and D_{85} is set to 10 um (encompassing the upper range of colloidal particle size), the transport of colloids would be negligible wherever 15 percent of a soil exhibits a grain size less than 240 um. Figure 7.12 illustrates the cumulative frequency distribution of the D_{15} grain size of sands underlying the Fresh Kills landfill (all soil samples processed for geotechnical laboratory analysis with USCS soil classifications of SC, SM, SP, SC-SM, SP-SM, SW-SM; data reported in Table 4.6). As indicated, about 95 percent of these soils exhibit a D_{15} grain size less than or equal to 240 um. Therefore, colloidal transport is probably not significant in the groundwater system underlying the landfill. Consequently, in subsequent comparative analyses of metals concentrations in groundwater relative to water quality standards, dissolved sample analyses are provided where available, and should be considered to represent the preferred data for impact assessment.

7.2 Groundwater Quality Monitoring Program

This section describes the results of performance of the quarterly groundwater monitoring programs stipulated under Task (14) of Consent Order Appendix A-6, and includes reporting of data collected during a total of seven sampling events during 1991 (January and July quarters), 1992 (January, April, July, and October quarters) and 1993 (January quarter). Specifics regarding sample quantities (as a function of progress in the well installation programs), as well as sampling and analytical protocols were provided earlier in Report Section 4.7.

The bulk of this section includes a presentation and comparative analysis of water quality data obtained from each monitoring well. In addition to an assessment of analytical data relative to water quality standards and criteria, data from wells within each landfill section are compared

to each other both within and across the shallow, intermediate depth and deep water bearing (monitoring) zones.

Stratigraphically, the shallow/refuse water bearing zone represents the uppermost sequence of saturated soil materials, consisting primarily of fill/refuse, and occasionally shallow deposits of Recent peat, sand, silt and clay, and glacial sand, clay or till. The intermediate depth confined (or semi-confined) water bearing zone represents unconsolidated soil materials (sands) lying below the refuse and above the bedrock. The intermediate depth water bearing zone is vertically stratified; it consists of an upper horizon of shallow Recent/glacial sands at Landfill Sections 1/9, 3/4, and 6/7 and glacial sands at Section 2/8, and a generally deeper horizon of Cretaceous sands underlying significant portions of Landfill Sections 1/9 and 2/8, as well as the southern area of Section 6/7. The deep confined water bearing zone represents the weathered bedrock and consolidated (competent) bedrock units underlying the overburden soil materials.

The relationship between the identified groundwater monitoring zones, sand units column defined in report Section 5.0, and the hydrostratigraphic units defined in report Section 6.0, is provided graphically below:

Stratigraphic Unit	Monitoring Zone	Three-Dimensional Model Layer
Refuse/Fill	Shallow/Refuse	1 and 2
Recent Sand	Shallow/Refuse or Intermediate	2, 3
Glacial Sand	Shallow/Refuse or Intermediate	2, 3, 4, 5
Columbia Group Sand	Shallow/Refuse or Intermediate	3
Cretaceous Sand	Intermediate	3, 5, 6
Jurassic/Triassic/Ordovician Weathered Bedrock/Bedrock	Deep	7

All analytical data presented in this report have undergone internal laboratory analytical quality assurance review in accordance with the project specific Quality Assurance Program (QAPP) and Project (QAPjP) plans. Due to the large quantity of data generated by this investigation, however, additional quality assurance review has been deemed appropriate by the project sponsor (NYCDOS) and the oversight regulatory agency (NYSDEC). The status and findings of these

additional reviews, consisting of data validation, usability, and comparability analyses, are detailed in report Section 7.2.5.

To assist in the evaluation of data derived from the monitoring programs, a series of graphics and tabular data summaries has been prepared. Due to the necessarily large quantity of these presentations, and extensive reference to them in the ensuing discussions, a summary of their content is provided here to orient the reader, as follows:

- ***Figures 7.13 through 7.184***

Graphs that indicate the results of all indicator parameter ("general chemical") and inorganic metals and trace element analytical data across all sampling quarters for all monitoring wells within Landfill Sections 1/9 (Figures 7.13 - 7.55), 2/8 (Figures 7.56 - 7.98), 3/4 (Figures 7.99 - 7.141), and 6/7 (Figures 7.142 - 7.184). These graphs are useful from an overview perspective in evaluating the differences in constituent concentrations between monitoring zones, observed variability in constituent concentrations across sampling quarters, and for comparison of concentration data to water quality standards and criteria. Due to the generally large variation in constituent concentrations between monitoring zones (often several orders of magnitude), a logarithmic scale is provided on most these graphs. Data from wells screened in refuse deposits (XW and YW wells at Landfill Sections 1/9 and 6/7, respectively; and Veterans Avenue Leachate Collection System Pump Stations 'A' and 'B' (PSA, PSB) at Section 1/9) are plotted furthest to the left on each graph, followed by wells screened in shallow unconfined water bearing units ('S' designation appended to well identification number), wells screened in intermediate depth confined water bearings units ('I' designation appended to well identification number; Recent/glacial sand wells first, followed by Cretaceous sand wells), and wells screened in deep (bedrock) confined water bearing units ('D' designation appended to well identification number). Data from the deep bedrock industrial supply well at the NYCDOS Muldoon Avenue garage (Muldoon) are also indicated at the end of the bedrock monitoring zone data at Section 1/9. Where they exist, analytical data qualifiers are plotted above the corresponding sample data point on these graphs. Appendix L1 provides a key for these data qualifiers.

- ***Figures 7.185 through 7.240***

Box plots that compare the distribution of analyte concentration data by monitoring zones within each landfill section for a selected series of indicator parameters and metals. The box plots are constructed with an arithmetic scale to highlight the significant differences in analyte concentrations between the shallow/refuse water bearing unit and the deeper sand and bedrock units. An explanation of the depiction of data distribution associated with the box plot presentations is contained in Figure 7.11.

- ***Figures 7.241 through 7.246***

These figures are similar to the above, except that they compare analyte concentrations by monitoring zone across all landfill sections for a selected subset of indicator parameters.

- ***Figures 7.247 through 7.310***

Box plots that compare the distribution of analyte concentration data between each well within the intermediate depth monitoring zone at each landfill section for a selected series of indicator parameter and metals. These plots are useful in identifying the presence of elevated analyte concentrations within the dilute groundwaters generally characteristic of these zones. Such differentiation is often not possible on the logarithmetic scale graphs (Figures 7.13 - 7.184). Where background historical or literature data is available for comparative purposes, it is included on the plots along the far left of the X axis, and identified as 'NJ' (public supply well data from the middle unit of the Potomac-Raritan-Magothy aquifer system; Appendix N), or '1982' (site data from sampling performed by William F. Cosulich Associates, P.C. for NYCDOS during 1982; Appendix N). As appropriate, wells are grouped on these plots by the stratigraphic unit within which they are screened; the label 'QS' on the X axis precedes wells screened in Recent/glacial sands, and the label 'KS' precedes wells screened in Cretaceous sands.

- ***Figures 7.311 through 7.374***

These figures provide the same information as above, except for the deep (bedrock) monitoring zone. Where historical or literature background data is available, it is plotted with the 'NJ' (public supply well data from Newark Group bedrock aquifers; Appendix N) and '1982' labels.

- ***Figures 7.375 through 7.386***

Box plots of dissolved iron, magnesium, and manganese data for each well within the intermediate depth monitoring zone at each landfill section. These analytes encompass most of the limited metals data available for direct comparison with the literature/historical database, and are representative of constituents generally exhibiting elevated concentrations in background or "natural" groundwaters.

- ***Figures 7.387 through 7.398***

These figures provide the same information as above, except for the deep (bedrock) monitoring zone.

- ***Figures 7.399 through 7.410***

These graphs indicate in stacked bar format the mean total detected, estimated, and tentatively identified compound (TIC) concentrations for volatile, semivolatile, and pesticide/herbicide/PCB analytes at all monitoring wells within the four landfill sections. As with Figures 7.13 through 7.184, all data from all wells within each landfill section are plotted together on each graph. Wells screened in the shallow/refuse water bearing unit ('XW', 'YW', and 'S' wells) lie to the left on the X axis, intermediate ('I') depth wells lie within the center, and deep ('D') wells lie to the right. Unlike Figures 7.13 through 7.184, these graphs indicate the mean total concentrations for the organic compound groups, rather than all individual quarterly sample results (total organic compound concentrations by sampling quarter are indicated on Figures 7.18A, 7.61A, 7.104A, and 7.147A).

- ***Figures 7.411 through 7.466***

Spatial distribution (contour maps) of arithmetic mean concentrations for a selected series of indicator parameters by landfill section and monitoring zone, as follows: shallow/refuse monitoring zone (Figures 7.411 - 7.442), intermediate depth (Recent/glacial sand) monitoring zone (Figures 7.443 - 7.450), intermediate depth (Cretaceous sand) monitoring zone (Figures 7.451 - 7.458), and deep (bedrock) monitoring zone (Figures 7.459 - 7.466). Data for the shallow/refuse monitoring zone are presented by each landfill section, while the intermediate

depth and deep (bedrock) monitoring zone presentations encompass the entre landfill site, more appropriate for the sub-regional or regional extent of the geological materials comprising these monitoring zones. It should be noted that due to limited analytical data in the central portions of the landfill mounds, concentration contours in these regions indicated on the graphics are largely artifacts of the data interpolation process. Arithmetic mean data are used on these figures as the small sample sizes (1-6 data values) do not support application of geometric mean or median calculation of central tendency. Non-detect data were included as the detection limit values in the calculation of the data point averages. (Similar data presentations for the intermediate depth (Cretaceous sand) and deep (bedrock) monitoring zones for a suite of geochemical analytes are contained on Figures 7.572 - 7.581, as discussed in Section 7.3.3.6.)

- ***Figures 7.467 through 7.489***

These figures are contour maps similar to the above, except indicating the arithmetic mean total concentration of detected volatile, semivolatile, and pesticide/herbicide/PCB organic compounds. Only data rejected through the data validation/usability/comparability processes (Section 7.2.5) were excluded from the calculation of data point averages. Detection limit values were not used in the calculation of the data point averages, since summing the numerous detection limit values would overshadow the concentration distribution of detected constituents.

- ***Figures 7.490 through 7.502A***

These figures provide an assessment of temporal changes in water quality by comparing data from wells installed and sampled in 1982 with current data from the Consent Order specified perimeter well array, at locations where such wells were located proximally (generally within 1500 ft) and screen the same stratigraphic unit. Table 7.15 provides details regarding the wells selected for comparison. Analytical data for the 1982 wells is derived from Appendix N.

- ***Tables 7.3 through 7.14***

These charts provide a tabular summary of the results of the groundwater quality assessment performed for each landfill section and monitoring zone through reference to water quality criteria and the relationships observed on Figures 7.13 - 7.184 (shallow monitoring zone), Figures

7.247 -7.310 (intermediate depth monitoring zone), and Figures 7.311 - 7.374 (deep monitoring zone).

These charts indicate exceedances of groundwater quality criteria and standards; where observed concentration distributions do not exceed criteria (or no criteria are established), these charts also indicate elevated constituent concentrations based on a comparative review with other wells screened within the same monitoring zone (Figures 7.247 through 7.374). With the exception of outlier data (indicated on Figures 7.247 through 7.374, and noted on Tables 7.3 through 7.14), any single analyte concentration in excess of groundwater quality criteria (regardless of sample size) is indicated as an exceedance on the charts. The assessment of indicator parameter constituents indicated on the charts is based on the results of total (unfiltered) analysis; metals constituents are evaluated against the results of both total and dissolved (filtered) analysis.

- ***Tables 7.16 through 7.21***

Summary tabulation of organic compounds detected within the shallow/refuse, intermediate depth and deep (bedrock) monitoring zones.

- ***Appendix L***

Tabular compilation and summary statistics of all analytical data derived through performance of the quarterly monitoring program (January, July 1991; January, April, July, October 1992; January 1993). Section L1 contains the raw data compilation; Section L2 contains summary statistics by analyte, landfill section, and monitoring zone; and Section L3 contains summary statistics by analyte and monitoring well.

- ***Attachment 34***

Box plot presentation of seasonal variability for a series of analytes by landfill section and monitoring zone. It should be noted that due to the relatively short time frame associated with the monitoring program, these data are affected by the variable measurement of water chemistry resulting from the progressive increase in the quantity of wells installed over time, as well as analytical artifacts noted in Section 7.2.5.2 and 7.2.5.3.

7.2.1 Landfill Section 1/9

The following discussion, and subsequent discussions for the other landfill sections, focuses on a description of the lateral and vertical distribution of the leachate indicator parameters identified in Section 7.1, including general chemical parameters, inorganic metals, and organic compounds. As such, the discussion is not exhaustive in terms of all chemical species analyzed; rather it identifies trends in the data, and indicates where exceedances of groundwater quality standards and criteria are prevalent. Figures 7.13 - 7.184 provide full specificity for all general chemical and inorganic constituents, and total organic compounds (Figures 7.13 - 7.55 for Section 1/9). Tables 7.3 through 7.14 (Tables 7.3 - 7.5 for Section 1/9) specifically indicate exceedances of groundwater quality standards and criteria by well for most regulated general chemical and inorganic parameters, and Tables 7.16 through 7.21 (Tables 7.16A - 7.21A for Section 1/9) provide similar information for the organic compounds, indicating all detected values for these constituents.

7.2.1.1 Shallow/Refuse Monitoring Zone

Virtually all of the general chemical leachate indicator parameters occur at elevated concentrations in the shallow/refuse monitoring zone at Landfill Section 1/9, with the exception of those constituents that would be expected to exhibit low concentration ranges within the predominantly anaerobic landfill environment (e.g., sulfate and nitrate). As indicated on Figures 7.241 - 7.246, the leachate at Landfill Section 1/9 exhibits the highest strength relative to these constituents compared to the other landfill sections within Fresh Kills. Summary statistics for the primary indicator parameters are provided below:

Landfill Section 1/9 Shallow/Refuse Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Ammonia	20	4,960,000	530,500
TKN	486	17,200,000	714,000
COD	20,000	7,110,000	1,000,000
BOD_5	2,000	1,200,000	51,000
TOC	13,500	2,650,000	398,500
Alkalinity	70,000	12,300,000	3,505,000
TDS	760,000	23,300,000	4,510,000
Chloride	129,000	9,130,000	1,355,000
Sulfate	1,000	1,080,000	17,200

With the exception of two wells in the northeastern area of Section 1/9 (1W92:IT025S, 026S), all shallow wells exceed the NYSDEC Water Quality Standard of 2,000 ug/L for ammonia. As indicated on Figure 7.412, the highest concentrations of ammonia in the shallow/refuse monitoring zone occur in the northwestern (1W92;IT013S, 039S, 040S) and southeastern (1W92:IT029S, 1W89:XW-5) areas of the landfill.

Similar to ammonia, which is formed in the landfill environment primarily through the anaerobic process of ammonification of organic matter, a series of indicator parameters (either directly or indirectly) measure the presence of organic acids and other organic matter in groundwater. These are biochemical and chemical oxygen demand, total organic carbon, and alkalinity. As would be expected, their concentration distribution is similar to that identified for ammonia, as indicated on Figures 7.413, 7.416, 7.418, and 7.411, respectively.

Total Dissolved Solids represents a gross measure of leachate contamination, and is linked in its concentration distribution with chloride (a major dissolved solute comprising TDS in the landfill environment). Except where they are influenced by the presence of seawater (discussed subsequently for the intermediate depth monitoring zone), these analytes mirror the concentration

distribution observed for the nitrogen and carbon series indicator parameters, as indicated on Figure 7.415 for chloride.

Under the anaerobic conditions prevalent within the landfill, sulfate is chemically reduced to sulfide, generally resulting in low concentrations of this analyte. As indicated on Figure 7.21, this is primarily the case at Section 1/9, with only two wells consistently exceeding the NYSDEC Water Quality Standard of 250,000 ug/L (wells 1W91:IT004S and 1W92:IT026S). These latter data may be indicative of fresh leachates in the areas of these wells (supported somewhat by dissolved oxygen measurements at these locations).

The primary elemental inorganic leachate indicator parameters (sodium, calcium, and potassium) are all present at elevated concentrations in the shallow/refuse monitoring zone relative to natural freshwaters. All wells exceed the NYSDEC water quality criterion of 20,000 ug/L for sodium (the other constituents are not regulated). Iron, magnesium, boron and chromium consistently exceed water quality criteria as indicated on Figures 7.43, 7.45, 7.36 and 7.39, respectively. Manganese (Figure 7.46) is observed to exceed quality criteria primarily in the northeastern and eastern areas of the landfill. Boron exhibits a concentration distribution similar to that observed with the general chemical parameters, with highest concentrations recorded in the northwestern (1W91:IT013S) and southeastern (1W91:IT007S, 1W92:IT013S, 015S, 029S) areas of the Landfill (Figure 7.414).

Barium, lead, and zinc exhibit fairly routine excursions above quality criteria with no apparent spatial pattern; lead and zinc data are often highly variable and qualified, a likely reflection of turbidity variation in the water samples. Virtually no well samples exceed quality criteria for copper or nickel (Figures 7.42 and 7.47, respectively). Regulated trace elements (antimony, arsenic, beryllium, cadmium, hexavalent chromium, selenium and silver) uniformly exhibit an extremely low (and generally qualified) concentration distribution. The only non-qualified exceedances of water quality standards for these elements occur at wells 1W91:IT001S and 1W92:IT036S (arsenic), and 1W91:IT002S, 003S, 04S, and 011S (cadmium).

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 1/9 Shallow/Refuse Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Sodium	48,200	11,100,000	1,300,000
Calcium	10,200	395,000	48,100
Potassium	3,590	1,220,000	302,000
Iron	330	277,000	9,990
Manganese	9.8	52,400	93
Magnesium	18,200	402,000	52,050
Barium	56.6	5,090	936
Boron	21.0	10,700	4,460
Chromium	2.0	573	79.8
Copper	2.0	860	10.8
Lead	1.0	2,090	13.6
Nickel	4.0	285	48.5
Zinc	3.0	2,510	105

Based on analytical laboratory test procedures, the organic compounds are divided into Volatile, Semivolatile, and Pesticide/Herbicide/PCB groups for discussion purposes. It should be noted that, while PCBs are analyzed under the test method applied for the quantification of pesticides and are consequently included in the general grouping for these compounds in the following discussions, virtually no PCBs were detected in any sampling at any of the landfill sections.

As indicated on Figures 7.18A (Total Organics Scatterplot) and 7.399 - 7.401 (Organic Group Bar Charts), the occurrence of organic compounds as a whole in the shallow/refuse monitoring zone is variable and sporadic, especially in terms of non-qualified data. In review of the chart

presentations and the spatial distribution maps (Figures 7.467 - 7.469), it should be noted that detected concentrations (indicated as mean total concentrations) often represent a single occurrence that was not repeated in subsequent sampling events. Therefore, these graphics tend to portray a wider distribution of organic compounds than may reliably be considered to exist. This is evident through review of Tables 7.16 - 7.18, which summarize all detected organic compounds.

The focus of the ensuing discussion is on those few constituents that repeatedly occur as non-qualified concentrations at specific locations. As indicated through review of all referenced tabular and graphic presentations, even in these cases the concentration distribution of non-qualified organic compounds is uniformly low within the shallow/refuse monitoring zone "source area".

At Section 1/9, the presence of organic compounds is fairly widespread within the shallow/refuse monitoring zone; this landfill exhibits the greatest diversity in detected compounds, and exhibits the highest mean total concentrations of the four landfill sections comprising Fresh Kills. Summary statistics of the mean total organic compound groups are summarized below:

Landfill Section 1/9 Shallow/Refuse Monitoring Zone			
Compound Group	**Mean Total Concentration (ug/L)**		
	Minimum	**Maximum**	**Median**
Volatiles	ND	763	27
Semivolatiles	ND	383	20
Pesticides/ Herbicides/PCBs	ND	2.2	0.2

As indicated on Figures 7.467 - 7.469, the spatial concentration distribution of the organic compounds is similar to that noted earlier for the general chemical indicator parameters, with the highest mean total concentrations observed in the northwest and southeast areas of the landfill.

The most consistently detected (non-qualified) volatile organic compounds are ethylbenzene, xylene, chlorobenzene, and toluene, with concentrations ranging from 1 to 500 ug/L. Table 7.16A provides a full delineation of all detected volatile organic compounds by well and monitoring quarter. The most consistently detected (non-qualified) semivolatile organic compounds are naphthalene, 2-4-dimethylphenol, and bis(2-ethylhexyl)phthalate. The latter compound was routinely detected in field and laboratory QC blanks. With the exception of several qualified values, the observed concentration distribution of all of these compounds is less than 100 ug/L. Table 7.17A provides a full tabulation of all detected semivolatile organic compounds within the shallow/refuse monitoring zone at Section 1/9. Of the Pesticide/Herbicide/PCB group, only the herbicide Silvex is detected consistently at Section 1/9, with a maximum concentration of 3 ug/L. PCB compounds (Aroclor-1232, 1242) were detected on one occasion at wells 1W89:XW-5, XW-7, and the Veterans Avenue Leachate Collection Pump Station "A", with a maximum estimate concentration of 5.3 ug/L. Table 7.18A provides a full tabulation of all detected Pesticide/Herbicide/PCB compounds in the shallow/refuse monitoring zone at Section 1/9.

7.2.1.2 Intermediate Depth Monitoring Zone

As indicated on Figures 7.13 - 7.55 (scatterplots), Figures 7.185 - 7.198 (boxplots), and Figures 7.399 - 7.401 (organic compound barplots), the majority of leachate indicator parameters and organic compounds exhibit a siginficant reduction in concentration (often several orders of magnitude) within the intermediate depth monitoring zone relative to the shallow/refuse monitoring zone. Exceptions relate to chloride, and other seawater associated constituents (e.g., sodium, sulfate), which are discussed in more detail below. Due to the complexity of its structure, the intermediate depth monitoring zone has been segregated into two components for discussion purposes: A generally shallow Recent sand horizon, and a deeper Cretaceous sand horizon. Summary statistics for the general chemical indicator paramters are provided for each monitoring zone horizon.

Landfill Section 1/9 Intermediate Depth (Recent Sand) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Ammonia	20	26,800	3,360
TKN	200	70,400	12,000
COD	7,600	426,000	37,900
BOD5	2,000	183,000	2,000
TOC	1,600	201,000	26,900
Alkalinity	26,000	1,120,000	665,000
TDS	116,000	36,300,000	12,600,000
Chloride	27,500	24,700,000	8,155,000
Sulfate	1,000	2,700,000	363,500

Landfill Section 1/9 Intermediate Depth (Cretaceous Sand) Monitorign Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Ammonia	20	40,200	613
TKN	200	85,200	2,110
COD	5,000	384,000	28,800
BOD5	2,000	13,800	2,000
TOC	1,000	55,300	10,200
Alkalinity	10,000	740,000	126,000
TDS	131,000	35,200,000	4,700,000
Chloride	12,000	20,200,000	3,040,000
Sulfate	6,300	3,730,000	139,000

In general, these data indicate water quality degradation in the Recent sand horizon relative to the deeper Cretaceous unit, and a seawater influence in some areas of both horizons, represented by the extremely high TDS and chloride maximum concentrations (1.5 - 3 times maximum concentrations measured in the shallow/refuse monitoring zone).

The existence of a seawater influence (salt water intrusion) in portions of the confined sand units at Section 1/9 was discussed previously in Report Sections 4.0, 5.0, and 6.0. The most plausible explanation for its presence is the historical pumping of an irrigation supply well screened in the Cretaceous sand unit to the south of Landfill Section 1/9. Numerical analysis performed in Section 6.6.2 indicates that drawdown associated with such pumpage would result in induced recharge of Arthur Kill channel waters through shallow Recent sand units and into deeper Cretaceous sands. Such a condition would also act to facilitate vertical migration of leachate from the refuse mound into these sand units, although some migration would occur in any event due to the hydrostratigraphy of the area. Relative to the ensuing review of water quality data, the seawater influence is pronounced, and especially in the deeper sand units, acts to minimize the utility of many of the leachate indicators, since these analytes exist in elevated concentrations in both leachate and seawater. Additional definition of this issue is provided through the application of geochemical analysis (Section 7.3).

Within the Recent sand horizon at Section 1/9, data is available from Recent sand Unit 1, a thick sequence bordering the Arthur Kill along the western landfill margin. Mean ammonia concentration data indicate that much of this horizon has been affected by leachate migration. Ammonia data from all intermediate depth wells are compared to each other and available historical/literature background data on Figure 7.248, and the spatial distribution of mean ammonia data is indicated on Figure 7.444. The ground water quality standard of 2,000 ug/L is exceeded at all Recent sand wells (1W91:IT10I1, 11I1, 12I1, and 1W92:IT009I1, 016I1, and 017I). Total Kjeldahl nitrogen data are similarly elevated (Figures 7.261 and 7.449).

Of the analytes that are indicators of organic content, alkalinity is clearly elevated in this horizon (Figures 7.247, 7.443), with TOC and COD showing a similar but less pronounced trend (Figures 7.262, 7.450; and 7.252, 7.448). Except for location 1W91:IT012I2, BOD_5 concentrations are not elevated in this monitoring horizon.

Total dissolved solids and chloride concentrations are extremely high in the Recent sands relative to both the shallow/refuse monitoring zone and background data (Figures 7.26, 7.260; and 7.23, 7.251). These data indicate seawater mixing, and possibly a leachate influence, although the latter is masked by the former. Virtually all wells exceed the NYSDEC water quality criterion for sulfate (250,000 ug/L). These concentrations are generally several orders of magnitude in excess of those measured in the shallow/refuse monitoring zone, and again indicate the influence of seawater mixing.

Relative to the inorganic constituents, sodium, calcium, and potassium are all present at elevated concentrations in the Recent sand horizon, relative to both the shallow/refuse monitoring zone (Figures 7.51, 7.48, and 7.38, respectively), and background data (Figures 7.257, 7.256). All wells exceed the water quality standard of 20,000 ug/L for sodium . As with TDS, chloride, and sulfate, these data are also indicative of seawater mixing.

Iron, magnesium, manganese, and boron routinely exceed water quality critiera, exceptions being 1W92:IT045I for boron and magnesium, 1W92:IT009I1 for boron, and 1W91:IT010I1 and 012I1 for manganese. Virtually none of the Recent sand monitoring zone wells exceed quality critieria for barium, chromium, copper, lead, nickel, or zinc. Regulated trace elements uniformly exhibit an extremely low (and generally qualified) concentration distribution. The only non-qualified exceedence of water quality standards for these elements is for cadmium at well 1W91:IT010I1. Summary statistics of the primary inorganic metal analytes for the Recent sand horizon are provided below:

Landfill Section 1/9 Intermediate Depth (Recent Sand) Monitoring Zone			
	Concentration (ug/L0		
Analyte	**Minimum**	**Maximum**	**Median**
Sodium	16,300	6,020,000	3,910,000
Calcium	13,300	256,000	189,000
Potassium	1,910	212,000	141,000
Iron	224	45,000	11,500
Manganese	4.2	1,770	569

Landfill Section 1/9 Intermediate Depth (Recent Sand) Monitoring Zone			
Analyte	Concentration (ug/L0		
	Minimum	Maximum	Median
Magnesium	2,600	761,000	433,000
Barium	86	605	150
Boron	386	2,020	1,470
Chromium	2.0	38.7	5.0
Copper	1.0	311	2.5
Lead	1.0	11.3	1.0
Nickel	2.0	21.8	4.0
Zinc	1.0	48.1	11.9

As indicated on Figures 7.18A (scatterplot), 7.399 - 401 (bar charts) and 7.479 - 7.481 (spatial distribution maps), the concentration distribution of organic compounds in the Recent sand horizon is very low. Mean total organic compound data are summarized below:

Landfill Section 1/9 Intermediate Depth (Recent Sand) Monitoring Zone			
Compound Group	Mean Total Concentration (ug/L)		
	Minimum	Maximum	Median
Volatiles	ND	12	6
Semivolatiles	ND	5	ND
Pesticides/Herbicides/PCBs	ND	0.1	ND

With the exception of well 1W92:IT045I1, where qualified concentrations of chloroform were detected twice (maximum estimate concentration 4 ug/L) and well 1W91:IT012I1 (toluene detected twice at an estimated concentration of 1 ug/L), no volatile organic compounds were repeatedly identified in any of the Recent sand wells. No seimvolatiles, pesticides or herbicide compounds were detected repeatedly in any Recent sand well. PCBs were not detected in any well samples.

Within the Cretaceous sand horizon at Section 1/9, data is available from sand Unit 1 (Sheets 5.63, 5.66), a thick basal sequence that is correlated to the east into Section 2/8. As is evident from the data presented in the ensuing discussion, this horizon is characterized by two distinct regions: (1) western and southern Section 1/9, where seawater mixing is prevalent and leachate mixing is suggested at several locations, and (2) eastern Section 1/9, where freshwater (non-contaminated) chemistry is observed. Ammonia concentrations exceed the water quality standard of 2,000 ug/L along most of the western and southwestern area of the landfill (Figure 7.452); wells to the north and east generally exhibit concentration lower by one or two orders of magnitude (Figure 7.13). The highest concentrations of ammonia occur at wells 1W91:IT008I, and 1W92:IT009I2, 016I2. Alkalinity, chemical oxygen demand and total organic carbon exhibit a similar pattern (Figures 7.451, 7.456, and 7.458). No apparent relationship is observed in the BOD data (Figure 7.453). Total dissolved solids and chloride (Figures 7.26 and 7.455) clearly exhibit the pronounced seawater influence within the Cretaceous sands in the western and southern areas of Section 1/9. Sulfate concentrations exceed the groundwater standard of 250,000 ug/L in the western and southern areas of Section 1/9; such exceedences are a result of seawater mixing.

Again consistent with seawater mixing, sodium, calcium, and potassium are present at elevated concentrations in the western and southern areas of Section 1/9 relative to both the shallow/refuse monitoring zone and the eastern freshwater Cretaceous region (Figures 7.51, 7.38, 7.48; 7.257, 7.256). Except for wells located in the northeast and southeast (1W91:IT004I, 005I1, 005I2, 005I3; 1W92:IT045I), all wells routinely exceed the NYSDEC water quality standard of 20,000 ug/L for sodium.

Water quality standards for iron and manganese are exceeded at all well locations (freshwater and saline), indicating that these analytes exist at high concentrations naturally in the Cretaceous sediments (refer to Sections 7.1 and 8.2.2.1.2). Manganese and boron (Figure 7.454) exceed water quality standards in the areas of seawater mixing along the western and southern margins of the landfill. Water quality standards are exceeded for several metals (barium, chromium, copper, lead, and zinc) at only two widely separated locations (1W91:IT001I in the northwest, and 1W92:IT044 and 045I in the southeast; Figures 7.34, 7.39, 7.42, 7.44 and 7.55). No wells exceed the water quality standard for zinc.

Regulated trace elements (antimony, arsenic, beryllium, cadmium, hexavalent chromium, selenium, and silver) exhibit a uniformly low concentration distribution. Beryllium is the only element that exceeds water quality criteria; these exceedences are observed at the same locations noted above for several other metal analytes (001, 044, 045). The elevated metals concentrations noted at these well cluster locations are likely associated with the high turbidites measured at these locations (Figure 7.28, as noted in Table 7.4).

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 1/9 Intermediate Depth (Cretaceous Sand) Monitoring Zone			
Analyte	**Concentration (ug/L)**		
	Minimum	**Maximum**	**Median**
Sodium	11,300	7,760,000	1,480,000
Calcium	9,370	422,000	213,500
Potassium	1,530	373,000	58,000
Iron	2,260	195,000	20,300
Manganese	208	5,570	1,170
Magnesium	3,040	970,000	163,000
Barium	67.4	1,160	217
Boron	2.0	2,370	233
Chromium	2.0	174	5.0
Copper	2.0	247	3.0
Lead	1.0	91	2.0
Nickel	2.0	411	4.0
Zinc	1.0	1,820	32.3

Similar to the Recent sand horizon, the concentration distribution of organic compounds in the Cretaceous sands in uniformly low (Figures 7.399 - 401), although mean total concentrations are higher (in terms of maximum detected concentrations):

Landfill Section 1/9 Intermediate Depth (Cretaceous) Monitoring Zone			
Compound Group	Mean Total Concentration (ug/L)		
	Minimum	Maximum	Median
Volatiles	ND	65	2
Semivolatiles	ND	43	2
Pesticides/Herbicides/PCBs	ND	0.4	ND

Several volatile organic compounds have been detected more than once at several well locations; with the exception of well 1W92:IT044I3 (discussed below), these data have been qualified, and exhibit a maximum concentration os 2 ug/L (Table 7.19A). Well 1W91:IT008I exhibits the highest detected VOC concentration in the Cretaceous monitoring zone (130 ug/L, methylene chloride); but this compound was not detected in several prior or subsequent sampling quarters. 2-Butanone was detected twice at well 044I3 at concentrations of 58 and 130 ug/L. It is possible that upward groundwater flux from the bedrock unit in this area is responsible for the presence of this compound (refer to Section 7.2.1.3).

Very few semivolatile organic compounds were detected in the Cretaceous sands, the most by far being associated with bis(2-ethylhexyl)phthalate, a compound routinely identified in quality control blank samples (this compound is responsible for the elevated mean total semivolatile organic compound concentration for well 1W91:IT004I on Figure 7.483). Of significance is the repeated detection of naphthalene (non-qualified concentrations of 16-24 ug/L) at well 1W92:IT015I, located at the southern tip of the landfill, where leachate migration is supported by the general chemical and geochemical database.

The concentration distribution for detected pesticides and herbicides within the Cretaceous sand is extremely low (maximum concentration of 2.1 ug/L; Table 7.21A). The compound 2,4-D occurs several times at locations 1W91:IT007I and 012I, and is the only compound to occur more than once at the same location. Concentrations at these locations range from 0.1 to 0.61 ug/L, an order of magnitude below the groundwater quality standard of 4 ug/L.

7.2.1.3 Deep (Bedrock) Monitoring Zone

As indicated on Figures 7.185 - 7.198, the concentration distribution of general chemical and inorganic analytes within the bedrock monitoring zone is generally lower than that observed in the intermediate depth zone, reflecting a more dilute water chemistry that is less influenced by seawater mixing and in virtually all areas, not influenced by leachate migration. The bedrock monitoring zone differs from the overlying sand horizons in that two specific organic compounds occur regularly in a number of monitoring wells.

Summary statistics for the general chemical indicator parameters are provided below:

Landfill Section 1/9 Deep (Bedrock) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Ammonia	20.0	1,550	199
TKN	200	2,580	516
COD	5,000	235,000	16,150
BOD5	2,000	75,000	2,000
TOC	1,000	52,800	4,430
Alkalinity	1,000	1,540,000	50,000
TDS	116,000	16,000,000	940,000

Landfill Section 1/9 Deep (Bedrock) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Chloride	500	8,640,000	285,000
Sulfate	2,030	1,160,000	30,000

As indicated on Figure 7.13, none of the monitoring wells exceed the ammonia water quality standard of 2,000 ug/L. The spatial distribution map of mean ammonia concentration (Figure 7.460) indicates highest observed concentration as well 1W92:IT045D, located off the southeast of the landfill area. Alkalinity, BOD, TKN, and TOC data indicate a similar pattern (Figures 7.459, 7.461, 7.465, 7.466), suggesting that dilute leachate mixing may be occurring to the north of this area, as simulated by the three-dimensional solute transport analysis (Sheet 6.71). COD data appear elevated over a larger area to the west and northwest (Figures 7.464, 7.316).

Total dissolved solids (Figure 7.324), chloride (Figure 7.463), sulfate (Figure 7.579), and boron (Figure 7.462) are elevated in the southwestern area of the landfill, indicative of seawater mixing. These analytes routinely exceed water quality standards in this area.

Sodium, potassium, and calcium are observed at elevated concentrations at well 1W92:015D (within the seawater influenced area). A distinct pattern is not clear for these analytes in other presumably seawater influenced wells. The NYSDEC water quality criterion for sodium of 20,000 ug/L is exceeded at virtually all wells within the deep monitoring zone.

Iron concentrations exceed the water quality standard of 300 ug/L at all locations except along the eastern landfill boundary (Figure 7.43). An elevated concentration distribution would be expected given literature/background data (Section 7.1), and presumed freshwater site chemistry (Table 8.3A). Manganese concentrations are similarly elevated except in the north and east. Magnesium concentrations exceed the water quality standard of 35,000 ug/L only in the seawater influenced areas of the site (Figure 7.45). Virtually none of the bedrock wells exceed quality criteria for barium, chromium, copper, lead, nickel, or zinc). With the one exception (cadmium

at well 1W91:010D), none of the deep wells exhibit non-qualified exceedences for trace elements (Figures 7.32, 7.33, 7.35, 7.37, 7.40, 7.49, 7.50).

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 1/9 Deep (Bedrock) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Sodium	10,900	3,660,000	107,500
Calcium	10,200	1,510,000	95,700
Potassium	1,500	414,000	11,450
Iron	230	446,000	12,300
Manganese	2.7	18,400	469
Magnesium	49.2	403,000	10,600
Barium	21.8	894	172
Boron	28	2,770	574
Chromium	2.0	17.8	5.0
Copper	1.0	41.3	4.2
Lead	1.0	1,840	1.1
Nickel	2.0	26.1	5.0
Zinc	1.0	2,240	80.5

Unlike the other monitoring zones two volatile organic compounds (2-butanone and toluene) are detected fairly regularly at a number of well locations within the bedrock across all of the landfill sections. These compounds result in the elevated distribution of organic compounds indicated on Figures 7.19A and 7.399 at Section 1/9. Detected semivolatile and pesticide/herbicide

compounds are sparse and exhibit a very low concentration distribution, as indicated in the summary statistics below, and on Figures 7.400, 7.401 and 7.488, 7.489.

Landfill Section 1/9 Deep (Bedrock) Monitoring Zone			
	Mean Total Concentration (ug/L)		
Compound Group	Minimum	Maximum	Median
Volatiles	ND	356	76
Semivolatiles	ND	33	2
Pesticides/Herbicides/ PCBs	ND	0.5	ND

The distribution of total mean volatile organic compound concentration is indicated on Figure 7.485. With the exception of several repeated occurrences of chloroform and 2-hexanone at well 1W91:IT007D, virtually all of the routinely detected volatile organic compounds observed at Section 1/9 consist of 2-butanone and toluene (Table 7.19A). Consequently, separate distribution maps were prepared for these compounds (Figures 7.486, 7.487), as their presence is noted within the bedrock unit across the entire Fresh Kills Landfill area.

The source of this contamination is unknown, but is not believed to be associated with leachate migration because: (1) to occur at measurable concentrations in the deep monitoring zone, these constituents would need to be present at source concentrations in the ppm range, a condition that is not observed in the data (maximum source area concentrations for these compounds are in the range, of 100 - 600 ug/l), (2) the maximum concentration of toluene detected in the intermediate depth monitoring zone is 6 ug/L (it is detected at only five other locations at estimated concentrations of 1 ug/L). 2-Butanone is virtually undetected in the other monitoring zones (Tables 7.16A-D, 719A-D); the only significant exception in the intermediate depth monitoring zone being at location 1W92:IT044I3, where vertical flow gradients would suggest upward migration of this contaminant from the bedrock to the Cretaceous sands, (3) the vertical hydraulic head distribution (Table 6.7) does not support downward migration of contaminants from overlying strata to the bedrock, (4) review of indicator parameter chemistry (Table 7.5) and geochemistry (Table 7.29 in report Section 7.3.3.3) does not support leachate migration to and

contamination of the bedrock water bearing unit, and (5) the results of numerical groundwater flow and solute transport analysis (Sections 6.2 -6.6).

In order to evaluate if the presence of these compounds were artifacts of the sampling or well installation process, monitoring well purging, flushing, and time series sampling was performed at three on-site wells during the period August 4 through August 20, 1993. The three selected well for this activity (1W91:004D, 2W91:307D, 6W91:169D) exhibit a range in hydraulic conductivity and reported concentration distribution for 2-butanone and toluene. Results of laboratory analysis of time series data collected from these wells are inconclusive (Attachment 38). In three sample collected over one day of continuous pumping from well 307D, 2-butanone was not detected, while toluene was detected at concentrations ranging from 6 to 9 ug/L. This is contrasted with prior analytical data from this well indicating a measured range in concentration of 80 - 240 ug/L for 2-butanone, and 38 - 97 ug/L for toluene. Analysis of samples obtained following purging and flushing of well 169D did not detect either 2-butanone or toluene; in subsequent samples obtained from this well (allowing two weeks for recovery due to minimal yield), both compounds were detected. Both compounds were also detected in well 004D during an initial sampling event; insufficient yield precluded additional sample collection.

In conclusion, field testing has indicated that, at least in some areas, detection of these constituents may be spurious. NYCDOS is currently investigating the potential for an upgradient, off-site source for these compounds.

Aside from the project monitoring well array, xylene has been detected on several occasions (concentrations ranging from 40 - estimated 460 ug/l) in the NYCDOS Muldoon Avenue garage well, a deep (580 ft) industrial supply well used periodically for the washing of trucks. This well is scheduled for abandonment by NYCDOS during January 1994.

7.2.1.4 Temporal Relationships

Figures 7.490 - 7.502A are box plots for selected typical leachate indicator parameters. In these figures, data from the current groundwater quality investigation are plotted with data from water quality sampling conducted in 1982. Data from both shallow (Recent/glacial sand) and deep (Cretaceous sand) horizons within the intermediate depth monitoring zone are presented for

Section 1/9 (Table 7.15). Using these figures, existing water quality data may be compared to historical data, thus providing insight into changes in water quality over time. Figures 7.490 - 7.502A indicate little variation between the two sets of data at Section 1/9. Specifically, concentrations of alkalinity, ammonia, BOD, COD, sulfate, TDS, and TKN as measured in the current sampling effort are generally equal to or less than those measured in 1982. Only chloride, TDS, and several total metals analytes appear elevated relative to the 1982 data, and these generally occur within areas influenced by sea water intrusion.

A comparison of seasonal variation of selected general chemical and inorganic parameters was performed for the shallow, intermediate, and deep monitoring zones at Landfill Section 1/9. Box plots of seasonal data are contained in Attachment 34. A review of these data indicate the presence of some seasonal variation for a number of analytes. BOD, chloride, sulfate and sulfide appear to vary seasonally in the shallow zone. BOD concentrations in the winter are characterized by a higher median as well as a higher degree of variation. Median values of lead are highest in the winter. Chloride data show an increasing median value from summer to fall, while sulfate data exhibit a higher degree of variability in the summer months. The median concentration of sulfide appears to be significantly lower in the summer data.

Less variability is seen in the data from the intermediate zone. BOD concentrations exhibit both higher variability and a higher median value in the winter sampling. Winter data for sulfide exhibits a higher degree of variability than in other quarters. The variability of chromium and zinc are highest in the summer quarters.

Several parameters appear to exhibit seasonal variation in the deep (bedrock) monitoring zone. BOD and TOC variability is highest in the fall quarters. Both the median and variability of sulfide are at their maximum in the spring months. Variation is noted in the summer quarters for several parameters: chloride reaches its highest median value, and variability in TDS, barium, and boron data are at their highest. Manganese and magnesium exhibit their highest median and variability in the summer months also. As noted in Section 7.2, it is likely that many of the currently observed variations simply represent an artifact of the limited time frame available for seasonal analysis.

7.2.2 Landfill Section 2/8

The following discussion identifies trends in the data and where exceedances of groundwater quality standards and criteria are prevalent for landfill Section 2/8. Figures7.56 - 7.98 provide full specificity for all general chemical and inorganic constituents, and total organic compounds. Tables 7.6 through 7.8 specifically indicate exceedances of groundwater quality standards and criteria by well for most regulated general chemical and inorganic parameters, and Tables 7.16B through 7.21B provide similar information for the organic compounds, indicating all detected values for these constituents.

7.2.2.1 Shallow/Refuse Monitoring Zone

Virtually all of the general chemical leachate indicator parameters occur at elevated concentrations in the shallow/refuse monitoring zone at Landfill Section 2/8, with the exception of those constituents that would be expected to exhibit low concentration ranges within the predominantly anaerobic landfill environment (e.g., sulfate and nitrate). As indicated on Figures 7.241 - 7.246, the leachate at Landfill Section 2/8 exhibits the lowest strength relative to these constituents compared to the other landfill sections within the Fresh Kills Landfill. Summary statistics for the primary indicator parameters are provided below:

Landfill Section 2/8 Shallow/Refuse Monitoring Zone			
	Concentration (ug/L)		
Analyte	Minimum	Maximum	Median
Ammonia	20	3,130,000	87,600
TKN	221	4,260,000	193,000
COD	5,000	874,000	221,500
BOD5	2,000	99,000	17,000
TOC	10,800	556,000	150,000
Alkalinity	98,000	7,400,000	1,280,000
TDS	230,000	3,800,000	1,910,000

Landfill Section 2/8 Shallow/Refuse Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Chloride	34,600	2,020,000	545,000
Sulfate	1,000	301,000	14,800

With the exception of three wells (2W91:IT306S, 308S and 2W92:IT324S), all shallow wells exceed the NYSDEC Water Quality Standard of 2000 ug/L for ammonia. Well 2W91:IT308S did exceed the groundwater quality standard for the July 1991 and April 1992 sampling quarters, but was below the groundwater quality standard for the other five sampling quarters. As indicated on Figure 7.420, the highest concentrations of ammonia in the shallow/refuse monitoring zone occur in the eastern half (2W93:IT303S, 315S, 316S, 317S, 318S, 320S) of the landfill section.

Similar to ammonia, which is formed in the landfill environment primarily through the anaerobic process of ammonification of organic matter, a series of indicator parameters measure the presence of organic acids and other organic matter in groundwater. These parameters are biochemical and chemical oxygen demand, total kjeldahl nitrogen, total organic carbon, and alkalinity. As would be expected, their concentration distribution is similar to that identified for ammonia, as indicated on Figures 7.421, 7.424, 7.425, 7.426, and 7.419, respectively.

Total dissolved solids represents a gross measure of leachate contamination, and is linked in its concentration distribution with chloride (a major dissolved solute comprising TDS is the landfill environment). Except where they are influenced by the presence of seawater (as discussed for the intermediate depth monitoring zone for Section 1/9), these analytes mirror the concentration distribution for the nitrogen and carbon series indicator parameters, as indicated on Figures 7.423, 7.66 and 7.69. The only difference is that the highest concentration of chloride is found in the northern corner of the landfill at 2W92:IT312S.

Under the anaerobic conditions prevalent within the landfill, sulfate is chemically reduced to sulfide, generally resulting in low concentrations of this solute. As indicated on Figures 7.64 and

7.65, this is primarily the case at Section 2/8, with only one well consistently exceeding the NYSDEC water quality standard of 250,000 ug/L (2W92:IT306S).

The primary elemental inorganic leachate indicator parameters (sodium, calcium, and potassium) are all present at elevated concentrations in the shallow/refuse monitoring zone relative to natural freshwaters. The only wells not showing elevated concentrations of these three parameters are 2W91:IT306S (potassium), 2W91:IT308S (potassium), and 2W92:IT324S (sodium and potassium). All wells except 2W92:IT324S exceed the NYSDEC water quality criterion of 20,000 ug/L for sodium (the other parameters are not regulated). Iron and magnesium exceed water quality standards for all wells except 2W91:IT306S (magnesium) as indicated on Figures 7.86 and 7.88. Boron concentrations (Figure 7.79) exceed the NYSDEC water quality criterion of 1,000 ug/L for all wells except for 2W91:IT306S, 308S, 2W92:IT311S and 324S. Barium concentrations (Figure 7.77) exceed the NYSDEC water quality criterion along the northern and eastern area of the landfill. Manganese concentrations (Figure 7.89) exceed the NYSDEC water quality criterion of 300 ug/L in the western and central part of the landfill.

Concentrations of chromium (Figure 7.82), copper (Figure 7.85), lead (Figure 7.87), and zinc (Figure 7.98) only sporadically exceed NYSDEC water quality criteria in the northern and eastern parts of the landfill. The sporadic nature of the water quality exceedences likely reflects turbidity in the samples. No well samples exceed water quality criteria for nickel (Figure 7.90). Regulated trace elements (antimony, arsenic, beryllium, cadmium, hexavalent chromium, selenium, and silver) uniformly exhibit extremely low (and generally qualified) concentrations. The only non-qualified exceedences of water quality standards for these elements occur at wells 2W91:301S (antimony, arsenic, hexavalent chromium), 2W91:IT302S (hexavalent chromium), and 2W91:IT306S (hexavalent chromium). It should be noted that these exceedences are not routine and usually are limited to one sampling quarter. This suggests that the exceedence reflects turbidity in the sample.

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 2/8 Shallow/Refuse Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Sodium	48,200	11,100,000	1,300,000
Calcium	31,000	314,000	134,000
Potassium	3,590	1,220,000	302,000
Iron	6,580	130,000	23,700
Manganese	17.4	6,130	393
Magnesium	8,610	125,000	63,600
Barium	85.6	6,330	1.510
Boron	45.6	8,920	2,200
Chromium	2	145	12.7
Copper	2	389	92.4
Lead	1	1,210	3.2
Nickel	3.7	143	10.8
Zinc	3	2,020	73

As indicated on the Total Organic Compounds scatterplot (Figure 7.61A) and the organic group bar charts (Figures 7.402 - 7.404), the occurrence of organic compounds is minimal within the shallow/refuse monitoring zone, with only two wells slightly exceeding the NYSDEC criterion for total organic compounds of 100 ug/L (2W92:IT317S and 320S). In review of the chart presentations and the spatial distribution maps, it should be noted that detected concentrations (indicated as mean total concentrations) often represent a single occurrence that was not repeated in subsequent sampling events. Therefore, these graphics tend to portray a wider distribution of organic compounds than may reliably be considered to exist. This is evident through review of Tables 7.16B through 7.18B, which summarize all detected organic compounds.

The focus of this discussion is on those few constituents that repeatedly occur as non-qualified concentrations at specific locations. As indicated through review of all referenced tabular and

graphic presentations, even in these cases the concentration distribution of non-qualified organic compounds is uniformly low within the shallow/refuse monitoring zone "source area".

This landfill section exhibits the lowest diversity in detected compounds, and exhibits the lowest mean total concentrations of the four landfill sections comprising Fresh Kills. Summary statistics of the mean total organic compound groups are summarized below:

Landfill Section 2/8 Shallow/Refuse Monitoring Zone			
	Mean Total Concentration (ug/L)		
Compound Group	Minimum	Maximum	Median
Volatiles	ND	67	1
Semivolatiles	ND	163	5
Pesticides/Herbicides/PCBs	ND	0.2	0.1

As indicated on Figures 7.470 - 7.472, the highest mean total concentrations of organic compounds of organic compounds are observed in the southeastern and eastern areas of the landfill.

No non-qualified volatile, semi-volatile, or pesticide/herbicide/PCB organic compounds were consistently detected in the shallow/refuse monitoring zone of this landfill section. Tables 7.16B, 7.17B, and 7.18B provide a full delineation of all detected volatile, semi-volatile, and pesticide/herbicide/PCB organic compounds by well and monitoring quarter. PCBs were not detected at any well location

7.2.2.2 Intermediate Depth Monitoring Zone

As indicated by scatterplots (Figures 7.56-7.98) and boxplots (Figures 7.199-7.212), the majority of leachate indicator parameters and organic compounds exhibit a significant reduction in concentration (often several orders of magnitude) within the intermediate depth monitoring zone relative to the shallow/refuse monitoring zone. Exceptions relate to chloride and other seawater associated solutes (e.g., sodium and sulfate), which are discussed in detail for landfill Section 1/9 (Section 7.2.2.1). As for Section 1/9, the intermediate depth monitoring zone has been segregated

into two components for discussion purposes: a generally shallow Recent/glacial sand horizon, and a deeper Cretaceous sand horizon. In Section 2/8, the Recent/glacial sand monitoring zone consists only of one area of glacial sand. Data for selected parameters within the intermediate monitoring zone are compared with historical/literature data on Figures 7.263 through 7.268. Summary statistics for the general chemical indicator parameters are provided for each monitoring zone horizon below:

Landfill Section 2/8 Intermediate Depth (Glacial Sand) Monitoring Zone			
	Concentration (ug/L)		
Analyte	Minimum	Maximum	Median
Ammonia	20	9,860	431
TKN	200	13,300	5,300
COD	53,600	312,000	120,050
BOD5	2,000	101,000	2,000
TOC	30,300	207,000	77,250
Alkalinity	101,000	1,050,000	840,000
TDS	440,000	2,760,000	1,920,000
Chloride	88,000	1,160,000	549,000
Sulfate	18,900	65,500	41,700

Landfill Section 2/8 Intermediate Depth (Cretaceous Sand) Monitoring Zone			
	Concentration (ug/L)		
Analyte	Minimum	Maximum	Median
Ammonia	20	187	20
TKN	200	440	200
COD	5,000	36,000	5,460
BOD5	2,000	2,000	2,000
TOC	2,240	30,300	7,060
Alkalinity	78,000	310,000	120,000

Landfill Section 2/8 Intermediate Depth (Cretaceous Sand) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
TDS	72,000	800,000	202,000
Chloride	10,500	175,000	18,600
Sulfate	5,480	84,800	21,300

In general, these data indicate water quality degradation in the glacial sand horizon relative to the deeper Cretaceous unit. The concentrations of the solutes indicate little, if any, seawater mixing in this landfill section.

Within the glacial sand horizon at Section 2/8, data is available only from three wells in isolated lenses of glacial sand (2W91:IT308I1, 308I2, and 2W92:IT311I1). Ammonia concentration data indicates that only well 2W91:IT308I1 exceeds the NYSDEC criterion of 2,000 ug/L, and only sporadically (Figure 7.56). No wells in the Cretaceous sand horizon exceed the water quality criterion. The spatial distribution of mean ammonia data is indicated on Figures 7.444 and 7.452.

Similar to ammonia, biochemical and chemical oxygen demand, total kjeldahl nitrogen, total organic carbon, and alkalinity all are indicator parameters of organic acids and other organic matter. All of these parameters are elevated in the glacial sand horizon relative to the Cretaceous sand horizon (Figures 7.59, 7.60, 7.58, 7.61, 7.62). The spatial distribution of these parameters are indicated in Figures 7.443, 7.445, 7.448, 7.449, 7.450 (glacial sand) and Figures 7.451, 7.453, 7.456, 7.457, and 7.458 (Cretaceous sand).

Total dissolved solids and chloride concentrations are both much higher in the glacial sand horizon relative to the Cretaceous sand horizon. Only wells 2W91:IT308I1 and 308I2 exceed the NYSDEC water quality criterion of 250,000 ug/L for chloride. Spatial distribution of chloride is indicated on Figures 7.447 and 7.455.

Under the anaerobic conditions prevalent within the landfill, sulfate is chemically reduced to sulfide, generally resulting in low concentrations of this solute. As indicated in Figure 7.64, no intermediate depth wells have sulfate concentrations above the NYSDEC water quality standard.

The primary elemental inorganic leachate indicator parameters (sodium, calcium, and potassium) have higher concentrations in the glacial sand horizon than in the Cretaceous sand horizon, except for potassium (Figures7.81, 7.91, 7.94). Wells 2W91:IT308I1, 308I2, and 2W92:IT311I1 all exceed the NYSDEC water quality criterion of 20,000 ug/L for sodium (the other parameters are not regulated). Iron concentrations exceed water quality standards for all wells (Figure 7.86). Magnesium concentrations exceed water quality standards for wells 2W91:IT308I1, 308I2, and 2W92:IT311I1 (Figure 7.88). Barium concentrations sporadically exceed water quality standards for 2W91:IT308I1 and 308I2 (Figure 7.77). Manganese concentrations routinely exceed water quality standards for wells 2W91:IT305I, 308I1, 308I2, 2W92:IT311I1, and 309I (Figure 7.89). No wells exceed water quality standards for boron (Figure 7.79), chromium (Figure 7.82), copper (Figure 7.85), lead (Figure 7.87), nickel (Figure 7.90), or zinc (Figure 7.98).

Regulated trace elements (antimony, arsenic, beryllium, cadmium, hexavalent chromium, selenium, and silver) uniformly exhibit extremely low (and generally qualified) concentrations. No wells have concentrations of these elements that exceeds water quality criteria (Figures 7.75, 7.76, 7.78, 7.80, 7.83, 7.92, 7.93).

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 2/8 Intermediate Depth (Glacial Sand) Monitoring Zone			
	Concentration (ug/L)		
Analyte	**Minimum**	**Maximum**	**Median**
Sodium	37,900	552,000	339,500
Calcium	58,400	356,000	197,000
Potassium	610	13,500	5,940
Iron	2,200	17,600	9,250
Manganese	176	8,990	3,350
Magnesium	36,800	91,600	57,100
Barium	114	2,700	833
Boron	36.8	928	776
Chromium	2	19.3	2

Landfill Section 2/8 Intermediate Depth (Glacial Sand) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Copper	4.4	79.4	12
Lead	1	10.1	1
Nickel	12.2	57.8	29.0
Zinc	9.3	74.9	40.2

Landfill Section 2/8 Intermediate Depth (Cretaceous Sand) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Sodium	10,100	24,800	14,800
Calcium	18,000	123,000	40,400
Potassium	1,460	18,600	4,360
Iron	872	14,400	3,830
Manganese	37.4	437	249
Magnesium	2,530	12,100	7,560
Barium	85.5	322	187
Boron	18.5	87.4	38.4
Chromium	2	47.9	5
Copper	2	27.3	2.8
Lead	1	5.1	1

Landfill Section 2/8 Intermediate Depth (Cretaceous Sand) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Nickel	14	28.9	5
Zinc	1	43.9	10.4

As indicated on the total organic compounds scatterplot (Figure 7.61A) and the organic group bar charts (Figures 7.402 - 7.404), the occurrence of organic compounds as a whole in the intermediate depth monitoring zone is minimal for detected concentrations and sporadic for non-qualified data, with only two wells that exceed the NYSDEC criterion for total organic compounds of 100 ug/L for one sampling quarter each (2W91:IT306I1 and 2W92:IT311I2). In review of the chart presentations and the spatial distribution maps (Figures 7.479 - 7.484), it should be noted that detected concentrations (indicated as mean total concentrations) often represent a single occurrence that was not repeated in subsequent sampling events. Therefore, these graphics tend to portray a wider distribution of organic compounds than may reliably be considered to exist. This is evident through review of Tables 7.19B through 7.21B, which summarize all detected organic compounds.

The focus of this discussion is on those few constituents that repeatedly occur as non-qualified concentrations at specific locations. As indicated through review of all referenced tabular and graphic presentations, even in these cases the concentration distribution of non-qualified organic compounds is uniformly low within both the glacial and Cretaceous sand horizons.

At Section 2/8, the presence of organic compounds is widespread, but at extremely low concentrations within the two intermediate monitoring zones; this landfill section exhibits the lowest diversity in detected compounds, and exhibits very low mean total concentrations. Summary statistics of the mean total organic compound groups are summarized below:

Landfill Section 2/8 Intermediate Depth (Glacial Sand) Monitoring Zone			
Compound Group	Mean Total Concentration (ug/L)		
	Minimum	Maximum	Median
Volatiles	3	4	3
Semivolatiles	ND	5	3
Pesticides/Herbicides/PCBs	ND	0.1	ND

Landfill Section 2/8 Intermediate Depth (Cretaceous Sand) Monitoring Zone			
Compound Group	Mean Total Concentration (ug/L)		
	Minimum	Maximum	Median
Volatiles	ND	31	1
Semivolatiles	ND	94	2
Pesticides/Herbicides/PCBs	ND	0.1	ND

As indicated on Figures 7.479 - 7.484, the spatial distribution of the organic compound concentrations shows no distinct patterns. The total volatile compounds for well 2W92:IT311I2 is the only mean concentration of over 10 ug/L. Only two wells, 2W91:IT308I1 and 307I, have pesticide/herbicide/PCB mean concentrations of above detection.

No non-qualified volatile, semi-volatile, or pesticide/herbicide/PCB organic compounds were consistently detected in the intermediate depth monitoring zone of this landfill section. Tables 7.19B through 7.21B provide a full delineation of all detected volatile, semi-volatile, and pesticide/herbicide/PCB organic compounds by well and monitoring quarter. No PCBs were detected at Section 2/8.

7.2.2.3 Deep (Bedrock) Monitoring Zone

As indicated by scatterplots (Figures 7.56-7.98) and boxplots (Figures 7.199-7.212), the majority of leachate indicator parameters and organic compounds typically exhibit very low concentrations

within the deep monitoring zone relative to the shallow/refuse monitoring zone. Exceptions relate to chloride and other seawater parameters for some wells (e.g., sodium and sulfate), and the presence of 2-butanone and toluene. Summary statistics for the general chemical indicator parameters are provided below:

Landfill Section 2/8 Deep (Bedrock) Monitoring Zone			
	Concentration (ug/L)		
Analyte	Minimum	Maximum	Median
Ammonia	20	1,250	20
TKN	200	3,520	200
COD	4,120	171,000	7,860
BOD5	2,000	24,000	2,000
TOC	1,000	28,700	7,010
Alkalinity	42,000	1,160,000	109,000
TDS	86,000	4,900,000	330,000
Chloride	6,500	3,110,000	32,000
Sulfate	1,730	46,000	14,300

In general, these data indicate that the median concentrations of leachate indicator parameters are much lower in the deep monitoring zone than for the intermediate and shallow/refuse monitoring zones. The concentrations of the solute indicate only minor seawater mixing in this landfill section.

Within the deep monitoring zone at Section 2/8, ammonia concentration data indicate that no wells exceed the NYSDEC criterion of 2000 ug/L (Figure 7.56). Similar to ammonia, biochemical and chemical oxygen demand, total kjeldahl nitrogen, total organic carbon, and alkalinity all are indicator parameters of organic acids and other organic matter. All of these parameters have concentrations well below the other monitoring zones except for wells 2W91:IT301D and 303D (Figures 7.59, 7.60, 7.58, 7.61, 7.62). The spatial distribution of these parameters are indicated in Figures 7.459, 7.460, 7.461, 7.464, 7.465 and 7.466. These maps

indicate that the highest concentrations of these parameters occur in the northern section of this landfill. Wells 2W91:IT301D and 303D usually have the highest concentrations.

Only wells 2W91:IT301D and 302D consistently exceed the NYSDEC water quality criterion of 500,000 ug/L for total dissolved solids and 250,000 ug/L for chloride. The spatial distribution of chloride is indicated on Figure 7.463 and shows that well 2W91:IT303D may be part of a seawater mixing zone that extends into Section 6/7 of the landfill.

Under the anaerobic conditions prevalent within the landfill, sulfate is chemically reduced to sulfide, generally resulting in low concentrations of this solute. As indicated in Figure 7.64, no deep wells exhibit sulfate concentrations in excess of the NYSDEC water quality standard.

The concentrations of the primary elemental inorganic leachate indicator parameters (sodium, calcium, and potassium) are typically slightly higher in the deep monitoring zone than in the intermediate monitoring zone (Figures7.81, 7.91, 7.94). Wells 2W91:IT301D, 303D, and 311D routinely exceed the NYSDEC water quality criterion of 20,000 ug/L for sodium (the other parameters are not regulated); further evidence that wells 303D and 301D may be in zones of seawater mixing. Iron concentrations exceed water quality standards for all wells (Figure 7.86). Coupled with the low total dissolved solids of these wells, it seems likely that iron-bearing minerals within the aquifer are the source of iron. Manganese concentrations sporadically exceed water quality standards with only well 2W91:IT301D routinely exceeding the standard (Figure 7.89). No wells routinely exceed the water quality criterion for magnesium (Figure 7.88), barium (Figure 7.77), or lead (Figure 7.87) except for well 2W91:IT301D. No wells exceed water quality standards for boron (Figure 7.79), chromium (Figure 7.82), copper (Figure 7.85), nickel (Figure 7.90), or zinc (Figure 7.98).

Regulated trace elements (antimony, arsenic, beryllium, cadmium, hexavalent chromium, selenium, and silver) uniformly exhibit extremely low (and generally qualified) concentrations. No wells have concentrations of these elements that exceed water quality criteria (Figures 7.75, 7.76, 7.78, 7.80, 7.83, 7.92, 7.93).

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 2/8 Deep (Bedrock) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Sodium	9,930	968,000	20,250
Calcium	3,450	452,000	28,900
Potassium	1,780	202,000	13,000
Iron	138	43,900	2,265
Manganese	3.6	2,990	99.2
Magnesium	600	54,500	6,960
Barium	13.9	2,380	248
Boron	18.8	562	165
Chromium	2	693	5
Copper	1	87.2	2.5
Lead	1	183	1
Nickel	2	2,870	15
Zinc	1	408	19.3

As indicated on the Total Organic Compounds scatterplot (Figure 7.61A) and the organic group bar charts (Figures 7.402 - 7.404), the occurrence of organic compounds as a whole in the deep monitoring zone is minimal for detected concentrations and sporadic for non-qualified data, with six wells sporadically exceeding the NYSDEC criterion for total organic compounds of 100 ug/L for one sampling quarter each (2W91:IT302D, 303D, 304D, 305D, 306D, and 307D). In review of the chart presentations and the spatial distribution maps (Figures 7.479 - 7.484), it should be noted that detected concentrations (indicated as mean total concentrations) often represent a single occurrence that was not repeated in subsequent sampling events. Therefore, these graphics tend to portray a wider distribution of organic compounds than may reliably be considered to exist. This is evident through review of Tables 7.19B through 7.21B, which summarize all detected organic compounds. Significantly, the detected and estimated concentrations of volatile organic compounds for deep wells is much higher than observed in the shallow refuse zone, and is

associated with the presence of 2-butanone and toluene. Summary statistics of the mean total organic compound groups are summarized below:

Landfill Section 2/8 Deep (Bedrock) Monitoring Zone			
Compound Group	Mean Total Concentration (ug/L)		
	Minimum	Maximum	Median
Volatiles	1	1,317	39
Semivolatiles	ND	28	ND
Pesticides/Herbicides,PCBs	ND	0.2	ND

As indicated on Figures 7.479 - 7.484, the spatial distribution of the organic compound concentrations shows a distinct pattern only for the volatile organic compounds. The only consistently detected non-qualified volatile organic compound found was 2-butanone although toluene is also present in elevated concentrations. No semi-volatile or pesticide/herbicide/PCB organic compounds were consistently detected in the deep monitoring zone. Spatial distribution maps of 2-butanone and toluene show that wells 2W91:IT303D, 305D, and 302D all have elevated concentrations of 2-butanone. 2W91:IT305D also has a relatively high concentration of toluene. Tables 7.19B - 7.21B provide a full delineation of all detected volatile, semi-volatile, and pesticide/herbicide/PCB organic compounds by well and monitoring quarter. PCBs were not detected in any monitoring well at Section 2/8. As noted in the Landfill Section 1/9 discussion, the presence of 2-butanone and toluene in a series of bedrock wells at Section 2/8 is not believed to be reflective of vertical leachate migration based on the geochemical and hydrogeological database.

7.2.2.4 Temporal Relationships

Figures 7.490 - 7.502A are box plots for selected typical leachate indicator parameters. In these figures, data from the current groundwater quality investigation are compared with data collected from a series of water quality samples obtained in 1982. Data from the intermediate monitoring zone (Cretaceous sand unit) are presented for Section 2/8. Using these figures, existing water quality data may be compared to historical data, providing insight into changes in water quality

through time at Section 2/8. An examination of Figures 7.490 - 7.502A shows that for the locations where data are available (Table 7.15) water quality in the Cretaceous sand units has not changed noticeably since 1982. Specifically, concentrations of alkalinity, ammonia, BOD, chloride, COD, sulfate, TDS, TKN, and TOC as measured in the current sampling program are generally equal to or less than concentrations measured in 1982.

A comparison of seasonal variation of selected general chemical and inorganic parameters was performed for the shallow/refuse, intermediate, and deep monitoring zones at Landfill Section 2/8. Box plots of seasonal data are contained in Attachment 34. Apparent seasonal variation at Fresh Kills is most pronounced at Section 2/8, with the highest degree of variation occurring in the fall sampling quarter. In the shallow/refuse zone, alkalinity, ammonia, BOD, sulfide, TKN, TOC, boron potassium, and sodium all exhibit maximum variation and highest median values in the fall sampling event. Conversely, sulfate, chromium, cobalt, iron, and manganese show the lowest median values and lowest variability in the fall sampling rounds. Two analytes exhibit annual variation. Chloride shows a trend of increasing median values and variation from winter to fall. Median values and variation for lead decrease throughout this same period. Some seasonal variation is also noted in the intermediate depth monitoring zone at Section 2/8. Variability is highest in the spring and summer quarters for alkalinity, chloride, boron, calcium, and sodium. Variability of hardness and TKN values was significantly lower in the fall. Variability in sulfide and cobalt is highest in the spring and summer, respectively. Variability of TOC and zinc is highest in the winter. Median value and variation are highest in the winter quarters for turbidity, and lead. Several significant seasonal differences in sample variability were noted in the deep (bedrock) monitoring zone. Variability was highest in the winter months for turbidity, calcium, cobalt, iron, lead, manganese, and zinc. A similar trend is noted in spring data for TDS and sodium. The significant seasonal variability observed in the shallow/refuse monitoring zone at Section 2/8 is probably the result of the limited quantity of shallow wells installed in the fall of 1991 at that landfill (and their location relative to the refuse mound) versus the fall of 1992.

7.2.3 Landfill Section 3/4

The following discussion identifies trends in the data and notes where exceedances of groundwater quality standards and criteria are prevalent for landfill Section 3/4. Figures 7.99 - 7.141 provide full specificity for all general chemical and inorganic constituents, and total organic

compounds. Tables 7.9 through 7.11 specifically indicate exceedences of groundwater quality standards and criteria by well for most regulated general chemical and inorganic parameters, and Tables 7.16C through 7.21C provide similar information for the organic compounds, indicating all detected values for these constituents.

7.2.3.1 Shallow/Refuse Monitoring Zone

Virtually all of the general chemical leachate indicator parameters occur at elevated concentrations in the shallow/refuse monitoring zone at Landfill Section 3/4, with the exception of those constituents that would be expected to exhibit low concentration ranges within the predominantly anaerobic landfill environment (e.g., sulfate and nitrate). As indicated on Figures 7.241 - 7.246, the leachate at Landfill Section 3/4 exhibits the second highest strength relative to these constituents compared to the other landfill sections within the Fresh Kills Landfill. Summary statistics for the primary indicator parameters are provided below:

Landfill Section 3/4 Shallow/Refuse Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Ammonia	28,500	2,980,000	312,500
TKN	52,000	7,400,000	412,000
COD	58,500	2,850,000	531,000
BOD5	2,000	288,000	20,550
TOC	28,000	1,100,000	267,000
Alkalinity	196,000	7,680,000	2,660,000
TDS	780,000	7,580,000	2,940,000
Chloride	86,800	3,170,000	855,000
Sulfate	1,000	193,000	6,960

All shallow wells exceed the NYDEC water quality standard of 2,000 ug/L for ammonia. As indicated on Figure 7.428, the concentration of ammonia, although it does not exhibit great variation, is generally highest in the eastern area (3W91:IT404S and 3W92:IT420S) of the landfill section. The highest concentration occurs at 3W92:IT420S.

Similar to ammonia, which is formed in the landfill environment primarily through the anaerobic process of ammonification of organic matter, a series of indicator parameters measure the presence of organic acids and other organic matter in groundwater. These parameters are biochemical and chemical oxygen demand, total kjeldahl nitrogen, total organic carbon, and alkalinity. The distributions of biochemical oxygen demand (Figure 7.427), total kjeldahl nitrogen (Figure 7.433), and alkalinity (Figure 7.427) are similar to that identified for ammonia. Unlike ammonia, chemical oxygen demand and total organic carbon are highest on the western side of the landfill section (3W92:IT427S and 3W91:IT408S). The cause of this unusual distribution is unknown.

Total dissolved solids represents a gross measure of leachate contamination, and is linked in its concentration distribution with chloride (a major dissolved solute comprising TDS in the landfill environment). Except where they are influenced by the presence of seawater (as discussed for the intermediate depth monitoring zone for Section 1/9), these analytes mirror the concentration distribution for total organic carbon and chemical oxygen demand, as indicated on Figure 7.431. The highest concentration of chloride is found in the southwestern and southeastern areas of the landfill at 3W92:IT427S and 423S, respectively.

Under the anaerobic conditions prevalent within the landfill, sulfate is chemically reduced to sulfide, generally resulting in low concentrations of this solute. As indicated on Figure 7.107, this is primarily the case at Section 3/4, with no wells exceeding the NYSDEC Water Quality Standard of 250,000 ug/L.

The primary elemental inorganic leachate indicator parameters (sodium, calcium, and potassium) are all present at elevated concentrations in the shallow/refuse monitoring zone (Figures 7.137, 7.124, and 7.134, respectively). All wells exceed the NYSDEC water quality criterion of 20,000 ug/L for sodium (the other parameters are not regulated). Iron, magnesium, and boron also exceed water quality standards for all wells, as indicated on Figures 7.129, 7.131, and 7.122. Barium (Figure 7.120) routinely exceeds the NYSDEC water quality criterion of 1000 ug/L

except at wells 3W91:IT403S, 3W92:IT412S, and 415S, and sporadically exceeds the criterion for wells 3W91:IT403S, 3W92:IT417S and 425S.

Chromium (Figure 7.125), copper (Figure 7.128), lead (Figure 7.130), manganese (Figure 7.132) and zinc (Figure 7.141) only sporadically exceed NYDEC water quality criteria; many of the detected values are qualified, and the distribution shows no distinct spatial pattern. The sporadic nature of the water quality exceedences likely reflects turbidity in the samples. No well samples exceed water quality criteria for nickel (Figure 7.90). Regulated trace elements (antimony, arsenic, beryllium, cadmium, hexavalent chromium, selenium, and silver) uniformly exhibit extremely low (and generally qualified) concentrations (Figures 7.118, 7.119, 7.121, 7.123, 7.126, 7.135, 7.136). The only non-qualified exceedence of water quality standards for these elements occur at well 3W91:401S and 406S (cadmium) and 3W91:IT406S (arsenic). It should be noted that these exceedences are not routine and usually are limited to one sampling quarter, indicative of turbidity in the sample.

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 3/4 Shallow/Refuse Monitoring Zone			
	Concentration (ug/L)		
Analyte	**Minimum**	**Maximum**	**Median**
Sodium	58,000	2,330,000	835,000
Calcium	28,900	370,000	112,000
Potassium	21,000	565,000	183,000
Iron	4,290	121,000	17,300
Manganese	18.1	1,200	150
Magnesium	34,600	122,000	67,700
Barium	491	4,100	1,700
Boron	634	6,770	3,680
Chromium	2	521	24.8

Landfill Section 3/4 Shallow/Refuse Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Copper	2	618	8.3
Lead	1	3,000	9.6
Nickel	4	160	23.6
Zinc	3	3,800	32.8

As indicated on the Total Organic Compounds scatterplot (Figure 7.104A) and the organic group bar charts (Figures 7.405 - 7.407), the occurrence of organic compounds as a whole in the shallow/refuse monitoring zone is minimal for detected concentrations and sporadic for non-qualified data, with three wells slightly exceeding the NYSDEC criterion for total organic compounds of 100 ug/L (3W91:IT402S, 404S, 3W92:IT419S). Only wells 3W92:IT433S significantly exceed the NYSDEC criterion. In review of the chart presentations and the spatial distribution maps, it should be noted that detected concentrations (indicated as mean total concentrations) often represent a single occurrence that was not repeated in subsequent sampling events. Therefore, these graphics tend to portray a wider distribution of organic compounds than may reliably be considered to exist. This is evident through review of Tables 7.16C through 7.18C, which summarize all detected organic compounds.

The focus of this discussion is on those few constituents that repeatedly occur as non-qualified concentrations at specific locations. As indicated through review of all referenced tabular and graphic presentations, even in these cases the concentration distribution of non-qualified organic compounds is uniformly low within the shallow/refuse monitoring zone "source area".

At Section 3/4, the presence of organic compounds is fairly widespread within the shallow/refuse monitoring zone; this landfill section exhibits a low diversity in detected compounds, and exhibits a relatively low mean total concentration. Summary statistics of the mean total organic compound groups are summarized below:

Landfill Section 3/4 Shallow/Refuse Monitoring Zone			
Compound Group	Mean Total Concentration (ug/L)		
	Minimum	Maximum	Median
Volatiles	ND	45	9
Semivolatiles	ND	303	9
Pesticides/Herbicides/PCBs	ND	0.3	ND

As indicated on Figures 7.473 - 7.475, the spatial concentration distribution of the organic compounds is similar to that noted earlier for the general chemical indicator parameters, with the highest mean total concentrations observed in the southeast and west areas of the landfill.

Only two non-qualified volatile and one semi-volatile compound were detected in the shallow/refuse monitoring zone. The non-qualified volatile organic compounds detected were chlorobenzene, with a maximum concentration of 25 ug/L, and benzene, with a maximum concentration of 14 ug/L. The only non-qualified semi-volatile organic compound detected was naphthalene, with a maximum concentration of 40 ug/L. No non-qualified pesticides or herbicide were consistently detected in the shallow/refuse monitoring zone of this landfill section. PCBs were not detected in any well samples. Tables 7.16C, 7.17C, and 7.18C provide a full delineation of all detected organic compounds by well and monitoring quarter.

7.2.3.2 Intermediate Depth Monitoring Zone

As indicated by scatterplots (Figures 7.99-7.141) and boxplots (Figures 7.279-7.294), the majority of leachate indicator parameters and organic compounds exhibit a significant variation in concentrations for each well location (often several orders of magnitude), ranging from concentrations similar to that in the shallow/refuse monitoring zone to concentrations similar to that in the deep monitoring zone. Exceptions relate to chloride and other seawater associated solutes (e.g., sodium and sulfate), which are discussed in detail for landfill Section 1/9 (Section 7.2.2.1). Both chloride and sulfate are typically higher in the intermediate depth monitoring zone

that in the shallow/refuse monitoring zone, suggesting a seawater mixture. Unlike the other landfill sections, only the Recent/glacial sand horizon exists within the intermediate depth monitoring zone at Section 3/4. Data for selected parameters are compared with historical/literature data in the boxplots (Figures 7.279-7.294). Summary statistics for the general chemical indicator parameters are provided for each monitoring zone horizon below:

Landfill Section 3/4 Intermediate Depth (Recent/Glacial Sand) Monitoring Zone			
	Concentration (ug/L)		
Analyte	Minimum	Maximum	Median
Ammonia	20	397,000	1,430
TKN	200	768,000	4,220
COD	7,670	644,000	150,000
BOD5	2,000	384,000	7,450
TOC	1,000	347,000	29,400
Alkalinity	58,000	2,880,000	590,000
TDS	106,000	21,500,000	6,495,000
Chloride	15,500	18,000,000	2,950,000
Sulfate	2,110	1,350,000	59,500

In general, these data indicate water quality degradation in the Recent/glacial sand horizon. The concentrations of chloride, sodium, and sulfate (important seawater indicator parameters) suggests degradation of water quality in some area due to a complex mixture of leachate and seawater.

Both Recent Sand horizon Unit 1 and isolated lenses of glacial sand are present within this landfill section. Ammonia concentration data indicates that all the wells sporadically exceed the NYSDEC criterion of 2000 ug/L (Figure 7.99). As discussed below, most of the other organic matter indicators are also found at elevated concentrations. The spatial distribution of mean ammonia data is indicated on Figure 7.444.

Similar to ammonia, biochemical and chemical oxygen demand, total kjeldahl nitrogen, total organic carbon, and alkalinity all are indicator parameters of organic acids and other organic matter. All of these parameters are sporadically elevated in the Recent/glacial sand horizon (Figures 7.102, 7.103, 7.101, 7.104, 7.105). The spatial distribution of these parameters are indicated in Figures 7.443, 7.445, 7.448, 7.449, 7.450.

Total dissolved solids and chloride concentrations are both sporadically higher in the Recent/Glacial sand horizon relative to the shallow/refuse monitoring zone. This suggests a possible seawater influence in this section. Only wells 3W91:IT404I and AW90:AK13I do not follow this pattern. All wells exceed the NYSDEC water quality criterion of 250,000 ug/L for chloride. Spatial distribution of chloride is indicated on Figures 7.447 and 7.455.

Under the anaerobic conditions prevalent within the landfill, sulfate is chemically reduced to sulfide, generally resulting in low concentrations of this solute. However, the median value of sulfate is higher in the intermediate monitoring zone relative to the shallow/refuse monitoring zone and wells AW90:AK13S and AK13I sporadically exceed the NYSDEC water quality standard (Figure 7.107).

The primary elemental inorganic leachate indicator parameters (sodium, calcium, and potassium) have higher concentrations in the intermediate monitoring zone than in the shallow/refuse monitoring zone for sodium (except wells 3W91:IT404I and AW90:AK13I) and calcium (Figures7.137, 7.124, 7.134). All wells exceed the NYSDEC water quality criterion of 20,000 ug/L for sodium (the other parameters are not regulated). Except for 3W91:IT405I1, iron concentrations exceed water quality standards for all wells (Figure 7.129). Magnesium concentrations also routinely exceed water quality standards for all wells (Figure 7.131). Boron concentrations exceed water quality standards for all wells except 3W91:IT404I,405I2 and AW90:AK13I (Figure 7.122). Barium concentrations sporadically exceed water quality standards for all wells but 3W91:IT404I and 434I (Figure 7.120). Manganese concentrations exceed water quality standards for wells 3W91:IT404I, 405I2, and AW90:AK13I, and sporadically exceed standards for wells 3W91:IT406I and AW90:AK13S (Figure 7.132). Lead concentrations sporadically exceed the water quality criterion at well AW90:AK13I (Figure 7.139). Chromium concentrations periodically exceed the water quality criterion at wells AW90:AK13S and AK13I. No wells exceed water quality standards for copper (Figure 7.128), nickel (Figure 7.133), or zinc (Figure 7.141). Most of the sporadic exceedences are probably due to turbidity (Figure 7.114).

Regulated trace elements (antimony, arsenic, beryllium, cadmium, hexavalent chromium, selenium, and silver) uniformly exhibit extremely low (and generally qualified) concentrations. No wells have concentrations of antimony (Figure 7.118), hexavalent chromium (Figure 7.126), selenium (Figure 7.135), or silver (7.136) that exceed water quality criteria. Water quality standards are sporadically exceeded for cadmium (AW90:AK13S), beryllium (AW90:AK13I), and arsenic (AW90:AK13S) (Figures 7.119, 7.121, 7.123). As above, most of these sporadic exceedences are probably due to turbidity.

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 3/4 Intermediate Depth (Recent/Glacial Sand) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Sodium	13,300	7,820,000	1,530,000
Calcium	17,700	970,000	273,500
Potassium	6,560	285,000	53,400
Iron	133	142,000	5,210
Manganese	7.1	10,000	613
Magnesium	1,020	792,000	151,000
Barium	15.6	1,750	858
Boron	23.9	4,520	639
Chromium	2	219	5.1
Copper	2	190	18.3
Lead	1	1,240	4.8
Nickel	2	200	11
Zinc	3	1,780	47.9

As indicated on the Total Organic Compounds scatterplot (Figure 7.104A) and the organic group bar charts (Figures 7.405 - 7.407), the occurrence of organic compounds as a whole in the

intermediate depth monitoring zone is minimal for detected concentrations and sporadic for non-qualified data, with two wells sporadically exceeding the NYSDEC criterion for total organic compounds of 100 ug/L (3W92:IT405I1 and 406I), most of which is volatile organic compounds. In review of the chart presentations and the spatial distribution maps (Figures 7.479 - 7.481), it should be noted that detected concentrations (indicated as mean total concentrations) often represent a single occurrence that was not repeated in subsequent sampling events. Therefore, these graphics tend to portray a wider distribution of organic compounds than may reliably be considered to exist. This is evident through review of Tables 7.19C through 7.21C, which summarize all detected organic compounds.

The focus of this discussion is on those few constituents that repeatedly occur as non-qualified concentrations at specific locations. As indicated through review of all referenced tabular and graphic presentations, even in these cases the concentration distribution of non-qualified organic compounds is uniformly low within the intermediate depth monitoring zone.

This landfill section exhibits the greatest diversity of organic compounds detected within the Recent/glacial sand horizon of all landfill sections, although mean total concentrations are low. Summary statistics of the mean total organic compound groups are summarized below:

Landfill Section 3/4 Intermediate Depth (Recent/Glacial Sand) Monitoring Zone			
	Mean Total Concentration (ug/L)		
Compound Group	**Minimum**	**Maximum**	**Median**
Volatiles	2	55	11
Semivolatiles	ND	31	7
Pesticides/Herbicides/PCBs	ND	0.3	ND

As indicated on Figures 7.479- 7.481, the location of the highest mean concentration for each of the three groups of organic compounds varies. The mean concentration of volatile organic compounds is highest in the southern part of this landfill section. Semi-volatile concentrations are highest in the northeastern part of the landfill section (3W92:IT434I). The concentration of pesticides and herbicides is higher on the western side of Section 3/4. No PCBs compounds were detected at Section 6/7

With the exception of carbon disulfide at well 3W91:IT405I1 and xyxlene at well AW90:AK13I, no non-qualified volatile, semi-volatile, or pesticide/herbicide organic compounds were consistently detected in the shallow/refuse monitoring zone of this landfill section. Tables 7.19C - 7.21C provide a full delineation of all detected organic compounds by well and monitoring quarter.

7.2.3.3 Deep (Bedrock) Monitoring Zone

As indicated by scatterplots (Figures 7.99-7.141) and boxplots (Figures 7.343-7.358), the majority of leachate indicator parameters and organic compounds have concentrations much lower than for the intermediate and shallow/refuse monitoring zones. Exceptions relate to chloride and volatile organic compounds. Summary statistics for the general chemical indicator parameters for the deep monitoring zone are provided below:

Landfill Section 3/4 Deep (Bedrock) Monitoring Zone			
	Concentration (ug/L)		
Analyte	**Minimum**	**Maximum**	**Median**
Ammonia	20	421	102
TKN	200	1,070	270.5
COD	5,000	188,000	6,400
BOD5	2,000	52,000	2,000
TOC	1,000	33,500	3,370
Alkalinity	6,000	226,000	82,000
TDS	40,000	6,520,000	360,000
Chloride	5,500	2,590,000	64,700
Sulfate	3,710	110,000	18,350

In general, these data indicate that the concentrations of leachate indicator parameters in the deep monitoring zone are much lower relative to the intermediate and shallow/refuse monitoring zone.

The concentrations of chloride and sodium (important seawater indicator parameters) suggest some minor seawater mixing.

Ammonia concentration data indicates that no wells exceed the NYSDEC criterion of 2000 ug/L (Figure 7.99). The spatial distribution of mean ammonia data is indicated on Figure 7.460. Similar to ammonia, biochemical and chemical oxygen demand, total kjeldahl nitrogen, total organic carbon, and alkalinity all are indicator parameters of organic acids and other organic matter. All of these parameters are have relatively low concentrations (Figures 7.102, 7.103, 7.101, 7.104, 7.105). The spatial distribution of these parameters are indicated in Figures 7.459, 7.461, 7.464, 7.465, 7.466. No significant trends exist other than all concentrations are low.

Total dissolved solids and chloride concentrations have relatively low concentrations. Only wells 3W91:IT409D and 407D exceed the NYSDEC water quality criterion of 250,000 ug/L for chloride. The spatial distribution of chloride is indicated on Figure 7.463. No wells exceed the NYSDEC water quality standard for sulfate (Figure 7.107).

The primary elemental inorganic leachate indicator parameters (sodium, calcium, and potassium) have highly variable concentrations in the deep monitoring zone (Figures 7.137, 7.124, 7.134). Well 3W91:IT409D has relatively elevated concentrations of both sodium and calcium. All wells exceed the NYSDEC water quality criterion of 20,000 ug/L for sodium (the other parameters are not regulated). Iron concentrations exceed water quality standards for all wells (Figure 7.129) and manganese sporadically exceeds water quality standards (Figure 7.132). As all other solute concentrations are low, minerals within the aquifer are the probable source of iron/manganese. An additional source of these solutes is turbidity in the samples. Magnesium concentrations do not exceed water quality standards except for well 3W92:IT409D (Figure 7.131). Barium concentrations do not exceed water quality standards except for well 3W92:IT407D (Figure 7.120). No wells exceed water quality standards for boron, chromium, copper, lead, nickel, or zinc (Figure 7.122, 7.139, 7.125, 7.128, 7.133, 7.141).

Regulated trace elements (antimony, arsenic, beryllium, cadmium, hexavalent chromium, selenium, and silver) uniformly exhibit extremely low (and generally qualified) concentrations. No wells have concentrations that routinely exceed water quality standards for these elements (Figures 7.118, 7.126, 7.135, 7.136, 7.119, 7.121, 7.123). Most of these sporadic exceedences are probably due to turbidity.

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 3/4 Deep (Bedrock) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Sodium	25,500	376,000	57,000
Calcium	5,470	730,000	18,800
Potassium	3,040	51,000	6,955
Iron	269	191,000	2,445
Manganese	18.1	9,420	214
Magnesium	503	145,000	2,910
Barium	13.9	2,380	248
Boron	18.8	562	165
Chromium	2	624	4
Copper	1	1,760	3.3
Lead	1	105	1
Nickel	2	597	5
Zinc	1	1,460	29.1

As indicated on the total organic compounds scatterplot (Figure 7.104A) and the organic group bar charts (Figures 7.405 - 7.407), the occurrence of organic compounds as a whole in the deep monitoring zone is minimal for detected concentrations and sporadic for non-qualified data, with one well sporadically exceeding the NYSDEC criterion for total organic compounds of 100 ug/L (3W92:IT409D), most of which is volatile organic compounds. In review of the chart presentations and the spatial distribution maps (Figures 7.485- 7.489), it should be noted that detected concentrations (indicated as mean total concentrations) often represent a single occurrence that was not repeated in subsequent sampling events. Therefore, these graphics tend to portray a wider distribution of organic compounds than may reliably be considered to exist. This is evident through review of Tables 7.19C through 7.21C, which summarize all detected organic compounds.

The focus of this discussion is on those few constituents that repeatedly occur as non-qualified concentrations at specific locations. As indicated through review of all referenced tabular and graphic presentations, even in these cases the concentration distribution of non-qualified organic compounds is uniformly low within the bedrock monitoring zone, with two exceptions (3W91:IT404D, 3W92:IT409D).

This landfill section exhibits a low diversity of detected compounds, and exhibits a low mean total concentration. Summary statistics of the mean total organic compound groups are summarized below:

Landfill Section 3/4 Deep (Bedrock) Monitoring Zone			
	Mean Total Concentration (ug/L)		
Compound Group	Minimum	Maximum	Median
Volatiles	ND	303	1
Semivolatiles	ND	38	1
Pesticides/Herbicides/PCBs	ND	0.2	ND

As indicated on Figures 7.485-7.489, wells 3W91:IT404D and 3W92:IT409D exhibit relatively high organic compound concentrations and these are represented primarily by the volatile organic compounds 2-butanone and toluene. No other non-qualified volatile, semi-volatile, or pesticide/herbicide/PCB organic compounds were consistently detected in the deep monitoring zone of this landfill section. Tables 7.19C - 7.21C provide a full delineation of all detected volatile, semi-volatile, and pesticide/herbicide/PCB organic compounds by well and monitoring quarter. As noted in previous discussion, 2-butanone and toluene are believed to be associated with an off-site source, as the geochemical and hydrogeological data does not support their presence through vertical leachate migration.

7.2.3.4 Temporal Relationships

Figures 7.490-7.502A are box plots for selected typical leachate indicator parameters. In these figures, data from the current groundwater quality investigation are compared with data collected from water quality sampling conducted in 1982. Data from the intermediate depth monitoring

zone (Recent sand) are presented for Section 3/4 (Table 7.15). Using these figures, existing water quality data can be compared to historical data, thus providing insight into changes in water quality through time at Section 3/4. Examination of Figures 7.490 - 7.502A shows that in Recent sands along the eastern boundary of the landfill, water quality has been degraded over the past ten years. Specifically, concentrations of alkalinity, ammonia, barium, chloride, TDS, and TKN as measured in the current sampling program are generally much higher than those measured in 1982.

A comparison of seasonal variation of selected general chemical and inorganic parameters was performed for the shallow/refuse, intermediate, and deep (bedrock) monitoring zones at Landfill Section 3/4. Box plots of seasonal data are contained in Attachment 34. A review of these box plots indicates that there is some degree of seasonal variation in the data for the shallow/refuse, intermediate, and deep zones. Some seasonal variation is observed in the shallow/refuse zone where BOD, chloride, and turbidity, achieve their highest median values in the fall sampling quarters. Chromium and zinc exhibit their highest degree of variability in winter. Lead and magnesium exhibit decreasing median values in the winter sampling events. Within the intermediate monitoring zone, variability in the data for sulfate, sulfide, chromium, cobalt, iron, lead, and zinc appear to be significantly higher in the winter sampling events. TKN data exhibit highest mean values and variation in the fall quarter. Variation in alkalinity data is lowest in the spring. median value and data variability are elevated for turbidity in the winter, and for COD in the winter and fall. The median value of TOC is elevated in the summer quarters, while the median value for BOD is reduced in the spring and summer. In the deep zone, variation in data for hardness and TKN is elevated in the summer and spring quarters, respectively. The median and variation for potassium are reduced in the spring sampling quarter.

7.2.4 Landfill Section 6/7

The following discussion identifies trends in the data and where exceedances of groundwater quality standards and criteria are prevalent for landfill Section 6/7. Figures 7.142 - 7.184 provide full specificity for all general chemical and inorganic constituents, and total organic compounds. Tables 7.12 - 7.14 specifically indicate exceedances of groundwater quality standards and criteria by well for most regulated general chemical and inorganic parameters, and Tables 7.16D - 7.21D

provide similar information for the organic compounds, indicating all detected values for these constituents.

7.2.4.1 *Shallow/Refuse Monitoring Zone*

Virtually all of the general chemical leachate indicator parameters occur at elevated concentrations in the shallow/refuse monitoring zone at Landfill Section 6/7, with the exception of those constituents that would be expected to exhibit low concentration ranges within the predominantly anaerobic landfill environment (e.g., sulfate and nitrate). As indicated on Figures 7.241 - 7.246, the leachate at Landfill Section 6/7 exhibits the third highest strength relative to these constituents compared to the other landfill sections within the Fresh Kills Landfill. Summary statistics for the primary indicator parameters are provided below:

Landfill Section 6/7 Shallow/Refuse Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Ammonia	326	1,060,000	204,500
TKN	1,060	1,860,000	310,000
COD	20,800	3,140,000	251,500
BOD5	2,000	420,000	17,900
TOC	189	761,000	172,000
Alkalinity	204,000	4,480,000	1,740,000
TDS	340,000	10,400,000	2,140,000
Chloride	52,000	4,830,000	740,000
Sulfate	1,000	412,000	3,925

With the exception of one well (6W91:IT152S), all shallow wells routinely exceed the NYDEC water quality standard of 2,000 ug/L for ammonia. Well 6W91:IT152S did exceed the groundwater quality standard for the July 1991, January1992, and July 1992 sampling quarters,

but was below the groundwater quality standard for the other three sampling quarters. As indicated on Figure 7.436, ammonia is relatively evenly distributed throughout the landfill section.

Similar to ammonia, which is formed in the landfill environment primarily through the anaerobic process of ammonification of organic matter, a series of indicator parameters measure the presence of organic acids and other organic matter in groundwater. These parameters are biochemical and chemical oxygen demand, total kjeldahl nitrogen, total organic carbon, and alkalinity. As would be expected, their concentration distribution is similar to that identified for ammonia, as indicated on Figures 7.437, 7.440, 7.441, 7.442, and 7.435, respectively. The concentrations of biochemical and chemical oxygen demand are slightly higher on the northwest side of the landfill section.

Total dissolved solids represents a gross measure of leachate contamination, and is linked in its concentration distribution with chloride (a major dissolved solute comprising TDS is the landfill environment). Figures 7.152 and 7.155 shows that the concentrations of chloride and total dissolved solids are routinely exceeded for wells 6W91:IT156D, 158D, 159D, 6W92:IT165D, and 167D.

Under the anaerobic conditions prevalent within the landfill, sulfate is chemically reduced to sulfide, generally resulting in low concentrations of this solute. As indicated on Figure 7.150, this is primarily the case at Section 6/7, with only one well occasionally exceeding the NYSDEC Water Quality Standard of 250,000 ug/L (6W92:IT152S).

The primary elemental inorganic leachate indicator parameters (sodium, calcium, and potassium) are all present at elevated concentrations in the shallow/refuse monitoring zone relative to natural freshwaters (Figures 7.180, 7.167, 7.177). All wells exceed the NYSDEC water quality criterion of 20,000 ug/L for sodium (the other parameters are not regulated). Iron and magnesium exceed water quality standards for all wells (Figures 7.172 and 7.174). Boron (Figure 7.165) exceeds the NYSDEC water quality criterion of 1,000 ug/L for all wells except for 6W91:IT152S. Barium (Figure 7.163) routinely exceeds the NYSDEC water quality criterion, but shows no distinct spatial pattern.

Chromium (Figure 7.168), copper (Figure 7.171), lead (Figure 7.173), manganese (Figure 7.175), and zinc (Figure 7.184) only sporadically exceed NYSDEC water quality criteria, and mostly for the YW series of wells. The sporadic nature of the water quality exceedences along with the fact that most exceedences occurred during the January 1991, July 1991, and January 1992 sampling quarters, suggests turbidity in the samples that was eliminated by a change in sampling protocol to dedicated pumps. No well samples have unqualified exceedences of water quality criteria for nickel (Figure 7.176). Regulated trace elements (antimony, arsenic, beryllium, cadmium, hexavalent chromium, selenium, and silver) uniformly exhibit extremely low (and generally qualified) concentrations. The only non-qualified exceedences of water quality standards for these elements occur at wells 6W89:YW5, YW7, and 6W91:IT161S (arsenic), and 6W89:YW5, YW7, YW10, 6W91:IT151S, and 152S (cadmium). It should be noted that these exceedences are not routine and usually are limited to one sampling quarter. This suggests that the exceedences reflects turbidity in the sample.

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 6/7 Shallow/Refuse Monitoring Zone			
	Concentration (ug/L)		
Analyte	Minimum	Maximum	Median
Sodium	56,300	2,420,000	516,000
Calcium	26,900	750,000	74,100
Potassium	13,400	421,000	110,000
Iron	1,840	329,000	14,150
Manganese	18.5	2,670	105
Magnesium	17,700	267,000	69,100
Barium	156	3,440	1,170
Boron	2	7,400	3,055
Chromium	2	570	12.3
Copper	1.0	1,230	5.5
Lead	1.0	1,440	5.6

Landfill Section 6/7 Shallow/Refuse Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Nickel	3	421	11.3
Zinc	3	6,150	63.3

As indicated on the Total Organic Compounds scatterplot (Figure 7.147A) and the organic group bar charts (Figures 7.408 - 7.410), the occurrence of organic compounds as a whole in the shallow/refuse monitoring zone is minimal for detected concentrations and sporadic for non-qualified data, with only one well consistently exceeding the NYSDEC criterion for total organic compounds of 100 ug/L by a slight amount (6W89:YW7). Nine other wells exhibit one or two exceedences (6W89:YW1, YW2, YW4, YW9, 6W91:IT151S, 157S, 160S, and 6W92:172S). Spatial distribution maps (Figures 7.476 - 7.478) show that the concentrations of volatile organic compounds are highest in the southeast area, concentrations of semi-volatile organic compounds are highest in southwest area of the landfill, and pesticide/herbicide concentrations are highest at the northern and southern ends of the landfill section. In review of the chart presentations and the spatial distribution maps, it should be noted that detected concentrations (indicated as mean total concentrations) often represent a single occurrence that was not repeated in subsequent sampling events. Therefore, these graphics tend to portray a wider distribution of organic compounds than may reliably be considered to exist. This is evident through review of Tables 7.16D through 7.18D, which summarize all detected organic compounds.

The focus of this discussion is on those few constituents that repeatedly occur as non-qualified concentrations at specific locations. As indicated through review of all referenced tabular and graphic presentations, even in these cases the concentration distribution of non-qualified organic compounds is uniformly low within the shallow/refuse monitoring zone "source area".

Section 6/7 exhibits a relatively low diversity in detected organic compounds, especially with respect to semi-volatile compounds, and exhibits low mean total concentrations. Summary statistics of the mean total organic compound groups are summarized below:

Landfill Section 6/7 Shallow/Refuse Monitoring Zone			
	Mean Total Concentration (ug/L)		
Compound Group	Minimum	Maximum	Median
Volatiles	ND	95	5
Semivolatiles	ND	430	6
Pesticides/Herbicides/PCBs	ND	1.6	ND

As indicated on Figures 7.475- 7.478, the spatial concentration distribution of the organic compounds does not correlate well with the the general chemical indicator parameters, which generally show highest concentrations in the northwestern area of the landfill.

The only consistently detected non-qualified volatile is chlorobenzene with a maximum concentration of 66 ug/L. Tables 7.16D provides a full delineation of all detected volatile organic compounds by well and monitoring quarter. The only consistently detected (non-qualified) semi-volatile compound is naphthalene with a maximum concentration of 68 ug/L. Table 7.17D provides a full delineation of all detected semi-volatile organic compounds by well and monitoring quarter. No non-qualified pesticides and herbicides were consistently detected in this landfill section. PCBs were identified once at three locations (6W89:YW5, 7, 10) with a maximum concentration of 6.1 ug/l. Table 7.18D provides a full delineation of all detected pesticide/herbicide/PCB organic compounds by well and monitoring quarter.

It should be noted that samples of groundwater well 6W89:YW7 by NYSDEC prior to the initiation of this investigation indicated the presence of a non aqueous phase liquid (NAPL) in groundwater. Subsequent sampling by NYCDOS did not encounter such a NAPL at this or any other monitoring location within the landfill. Excavation and removal of well YW-3 during the fall of 1993 in support of sedimentation basin construction provided information as to the likely initial cause and subsequent lack of NAPL at this location. Examination of refuse material removal from the excavation indicated the presence of a crushed fuel oil tank in the vicinity of YW-7. Examination of soil and refuse materials surrounding the tank indicated that only limited product (i.e., that adhering to the tank wall) was associated with the tank; this could have represented adequate volume to appear as NAPL in the initial, but not in subsequent, sampling events.

7.2.4.2 *Intermediate Depth Monitoring Zone*

As indicated by scatterplots (Figures 7.142-7.184) and boxplots (Figures 7.295-7.310), the majority of leachate indicator parameters and organic compounds exhibit a significant reduction in concentrations relative to the shallow/refuse monitoring zone (often several orders of magnitude). Exceptions relate to chloride and other seawater associated solutes (e.g., sodium and sulfate), which are discussed in detail for landfill Section 1/9 (Section 7.2.2.1). Both chloride and sulfate are higher in the southern area of the intermediate depth monitoring zone than in the shallow/refuse monitoring zone, suggesting a seawater mixture. The intermediate depth monitoring zone has been segregated into two components for discussion purposes at Section 6/7. The generally shallow Recent/glacial sand horizon is present througout most of the landfill, and a deeper Cretaceous sand sequence is present in the extreme southern area of the site. Concentrations are of all analytes are significantly lower for the deeper Cretaceous sand horizon relative to the shallow sands, indicative of natural freshwater chemistry in the deeper unit. Data for selected parameters are compared with historical/literature data in the boxplots (Figures 7.279-7.294). Summary statistics for the general chemical indicator parameters are provided for each monitoring zone horizon below:

Landfill Section 6/7 Intermediate Depth (Recent/Glacial Sand) Monitoring Zone			
	Concentration (ug/L)		
Analyte	Minimum	Maximum	Median
Ammonia	20	2,320	174
TKN	200	17,700	593
COD	5,000	229,000	11,000
BOD5	2,000	183,000	2,000
TOC	1,000	217,000	9,510
Alkalinity	54,000	1,030,000	190,000
TDS	580,000	17,500,000	2,080,000
Chloride	274,000	11,000,000	1,154,000
Sulfate	5,130	586,000	78,200

Landfill Section 6/7 Intermediate Depth (Cretaceous Sand) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Ammonia	20	271	114
TKN	200	636	297
COD	5,000	44,100	13,695
BOD5	2,000	3,300	2,000
TOC	1,000	33,200	4,740
Alkalinity	1,000	146,000	22,000
TDS	620,000	3,360,000	1,340,000
Chloride	250,000	2,370,000	492,000
Sulfate	1,000	153,000	8,950

In general, these data indicate a slight water quality degradation in the Recent/glacial sands relative to the Cretaceous monitoring zone. The concentrations of chloride, sodium, and sulfate (important seawater indicator parameters) suggest that the degradation of water quality is due to a complex mixture of leachate and seawater in the southern area of this landfill section.

Both Recent Sand Unit 1 and isolated lenses of glacial sand are present within this landfill section. The Cretaceous sand horizon is limited to the two wells in the far southern end of this landfill section (wells 6W91:IT157I and 6W92:IT166I2). Ammonia concentration data indicates that none of the wells exceed the NYSDEC criterion of 2,000 ug/L (Figure 7.142). The spatial distribution of mean ammonia data is indicated on Figures 7.444 and 7.452.

Similar to ammonia, biochemical and chemical oxygen demand, total kjeldahl nitrogen, total organic carbon, and alkalinity all are indicator parameters of organic acids and other organic matter. All of these parameters are reduced in concentration for both the Recent/glacial sand and Cretaceous sand horizons relative to the shallow/refuse monitoring zone (Figures 7.145, 7.146, 7.144, 7.147, 7.148). The only significant exception to this is well 6W92:IT165I, which consistently has elevated levels of leachate indicators. The spatial distribution of these

parameters are indicated in Figures 7.443, 7.445, 7.448, 7.449, 7.450. This suggests that very little leachate has migrated to the intermediate monitoring zone in this landfill section.

Total dissolved solids and chloride concentrations have relatively equal concentrations in Recent/glacial sand and Cretaceous sand horizons relative to the shallow/refuse monitoring zone (Figures 7.152 and 7.155). As leachate indicator parameters are not elevated in this monitoring zone, this suggests a possible slight seawater influence in this section. The only exception is well 6W92:IT165I, which has the highest concentration of chloride and TDS, and is likely mixed with leachate. All wells exceed the NYSDEC water quality criterion of 250,000 ug/L for chloride. Spatial distribution of chloride is indicated on Figures 7.447 and 7.455.

Under the anaerobic conditions prevalent within the landfill, sulfate is chemically reduced to sulfide, generally resulting in low concentrations of this solute. However, the median value of sulfate is much higher in the Recent/glacial sand horizon relative to the shallow/refuse monitoring zone, perhaps indicating a less reducing environment (Figure 7.150). Well 6W92:IT165I is the only well that routinely exceeds the NYDEC water quality standard of 250,000 ug/L.

Of the primary elemental inorganic leachate indicator parameters (sodium, calcium, and potassium), sodium and calcium concentration are about the same in the intermediate and shallow/refuse monitoring zones. Only well 6W92:IT165I (sodium, calcium) and 162I (calcium) have significantly higher concentrations in the intermediate monitoring zone than in the shallow/refuse monitoring zone (Figures7.167 and 7.180). The concentration of potassium in the intermediate monitoring zone is significantly lower than the shallow/refuse monitoring zone with the exception of well 6W92:IT165I. All wells exceed the NYSDEC water quality criterion of 20,000 ug/L for sodium (the other parameters are not regulated). Except for 6W92:IT167I, iron concentrations sporadically exceed water quality standards for all wells (Figure 7.172). Magnesium concentrations also exceed water quality standards for all wells, with well 6W92:IT165I having the highest concentration (Figure 7.174). Manganese concentrations sporadically exceed the water quality standard, and are generally higher than in the shallow/refuse monitoring zone. This could be the result of formation mineralogy or turbidity in the samples (Figure 7.175). The only wells exceed water quality standard for barium (Figure 7.163), boron (Figure 7.165), chromium (Figure 7.168), copper (Figure 7.171), lead (Figure 7.173), nickel (Figure 7.176), and zinc (Figure 7.184) are 6W92:IT162I (barium), 165I (boron), and 157I (chromium).

Regulated trace elements (antimony, arsenic, beryllium, cadmium, hexavalent chromium, selenium, and silver) uniformly exhibit extremely low (and generally qualified) concentrations (Figures 7.161, 7.162, 7.164, 7.166, 7.169, 7.178, and 7.179). No wells have elevated concentrations for any of these parameters.

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 6/7 Intermediate Depth (Recent/Glacial Sand) Monitoring Zone			
	Concentration (ug/L)		
Analyte	Minimum	Maximum	Median
Sodium	58,600	4,900,000	567,000
Calcium	26,800	579,000	100,000
Potassium	6,410	231,000	12,200
Iron	104	47,800	947
Manganese	142	13,300	441
Magnesium	36,400	486,000	95,700
Barium	54	1,970	387
Boron	184	2,430	297
Chromium	2	43.9	5
Copper	1	213	3.5
Lead	1	26	1
Nickel	2	66	4
Zinc	1	234	19.8

Landfill Section 6/7 Intermediate Depth (Cretaceous Sand) Monitoring Zone			
	Concentration (ug/L)		
Analyte	Minimum	Maximum	Median

Sodium	48,000	709,000	50,200
Calcium	93,300	119,000	107,000
Potassium	7,660	31,800	11,100
Iron	6,020	81,000	66,000
Manganese	385	2,940	2,530
Magnesium	43,600	86,600	50,600
Barium	132	660	543
Boron	61.2	106	72.4
Chromium	2	277	9.8
Copper	2	54.5	11.9
Lead	1	22.5	1
Nickel	2	145	5.9
Zinc	37.6	94.1	63.5

As indicated on the Total Organic Compounds scatterplot (Figure 7.147A) and the organic group bar charts (Figures 7.408 - 7.410), the occurrence of organic compounds as a whole in the intermediate monitoring zone is minimal for detected concentrations and sporadic for non-qualified data, with only one occurrence of a well exceeding the NYSDEC criterion for total organic compounds of 100 ug/L (6W92:167I).In review of the chart presentations and the spatial distribution maps (Figures 7.479- 7.484), it should be noted that detected concentrations (indicated as mean total concentrations) often represent a single occurrence that was not repeated in subsequent sampling events. Therefore, these graphics tend to portray a wider distribution of organic compounds than may reliably be considered to exist. Section 6/7, exhibits an extremely low diveristy in detected organic compounds; evident through review of Table 7.19D through 7.21D, which summarize all detected organic compounds.

The focus of this discussion is on those few constituents that repeatedly occur as non-qualified concentrations at specific locations. As indicated through review of all referenced tabular and graphic presentations, even in these cases the concentration distribution of non-qualified organic compounds is uniformly low within the intermediate monitoring zone.

Summary statistics of the mean total organic compound groups are summarized below:

Landfill Section 6/7 Intermediate Depth (Recent/Glacial Sand) Monitoring Zone			
	Mean Total Concentration (ug/L)		
Compound Group	Minimum	Maximum	Median
Volatiles	ND	9	1
Semivolatiles	ND	4	1
Pesticides/Herbicides/PCBs	ND	0.1	ND

Landfill Section 3/4 Intermediate Depth (Cretaceous) Monitoring Zone			
	Mean Total Concentration (ug/L)		
Compound Group	Minimum	Maximum	Median
Volatiles	1	2	1
Semivolatiles	ND	3	1
Pesticides/Herbicides/PCBs	ND	ND	ND

As indicated on Figures 7.479 - 7.484, no wells have mean concentrations of over 10 ug/L for any of the three organic compound groups in either the Recent/glacial sand horizon or the Cretaceous sand horizon.

No non-qualified volatile, semi-volatile, or pesticide/herbicide/PCB organic compounds were consistently detected in this landfill section. Tables 7.19D - 7.21D provide a full delineation of all detected pesticide and herbicide organic compounds by well and monitoring quarter. PCB compounds were not detected in any wells within the intermediate depth monitoring well.

7.2.4.3 Deep (Bedrock) Monitoring Zone

As indicated by scatterplots (Figures 7.142-7.184) and boxplots (Figures 7.295-7.310), the majority of leachate indicator parameters and organic compounds exhibit a significant reduction

in concentrations relative to the shallow/refuse monitoring zone (often several orders of magnitude). Exceptions relate to chloride and other seawater associated solutes (e.g., sodium and sulfate), which are discussed in detail for landfill Section 1/9 (Section 7.2.2.1). Both chloride and sulfate are higher in the southern area of the deep monitoring zone. Summary statistics for the general chemical indicator parameters are provided for each monitoring zone horizon below:

Landfill Section 6/7 Deep (Bedrock) Monitoring Zone			
	Concentration (ug/L)		
Analyte	Minimum	Maximum	Median
Ammonia	20	817	68
TKN	200	1,540	289
COD	5,000	45,600	8,605
BOD5	200	5,340	2,000
TOC	1,000	26,400	4,495
Alkalinity	32,000	712,000	121,000
TDS	24,000	8,240,000	336,000
Chloride	7,500	4,830,000	64,700
Sulfate	1,730	411,000	12,950

In general, these data indicate a slight water quality degradation in the southern part of this landfill section. The concentrations of chloride, sodium, and sulfate suggest that the degradation of water quality is due to a seawater mixture in the southern area of this landfill section.

Ammonia concentration data indicate that none of the wells exceed the NYSDEC criterion of 2,000 ug/L (Figure 7.142). The spatial distribution of mean ammonia data is indicated on Figure 7.460. Similar to ammonia, biochemical and chemical oxygen demand, total kjeldahl nitrogen, total organic carbon, and alkalinity all are indicator parameters of organic acids and other organic matter. All of these parameters are reduced in concentration relative to the shallow/refuse monitoring zone and are equivalent to the concentration distributions exhibited in the intermediate depth monitoring zone (Figures 7.145, 7.146, 7.144, 7.147, 7.148). The only significant

exception to this is alkalinity values in the southern part of the landfill section. The slightly elevated alkalinity most likely is a result of dissolution of the serpentinite. The spatial distribution of these parameters is indicated on Figures 7.459, 7.461, 7.464, 7.465, 7.466.

Total dissolved solids and chloride concentrations are elevated in the southern end of the landfill section (Figures 7.152 and 7.155). Since the leachate indicator parameters all have low concentrations, this suggests a seawater influence in this section. Most all wells exceed the NYSDEC water quality criterion of 250,000 ug/L for chloride. The spatial distribution of chloride is indicated on Figure 7.463, and indicate highest concentrations in the southern end of the landfill section.

The median value of sulfate is relatively high in the deep monitoring zone, perhaps indicating a less reducing environment or a mixture of seawater (Figure 7.150). No wells routinely exceed the NYDEC water quality standard of 250,000 ug/L.

Of the primary elemental inorganic leachate indicator parameters (sodium, calcium, and potassium), sodium is elevated in the southern part of the landfill (Figures 7.167, 7.177, 7.180). The concentration of potassium in the deep monitoring zone is significantly lower than the shallow/refuse monitoring zone. All wells, except for 6W92:IT153D, 154D, 157D, and 166D exceed the NYSDEC water quality criterion of 20,000 ug/L for sodium (the other parameters are not regulated). Iron concentrations routinely exceed water quality standards for all wells (Figure 7.172); only well 6W92:IT162D exceeds the water quality standard for manganese (Figure 7.175). The source of these elements is probably the minerals in the aquifer. Magnesium concentrations exceed water quality standards only at wells 6W92:IT155D, 156D, 158D, 159D, and167D (Figure 7.174). Minerals within the serpentinite are probably the source of the magnesium. The only well that exceeds the water quality standard for boron is 6W92:IT151D (Figure 7.165). No wells exceed water quality standards for barium (Figure 7.163), chromium (Figure 7.168), copper (Figure 7.171), lead (Figure 7.173), nickel (Figure 7.176), and zinc (Figure 7.184).

Regulated trace elements (antimony, arsenic, beryllium, cadmium, hexavalent chromium, selenium, and silver) uniformly exhibit extremely low (and generally qualified) concentrations (Figures 7.161, 7.162, 7.164, 7.166, 7.169, 7.178, and 7.179). No wells have elevated concentrations for any of these parameters.

Summary statistics of the primary inorganic metal analytes are provided below:

Landfill Section 6/7 Deep (Bedrock) Monitoring Zone			
Analyte	Concentration (ug/L)		
	Minimum	Maximum	Median
Sodium	7,190	2,830,000	42,750
Calcium	1,030	89,300	18,300
Potassium	930	57,900	9,390
Iron	109	44,700	2,140
Manganese	2	2,250	125
Magnesium	693	230,000	11,950
Barium	1	622	145
Boron	39.7	1,390	207
Chromium	2	445	5
Copper	1	101	2
Lead	1	31	1
Nickel	2	1,050	5
Zinc	1	167	22.8

As indicated on the Total Organic Compounds scatterplot (Figure 7.147A) and the organic group bar charts (Figures 7.408 - 7.410), the occurrence of organic compounds as a whole in the deep monitoring zone is fairly high in some areas, with four wells exceeding the NYSDEC criterion for total organic compounds of 100 ug/L (6W92:164D,169D, 170D, and 171D) and a number of other wells showing occasional high levels of organic compounds. In review of the chart presentations and the spatial distribution maps (Figures 7.479- 7.484), it should be noted that detected concentrations (indicated as mean total concentrations) often represent a single occurrence that was not repeated in subsequent sampling events. Therefore, these graphics tend to portray a wider distribution of organic compounds than may reliably be considered to exist.

occurrence that was not repeated in subsequent sampling events. Therefore, these graphics tend to portray a wider distribution of organic compounds than may reliably be considered to exist. This is evident through review of Tables 7.16D through 7.18D, which summarize all detected organic compounds.

At Section 6/7, the presence of organic compounds is fairly widespread within the deep monitoring zone; this landfill section exhibits a low diversity of detected compounds. Mean total concentrations are higher than the shallow/refuse zone and are represented primarly by the volatile organic compounds 2-butanone and toluene. Summary statistics of the mean total organic compound groups are summarized below:

Landfill Section 6/7 Deep (Bedrock) Monitoring Zone			
	Mean Total Concentration (ug/L)		
Compound Group	Minimum	Maximum	Median
Volatiles	ND	855	51
Semivolatiles	ND	46	1
Pesticides/Herbicides/PCBs	ND	0.9	ND

As indicated on Figures 7.485 - 7.489, eleven wells around the northern, western and southern margins have mean concentrations of volatile organic compounds exceeding 50 ug/L. The rest of the wells have concentrations under 10 ug/L. Only well 6W92:IT263D has a mean concentration of semi-volatile organic compounds exceeding 10 ug/L. Pesticide and herbicide compounds have uniformly low concentrations; PCBs are not detected.

The spatial distribution maps of 2-Butanone and toluene show that they are responsible for the distribution of the mean concentration of volatile organic compounds (Figures 7.486 and 7.487). 2-Butanone has the highest concentrations of the two compounds, and accounts for most of the mean concentration of volatile organic compounds. As noted in previous discussions, the source of these compounds in the deep monitoring zone of the Fresh Kills landfill is unknown. These compounds are not detected in either the intermediate monitoring zone nor the shallow/refuse

An upgradient source would lie to the east and northeast of Landfill Section 6/7. The presence of such an off-site source is currently being investigated by NYCDOS

No non-qualified semi-volatile or pesticide/herbicide organic compounds were consistently detected in this landfill section. Tables 7.16D, 7.17D, and 7.18D provide a full delineation of all detected pesticide/herbicide/PCB organic compounds by well and monitoring quarter.

7.2.4.4 Temporal Relationships

A comparison of seasonal variation in selected general chemical and inorganic parameters was performed for the shallow/refuse, intermediate, and deep monitoring zones at Landfill Section 6/7. Box plots of seasonal data are contained in Attachment 34. BOD, cobalt, lead, and zinc in the shallow/refuse zone all exhibit their highest variability in the winter. In the intermediate monitoring zone, cobalt, iron, and lead exhibit high variability in the spring sampling quarters; variability for turbidity and BOD is highest in the summer the fall, respectively. Median concentration data for TOC is elevated in the winter; hardness concentrations are elevated in both the spring and fall sampling quarters. In the deep monitoring zone, concentrations of ammonia and sulfide are elevated in the fall and winter sample quarters, respectively.

7.2.5 Analytical Data Quality Assurance

All analytical data presented in this report have undergone internal laboratory analytical quality assurance review in accordance with the project specific Quality Assurance Program (QAPP) and Project (QAPjP) plans (IT Corporation, 1991c; 1992a). Due to the large quantity of data generated by this investigation, however, additional quality assurance review has been deemed appropriate by the project sponsor (NYCDOS) and the oversight regulatory agency (NYSDEC). The status and findings of these additional reviews, consisting of data validation, usability, and comparability analyses, are summarized below.

7.2.5.1 *Data Validation*

Data validation is the process of reviewing and assessing the quality of data and providing assurance as to whether or not the data are of acceptable quality for their intended use. The acceptable quality of the data has been set forth in the Fresh Kills QAPjP in the form of Data Quality Objectives (Table 4.11). Data validation consists of data editing, screening, checking, auditing, verification, and certification.

Various types of data validation were performed over the sampling period from January 1991 to the present. The first level of validation takes place within the performing analytical laboratory (IT Corporation Analytical Services [ITAS]). The chemists responsible for the analytical group activity (e.g. gas chromatography [GC], GC/mass spectrometry, metals, and general chemistry) perform the initial analytical validation/review. This level of validation is performed by investigating the raw data for every sample analyzed and each calibration curve associated with the determinations. A second lab validation/review is performed by the Fresh Kills project manager following receipt of the data, after data input is made to the Laboratory Information Management System (LIMS), and prior to analytical data report delivery. These initial two validation processes ensure that the reported concentrations are correct, and the determinations or preparations were performed correctly in accordance with the guidelines established in the QAPjP Standard Operating Procedures (SOPs). A third form of internal laboratory validation is represented by a quality control review performed by the laboratory's quality control coordinator, and involves intensive review of a selected 20 percent of the analytical data generated. This validation/review process involves looking for trends in the data, investigating poor recoveries, and initiating interaction between the analytical staff and the quality control department.

In addition to the above, external data validation was performed independently by H2M laboratories under separate contract to NYCDOS. The external validators perform an intensive review of the raw analytical data in accordance with guidelines established by the NYSDEC Analytical Services Protocol (ASP) and the QAPjP. During this stage of validation, data which originally meet the laboratory's statement of work may be requalified as either estimated values ("J" qualifier applied to data values) or not acceptable relative to the guidelines of the QAPjP. These latter data are rejected, and marked with an "R" qualifier.

The guidelines under which an external data validator operates are somewhat different than those used internally by the laboratory when generating data. For example, when the laboratory receives a field or trip blank (quality control [QC] samples) along with a series of well samples for analysis, they are analyzed and are reported in an identical manner. However, when the external validator reviews these data, if the sample does not contain more than five times the level of analyte identified in the associated field or trip blank, that analyte is assigned a "J" qualifier, to indicate that the concentration being reported is estimated due to the presence of the analyte in the associated QC blank. Additionally, if the QC samples run for matrix spike and duplicate matrix spike analysis (a routine quality assurance procedure) do not recover any analyte within the prescribed recovery criteria, well sample data associated with these QC samples will be assigned a "J" qualifier by the external validator for the analyte not properly recovered (the QAPjP does not specify for the laboratory that the analysis of the MS and MSD must be performed until recovery criteria have been achieved).

Presently, seven sampling rounds have been completed at the Fresh Kills Landfill in accordance with the Consent Order groundwater monitoring program. During January 1991, laboratory analysis was performed on samples obtained from 24 wells, primarily wells installed by NYCDOS in 1989 at Landfill Sections 1/9 and 6/7. Analysis and internal validation were performed in accordance with the initial project QAPjP; analytical data from this round were not processed for external validation. In July of 1991, 91 wells were sampled and analyzed, and all of these samples were validated both internally and externally. During the 1992 sampling events, the percentage of samples that were submitted for external data validation was modified as follows: January 1992 sampling event, 25%; April and July 1992 sampling events, 20%. External validation of 20 percent of the October 1992 sampling event analytical data is pending. It should be noted that the 20 percent validation criterion is consistent with stipulated requirements contained in 6 NYCRR Part 360 (NYSDEC, 1993). Data qualifiers associated with the external validation process are included in the sample data tabular summary compilations contained in Section L1 of Appendix L.

Data validation performed by H2M Laboratories resulted in data classified as either compliant or non-compliant with respect to the protocols defined in the NYSDEC ASP, rather than the project-defined analytical protocols presented in the QAPjP. While no data had been rejected by the data validator from the July 1991 sampling quarter, approximately 50% of the data were

categorized as non-compliant. Typical non-compliances reported in data validation reports for the July 1991 monitoring event for the various test protocols are as follows:

Gas Chromatography/Mass Spectrometry: Periodic questionable compound identification; method blank analysis not necessarily performed on instruments used for sample analysis.

Gas Chromatography: Linear regression versus ASP suggested response factor calibration; excessively large data acceptability "window" for pesticides/PCBs resulting in false positive identification.

Metals: Chain of custody traceability between host and performing laboratory; graphite furnace calibration technique.

General Chemistry: Correlation coefficient range for sulfate determinations; correction for nitrite contribution to nitrate concentration; noncompliance of inorganic carbonate standard for TOC analysis.

Many of these issues continued to represent the primary causes of data qualification during the 1992 sampling round data validation process. However, the issues with the most significant potential to effect data quality have been addressed with appropriate QAPjP revisions and addenda, following consultation with NYSDEC.

7.2.5.2 Data Usability

Data usability analysis represents the process through which a determination is made as to whether a data set is sufficiently complete and of sufficient quality to support a decision or action. This is viewed in terms of the specific objectives of the data collection activity (for example, identification of leachate influenced groundwater within the context of the hydrogeological investigation). It is important to note that analytical data may be of poor quality with reference to precision and accuracy, but may still be deemed usable for specific objectives. Also, data may be of high precision and accuracy, yet may not be usable because the data failed stipulated comparability and/or completeness criteria.

All sample data from the January 1991, July 1991, April, July, October 1992 and January 1993 sampling events have been evaluated on a sample-by-sample basis for their usability. The evaluation includes a review of sample preservation, holding times, calibrations, chromatograms,

quantitation reports, internal standards, surrogate standards, instrument tune summaries, QC blanks, and QC samples. The raw data review was based upon the criteria set forth in the QAPjP, NYSDEC ASP, and EPA CLP guidelines and validation protocols.

Six categories have been established to define the quality of the data from a project management and decision making perspective, as to the relative usability of each data value. These six data usability categories are defined as follows:

CATEGORY A: Fully usable and defensible without qualification. This category contains usable, unqualified data or nondetectable concentrations below detection limits.

CATEGORY QT: Usable with qualifications due to sample tracking. Data in this category are usable, but qualified due to minor inconsistencies in maintaining complete internal laboratory sample tracking documentation.

CATEGORY Q: Usable with qualifications. Data in this category are qualified relative to minor deviations from criteria specified in the Fresh Kills QAPjP and 1991 NYSDEC ASP. Deviations in this category do not support rejection of the data. These data are usable under the conditions for which the qualification was designated.

CATEGORY QHT: Usable but qualified due to holding time exceedance. These data are qualified because the samples were analyzed outside the holding time requirements specified in the QAPjP and 1991 NYSDEC ASP. Data obtained for a sample analyzed outside of the holding time may be considered usable depending on the compound or analyte, the degree of holding time exceedance, and the concentration of the analyte detected.

CATEGORY RHT: Rejected due to holding time exceedance. These data are considered not useable because samples were not analyzed within the specified holding time limits specified in the QAPjP and 1991 NYSDEC ASP.

CATEGORY R: Rejected due to various deviations from the QAPjP requirements. These sample data are not useable because of significant deviation from the NYSDEC-approved QAPjP protocols and those specified in the 1991 NYSDEC ASP.

Data from any one sample can be assigned a number of these data usability categories because analyses were performed on a series of separate sample fractions (Volatile Organic Compounds, Semivolatile Organic Compounds, Metals, etc.) using various methods. Compounds within a

particular fraction may also be divided among these six categories. For example, acetone may be rejected and assigned to the "R" usability category, while the remainder of the Volatile Organic fraction may be fully usable ("A") for a particular sample.

Data usability reports completed to date are included in Appendix O of this report. Data qualifiers associated with usability analyses are included with sample data in Section L1 of Appendix L. Significant findings associated with usability analyses performed to date are summarized below:

Eighty one percent of the data collected during the January 1991 sampling quarter were determined to be completely usable and defensible without qualification, and were assigned an "A" qualifier. Thirteen percent of the remaining data were qualified due to deviation from project defined protocols, but nevertheless classified as usable, resulting in a complete usability determination of 94 percent for the January 1991 analytical data. The major usability issue relative to these data concerned failure of the laboratory to calibrate for 9 of the 116 semivolatile compounds and 3 of the 54 volatile compounds specified in the NYSDEC ASP, resulting in their rejection.

Eighty five percent of the July 1991 sampling quarter data were determined to be completely usable and defensible without qualification ("A" qualified). An additional 14 percent were qualified due to either internal sample tracking or deviation from project defined protocols, resulting in a complete usability determination of nearly 99 percent. Selection of retention time window size for the determination of pesticides/PCBs and herbicides was the major issue encountered during this sampling round. As a result of these selections, the reported data for these analytes must be evaluated judiciously for project decision making or regulatory purposes.

Approximately 90 percent of the data collected during the January 1992 sampling quarter were considered completely usable and defensible without qualification ("A" designation). In combination with the various "Q" categories, which also represent usable and defensible data, a complete usability determination of approximately 97 percent was identified for these data.

Approximately 90 percent of the April 1992 groundwater sample data collected were considered completely usable and defensible without qualification ('A' designated). Together with the 8

percent of data grouped in the 'Q' categories, which also present usable and defensible data, 98 percent of the data for April 1992 sampling quarter were considered usable.

More than 98 percent of the groundwater sample data comprising the July 1992 sampling quarter were found to be usable and defensible. Most of the data not considered usable were those results attributable to possible laboratory or field sampling contamination.

The data usability evaluation determined that almost 99 percent of the October 1992 groundwater data were usable. This value constitutes data found to be fully usable and defensible ('A' category), and that data usable and defensible with qualification ('Q' categories).

More than 98 percent of the January 1993 groundwater data fell in the 'A' and 'Q' data usability categories considered usable and defensible. Most of the remaining data values were considered to be qualified as a result of laboratory or sampling contamination.

- ***Field Duplicate Determinations***

Evaluation of the representativeness of analytical data generated during the various sampling events includes comparison of data obtained from field duplicate samples. The project QAPP specifies that one duplicate sample is collected in the field for each 20 well samples obtained. Field duplicates are field samples obtained from the same well and, sampled at the same time as the primary sample for analysis. Good comparison between the two samples indicates the ability of the sampling crew to obtain representative (similar) samples, increasing confidence in the accurate characterization of sampling locations. Field duplicate determinations also help determine the variability in analytical results due to sampling technique. The data quality objective for representativeness in the QAPjP was modified in July 1992, and each analyte was assigned a numerical window of 35 percent RPD. Generally, the only data capable of being compared were the metals and general chemistry analytes, due to the general lack of organic compounds present in most samples analyzed. The following discussion provides a breakdown of the field duplicate analyses on a quarterly basis.

Five expanded parameter samples and one baseline parameter sample were analyzed in duplicate during the July 1991 sampling event. Chlorides, total organic carbon and hardness values were areas of non-representativeness encountered with this set of data. Iron determination was

problematic for three sets of duplicates examined. Greater than 90 percent of all the data examined, achieved the specified RPD representativeness criteria. The primary instance of poor representativeness with respect to organic compound analysis was associated with sample from well 1W91:008I; sample concentration of gamma-BHC was reported as 0.25 ug/l and the field duplicate concentration was reported as 0.010 ug/l U (undetected).

Six expanded parameter samples and one baseline parameter sample were analyzed in duplicate during the January 1992 event. General chemistry parameters of ammonia - nitrogen displayed a representativeness problem for five of the six expanded samples, and TKN was problematic for four of the six samples. Zinc portrayed high RPD values in three of the seven field duplicates, and one sample (1W91:012I1) indicated poor representativeness for ten of the twenty five metals parameters (Al, As, Cr, Cu, Fe, Pb, Mn, Ni, V, and Zn). Dimethylphenol and naphthalene were reported for well 1W89:XW10 at 15 and 13 ug/l respectively; however, the field duplicate did not detect these compounds.

Seven Expanded Parameter samples and one Baseline Parameter sample were analyzed in duplicate during the April 1992 sampling event. No disparity was evident in the analysis of the general chemistry parameters. A lack of representativeness for zinc, aluminum, and copper was noted in three of the seven field duplicates (but not always the same samples). No disparity in limited organic compound identification was apparent.

During the July 1992 sampling event, eight Expanded Parameter samples were analyzed in duplicate. As in the previous sampling event, no trends were obvious regarding the comparison of general chemistry determinations. However, two sets of field duplicate results for metals (2W92:309I and 6W91:157I) displayed high RPD values for nine of the twenty five elements, notably aluminum, chromium, iron, lead, nickel, vanadium and zinc. Overall, aluminum was problematic for five of the samples, and zinc for six of the eight samples. 2-Butanone in well 2W91:307D exhibited a 64 percent RPD, and was the only organic compound for this sampling event to exceed the 35 percent RPD.

With an increase in the total number of wells being sampled for October 1992, the number of Expanded Parameter field duplicates increased to twelve. No trends were observed with respect to the representativeness of the general chemistry parameters. Biochemical oxygen demand and phenols were observed to exceed the 35 percent RPD criteria for three different samples, and

chloride, sulfate, and chemical oxygen demand each exceeded criteria in two sample pairs. The remaining 89 percent of the general chemistry parameters were well within the specified criteria. Zinc exceeded the RPD criteria for five of the eight duplicate samples, and aluminum determination was problematic for two samples. Generally, the remaining 96 percent of the metals data were well within the 35 per cent RPD criterion. The determination of acetone for well 1W92:029S resulted in a 200 percent RPD, due to the fact that the sample exhibited 25 ug/l of this analyte, and the field duplicate contained less than the detection limit of 10 ug/l.

Twelve expanded parameter field duplicates were collected during the January 1993 monitoring event. A total of 53 of the listed RPD values for the 12 sample pairs exceeded the DQO value of 35 percent RPD for representativeness. This accounts for 1.8 percent of the duplicate sample data exceeding the DQO. Of the twelve sample pairs evaluated, samples from AW90:AK13I, Pump Station B and 3W92:434I had the greatest number of parameter results exceeding the RPD. These samples had nine, eight and eight RPD values exceeding the DQO of 35 percent RPD for representativeness. The analytes in the metals fraction most often exceeding the DQO were cyanide, nickel and zinc, each exceeding 35 percent RPD in four duplicates and three times for copper. Phenol exceeded the DQO on three occasions, while COD, TKN sulfide and nitrate each exceeded 35 percent RPD twice. With the exception of xylene, which exceed the DQO three times, the remaining 13 compounds exceeded the DQO because one of the sample/duplicate sample results was less than the PQL and the other result not detected. In most cases, the use of the detection level for the ND result is what caused the RPD value to exceed 35 percent. The groundwater analytical results of the January 1993 monitoring event indicate that greater than 98 percent of the sample data met the DQO for sampling representativeness.

Relative to all analytes, 95 percent of all field duplicate analyses obtained between July 1991 and January 1993 meet or exceed project representativeness criteria.

- ***Field Blanks - Trip Blanks***

During the course of the analytical monitoring program at the Fresh Kills landfill, trip (travel) blanks and field (equipment) blanks have been transported and processed with the well samples to provide quality control with respect to field sampling and laboratory analytical practices. Trip

blanks are analyzed for volatile organic compounds and field blanks are analyzed for the entire Expande7d Parameter analyte list.

The July 1991 sampling event generated 23 field blanks and 33 trip blanks. In general, the field blanks associated with this quarter contained measurable concentrations of a number of analytes. Hardness values were determined for 17 of the blanks, and ammonia (16 samples) and COD (9 samples) were also commonly reported. Boron, calcium, iron, sodium, and zinc were consistently reported at levels above the instrument detection limit, and 2-bis(ethylhexyl)phthalate was found in all but one field blank. Acetone was the major contaminant found in 11 of the trip blanks. Methylethyl ketone (2-Butanone) was identified in 7 trip blanks, with two of them exhibiting concentrations greater than 100 ug/l.

Starting with the January 1992 event, installation of dedicated sampling devices (bladder pumps) was initiated in monitoring wells to improve consistency in sample collection procedures. Throughout the subsequent sampling events, additional wells were fitted with these devices. By the October 1992 sampling event, all wells were equipped with the dedicated pumps, progressively reducing the quantity of field (equipment) blanks obtained. Fifteen field blanks and 25 trip blanks were collected during the January 1992 sampling event. The quality of these field blanks was consistent with July 1991 event with the exception of the general chemistry parameters. Phenols were identified in 14 of the field blanks, and chemical oxygen demand (COD) for 13 of the blanks was identified well above the reporting limit. 2-bis(ethylhexyl)phthate was present in all 15 field blanks. Acetone was present in 9 of the trip blanks, and methylene chloride was identified in 14 of the trip blanks.

Nine field blanks and 21 trip blanks were obtained during the April 1992 sampling event. Prior to the inception of this event, most intermediate depth wells were equipped with dedicated equipment; thus the field blanks were generally associated only with the shallow well sampling effort. Phenols were identified in all field blanks, however the mean concentration was lower than reported during previous events. COD and ammonia continued to be detected in the field blanks (5 of 9 were positive). Copper, magnesium, and potassium were no longer found in the field blanks on a consistent basis. 2-bis(ethylhexyl)phthalate was present in all field blanks, and toluene was also present in 5 of them. The trip blanks exhibited less contamination than in previous events. Only eight trip blanks exhibited contamination, and methylene chloride was the primary analyte identified, found in four of the blanks.

Ten field blanks and 25 trip blanks were collected during the July 1992 sampling event. The level of general chemistry parameter contamination remained constant with respect to April 1992. Additionally, metals contamination was similar to that of the previous sampling events. 2-bis(ethylhexyl)phthalate was present in 8 of the 10 field blanks. Five trip blanks contained methylene chloride, and 19 of the 25 trip blanks reported the presence of volatile organics contamination.

Thirty-four trip blanks and one field blank were obtained during the October 1992 sampling event. Phenols, at a concentration near the detection limit, represented the only general chemistry contamination identified. Metals concentrations were slightly lower than in previous events, and generally the same 8 elements were identified (Al, B, Ca, Fe, Mg, K, Na, and Zn). Trip blanks obtained during this sampling event were very clean. Only 4 of 34 resulted in positive results (2 samples containing carbon disulfide, and one sample each containing chloroform and acetone).

Thirty-five trip blanks and one field blank were sampled during the January 1993 sample event. On January 18, one field blank and three samples from the PASNY site AW90:AK13D, AW90:AK13I and AW90:AK135 were collected.

Chloroform was detected below the PQL in 11 out of the 35 trip blanks and above the PQL in two trip blanks from February 3 and 23 (7 ug/l and 12 ug/l, respectively). The only other compounds detected above the PQL was methylene chloride at 8 ug/l sampled March 11, 1993. Low levels of other volatile organic compounds were detected including bromodichloromethane (2J ug/l - 2/23/93), xylene (2 BJ ug/l and 3 BJ ug/l - 3/22 and 3/23/93, respectively) and chlorobenzene (3J ug/l - 3/25/93).

The field blank from January 18, 1993 contained the same eight metals which were identified in the previous monitoring events, including Al, B, Ca, Fe, Mg, K, Na and Zn. Bis(2-ethylhexyl)phthalate was detected below the PQL at 6 JB ug/l while ammonia, chloride and phenols were detected at 44.0 ug/l, 315,000 ug/l and 17.0 ug/l, respectively.

7.2.5.3 Data Comparability

Data comparability represents a qualitative analysis that relates the confidence of one set of data as compared with another. For applicable comparability results, the analytical methodologies

employed should be identical from one event to another. During the time frame of the current investigation, relatively few significant modifications to the analytical program were implemented and the same laboratories generally were responsible for management and implementation of test procedures and protocol.

Data comparability, as defined for the investigation, includes review of analyte data between individual well locations, and between groups of wells within a monitoring zone, across sampling rounds. This process allows for the identification of specific analyte data, or groups of data, that appear to be inconsistent with the results of prior or subsequent analyses. A focused quality assurance review is then initiated on suspect data that may or may not have been identified within the confines of the validation and usability analyses, which are focused on review of data collected internally within a single sampling event.

Excessive variability has been identified for a number of analytes or reported concentration values as a result of the comparability analyses performed for the period January 1991-January 1993. In many cases, such variability is associated with single, isolated data values, presumably the result of data transcription error (these data are observed as far outliers on the box plots of analytical data referenced in report Section 7.2). Several more general instances of data variability have also been identified, however, that merit addition discussion. Pertinent information related to these findings is provided below. Inconsistent data identified through performance of the comparability analysis have been corrected or qualified in the analyte and sample specific data tabulations contained in Section L1 of Appendix L.

Significant variations identified through the comparability analyses include the following:

- The January 1991 round of metals analyses were not performed in complete accordance with either EPA CLP or NYSDEC ASP. The detection limits exceeded the assigned EPA Contract Required Detection Limits (CRDLs) resulting in higher than normal values for undetected quantities. For example, the CRDL for antimony is 60 ug/L but the data were reported at the laboratory detection limit of 300 ug/l. The variance in detection limits was associated with approximately ten metals, including the four elements (As, Pb, Se, Ti) that require Graphic Furnace Atomic Absorption Spectrophotometry (GFAAS) to improve resolution, but were analyzed with Inductively Coupled Plasma (ICP) emission spectrophotometry during the January 1991 sampling event. Starting with the July 1991 event and continuing until the present, the determination of metals for this investigation was performed completely in accordance with EPA CLP and NYSDEC ASP requirements. Therefore, direct comparison of the metals data generated during January 1991 with the

remainder of the sampling events is inappropriate for many of the metals parameters. To improve resolution of the detection limit associated with antimony, analysis of this element with GFAAS is scheduled for implementation coincident with initiation of the Long Term Groundwater Monitoring Program (Section 8.0).

- Commencing with the January 1992 event, the analytical technique for the determination of sulfides was significantly revised. During the January and July 1991 events, sulfide was determined by the methylene-blue calorimetric procedure. Starting in January 1992, the method used for the determination of sulfide was the iodimetric-thiosulfate back-titration, an oxidation-reduction procedure, which is not specific for just sulfides. Therefore, the comparability of the sulfide data from the 1991 events to all subsequent events is very limited.

- The nitrate nitrogen determination was revised in several stages since the inception of the monitoring program in January 1991. The major comparability issue emanates from the differences in applied techniques between the performing laboratories. During the July 1991 sampling event, the nitrate-nitrogen determination was performed by using a Lachat flow injection analyzer. The Lachat methodology determines nitrates by first reducing them chemically to nitrites and determining total nitrite-nitrogen. However, unless the naturally occurring nitrites are determined and mathematically subtracted, this method will result in a high bias due to the nitrite concentration present naturally in the samples. The July 1991 data was reported as nitrate-nitrogen only. However, the July 1991 nitrate data and subsequent laboratory determinations of nitrates do not include the second determination on the Lachat instrumentation for nitrites. Thus, the data for nitrates determined beginning July 1991 include concentrations of nitrate and nitrite and, therefore, cannot be accurately compared to the nitrates determined in the earlier events. Due to this condition, the nitrate data for rounds subsequent to July 1991 have been flagged as estimate concentrations with J'.

- A significant comparability issue concerns the Inductively Coupled Plasma emission spectrophotometric (ICP) metals determination of many wells sampled during July 1991. Ninety-one wells were sampled during that quarter, and ninety wells exhibited positive antimony results. Of the ninety results, forty-eight (48) were greater than the CRDL (Contract Required Detection Limit of 60 ug/l). In the following January, April, July, and October 1992 events, 22, 3, 6, and 5 samples, respectively, exhibited positive antimony results. Of these 36 positive reported concentrations, only 2 were greater than the CRDL.

  Review of all raw data revealed that a high bias for antimony exists in the Interference Check Standard (ICS) Solution 'A'. This QC solution contains relatively high concentrations of aluminum (540,000 ug/l), iron (200,000 ug/l), calcium (500,000 ug/l), and magnesium (530,000 ug/l) to mimic highly contaminated environmental samples, and is analyzed to allow for evaluation of interferences in the determination of low level and non-detect analytes in both the ICS solution and environmental samples. If the ICP analytical instrument and the analytical program for the instrument are working correctly,

the background corrected concentrations for both the low level analytes and the non-detect analytes will be correct. For the July 1991 samples, the analytical system was not properly correcting for the background emission (primarily for the Al, Fe, Ca, and Mg), resulting in enhanced concentrations for various elements, notably antimony. The ICS solution does not contain antimony, but the analytical determination of this solution revealed concentrations of 60 to 430 ug/l, sufficient to account for the concentrations being reported in the raw data for the 90 wells experiencing positive antimony concentrations. Consequently, all antimony values reported during the July 1991 sampling event should be considered suspect and not used for decision making purposes. (It should be noted that while these data should be rejected from a comparability perspective, the data were found to be totally acceptable within a validation and usability context. This results from the fact that the validation and usability analyses focus on review of data within the framework of a single sampling event, while the comparability analysis incorporates review of analytical data across a series of sampling events.) Additionally, cadmium, chromium, cobalt, copper, and nickel were discovered to be affected by the same matrix enhancement effect for a series of intermediate depth wells. These data from the July 1991 sampling quarter should also be considered suspect.

7.3 Geochemical Analysis

The aims of the geochemical component of this project are to determine the best ways to characterize and distinguish landfill leachate from native groundwater, and evaluate where native groundwater has mixed with leachate. To meet these aims in a typical landfill investigation, the concentrations of total metals and other constituents in pure leachate, native groundwater (upgradient of the landfill) and groundwater downgradient of the landfill are commonly compared to groundwater quality standards/criteria. From these comparisons, it is often concluded that contamination occurs wherever constituents found in the leachate are found at concentrations that exceed standards in downgradient groundwater.

This comparative approach, as applied previously in Section 7.2, is difficult to apply in the Fresh Kills landfill estuarine environment because both seawater and leachate may have high concentrations of the common parameters (such as chloride and sodium) typically associated with landfill contamination. Therefore, to evluate where contamination has occurred, leachate-groundwater mixtures must be distinguished from seawater-groundwater mixtures. A geochemical process-oriented approach (Siegel, Stoner, Byrnes, and Bennett, 1990) is the best way to analyze the data in this circumstance. The geochemical process approach may also help to increase the understanding of the groundwater flow regime beneath the Fresh Kills landfill,

and thus may provide independent verification of the results of numerical groundwater flow analysis.

7.3.1 Geochemical Process Approach

The geochemical process approach (GPA) goes beyond the comparative methods used to interpret water chemistry because it directly and explicitly evaluates the effect of groundwater mixing and chemical reactions on groundwater quality. Specifically, groundwater at the Fresh Kills landfill may exceed quality standards/criteria for some constituents, both when seawater naturally mixes with groundwater and when leachate mixes with groundwater. Therefore, the main objective of the geochemical process approach is to determine how to distinguish between naturally "poor" groundwater quality and where groundwater has actually been contaminated by leachate. This type of geochemical analysis considers only major inorganic solutes, isotopes, and common water chemistry parameters (Eh, pH, etc.). These parameters are most suitable for analysis by the geochemical process approach for two reasons. First, the chemical controls over inorganic solutes are well understood (e.g., Stumm and Morgan, 1981); second, these inorganic solutes constitute most of the material that is dissolved in the groundwater, and measurable concentrations of these constituents are readily and consistently determined through routine laboratory analysis.

The GPA recognizes that the utility of absolute concentrations of many parameters measured in groundwater is probably qualitative with respect to actually identifying the presence and extent of contamination. Groundwater contamination under landfills is commonly stratified with depth (e.g., Baedeker and Back, 1979a). In other words, concentrations of solutes associated with landfill leachate commonly decrease rapidly with depth below the water table. Consequently, groundwater samples from monitoring wells completed with long screens (commonly 10 feet long) can reflect unknown mixtures of highly contaminated and uncontaminated groundwater (Robbins and Martin-Hayden, 1991; Martin-Hayden, et al., 1991). During sampling when water levels are high, contaminated water can mix with a large enough volume of uncontaminated water to reduce concentrations, especially of trace metals, to below the detection limit -- although contamination actually is present. In contrast, when water levels are low in the screens, a greater volume of contaminated water is sampled relative to uncontaminated water, resulting in high measured concentrations. These sampling difficulties occur independent of sampling method

(Robbins and Martin-Hayden, 1991), and consequently, it is often inappropriate to simply compare observed concentrations with water quality standards/criteria to characterize where contamination occurs.

Many dissolved solutes (particularly metals) found in leachate are also primary constituents of minerals in the aquifer matrix. Total concentrations of solutes include suspended fine-grained minerals or refuse material introduced into monitoring wells during pumping or bailing. During analytical sample preparation, the chemical composition of the suspended materials is added to the dissolved concentrations. The result is elevated concentrations of metals, observed as increased outlier scatter in the analytical data set (e.g., Figures 7.1 - 7.10). Because of these interferences, the geochemical process approach uses solute concentrations of water passed through a 0.45 um filter. Filtration eliminates suspended materials, reducing the variability of the total solute concentrations. In essence filtered samples are "normalized", reflecting mostly dissolved solute concentrations with perhaps a small percentage of natural or induced colloids. Dissolved concentrations can be clear indicators of leachate contamination, because they are directly related to geochemical processes (Puls and Barcelona, 1989; Baedeker and Back, 1979a). In contrast, total concentrations often reflect particulate clay and silt unrelated to actual groundwater chemistry. Water in the Fresh Kills landfill can consist of complex mixtures of seawater, leachate, and groundwater, therefore it is especially important to exclude potential artifacts caused by particulate material when trying to identify contamination.

7.3.1.1 Evaluation of Mixtures from "Standard" Chemical Parameters

At the Fresh Kills site, it is critical to determine how to identify seawater-groundwater and leachate-groundwater mixtures from each other, and where all three waters may be mixed. An effective way to do this is by calculating how concentrations may change as different proportions of the waters are combined. The equation governing how concentrations change with mixing is well known from analytical chemistry. When two solutions such as leachate and groundwater, or seawater and groundwater mix, concentrations of the relatively "nonreactive" dissolved substances in the resultant mixture can be determined by the simple mixing equation:

$$Cmix\ (V1 + V2) = C1V1 + C2V2$$

where C1 and C2 are the concentrations of a substance of interest in Solution 1 and Solution 2, and V1 and V2 are the volumes of Solution 1 and Solution 2. This equation normalized to a unit volume of 1 liter is: Cmix = C1X1 + C2 (1-X1) where C1 and C2 are the concentrations of a solute of interest in Solution 1 and Solution 2 and X1 is the fraction of a mixture that is in Solution 1. For example, mixing 300 ml (0.3L) of leachate containing 1,000 mg/l of Na with 700 ml (0.7L) of groundwater containing 50 mg/l of Na:

$$Cmix = C1X1 + C2\ (1-X1)$$
$$Cmix = 1000\ (0.3) + 50\ (0.7) = 350\ mg/l\ Na$$

"Relatively nonreactive" solutes are those which are nearly unaffected by chemical reactions that might occur during the mixing process. Chloride and bromide are very nonreactive solutes because they only precipitate as solid minerals when solutions become extraordinarily concentrated, such as in a desert environment, and they are not affected by ion exchange or chemical oxidization or reduction reactions. Even though many other solutes, such as sodium and bicarbonate, are involved in some geochemical reactions, they often can be treated as nonreactive if chemical reactions affect the solute concentrations only to a very limited extent or if the reaction kinetics are very slow. Recent textbooks (e.g., Mazor, 1991) have shown that simple mixing can effectively describe solute concentrations in many hydrogeologic settings, including settings located near the ocean, such as the Fresh Kills landfill. The equations for simple mixing of two solutions, each having two parameters with different concentrations, reduces to the equation for a straight line. In other words, if a simple X-Y plot is prepared for two relatively "nonreactive" solutes found at different concentrations in Solution 1 and Solution 2, then concentrations of mixtures will fall on a straight line bounded by values for the solute concentrations in the pure unmixed solutions. At the Fresh Kills landfill, mixtures of groundwater and seawater and groundwater and leachate should define two different straight lines for common "nonreactive" solutes. Wherever all three waters mix, data on scatterplots will fall between the two straight lines defining the two solution mixtures.

Two additional types of specialized diagrams are also used in the GPA to characterize contamination: Piper diagrams and Stiff diagrams. The relative proportions of all the major dissolved ions in groundwaters are shown on Piper plots, which are used to classify different water types and to identify mixing trends and chemical reactions (Freeze and Cherry, 1979). Piper diagrams were initially developed to distinguish between seawater from possible landfill

contamination, a situation similar to that at the Fresh Kills landfill (Piper, 1941). Stiff diagrams show relative concentrations of dissolved species in a water sample and are an easy means to visually compare differences in chemical compositions of different waters. In both Piper and Stiff diagrams, chemical equivalent concentrations are used.

To convert laboratory reported concentrations (in mg/l) to "reactive" concentrations (chemical equivalence concentrations, meq/L), the reported concentrations are first multiplied by their respective valences (ion charges) and then divided by their chemical gram formula weight. This conversion is necessary because each dissolved solute has a different weight and charge. Consequently, two solutes with the same mass per unit volume (e.g., mg/L) will have different numbers of atoms that can participate in chemical reactions. How effective each atom will be in chemical reactions is controlled by its charge. What the conversion procedure effectively does, therefore, is to "normalize" the laboratory concentrations, expressing them in more meaningful geochemical terms (e.g., for assessment of electrochemical balance, and data presentation on Piper and Stiff diagrams).

7.3.1.2 Evaluation of Geochemistry and Solute Transport from Environmental Isotopes

For over four decades, environmental scientists have used isotopic analysis to characterize different water types, different sources of dissolved solutes, major geochemical environments, and the age of groundwater. The geochemical process approach draws on this technique to independently test conclusions based on other geochemical data, hydraulic measurements, and numerical models of groundwater flow and solute transport.

Isotopes are atoms of elements that are lighter or heavier than their most common form. There are two types of isotopes; stable and radiogenic. Stable isotopes do not form by radioactive decay of atoms, whereas radiogenic isotopes are elements formed by radioactive decay (Faure, 1986).

- ***Stable Isotopes***

In this study the stable isotopes of oxygen ($\delta^{18}O$), carbon ($\delta^{13}C$), and hydrogen (δD) were utilized. The most common form of oxygen (^{16}O) has an atomic weight of 16 mass units,

compared to the much rarer oxygen isotope, ^{18}O, which has an atomic weight of 18 mass units. The amounts of isotopes are expressed as ratios in "delta" (δ) notation as parts per thousand (o/oo or 1/1,000) relative to their abundances in internationally accepted standards which are assigned values of zero. For example, a $\delta^{18}O$ value of -10 o/oo means that the ratio (quotient) of ^{18}O to ^{16}O is 10 o/oo smaller than the standard. In other words, there is more ^{16}O (the lighter isotope) compared to ^{18}O in the sample than the standard, so the sample is 10 o/oo "lighter" than the standard. The internationally accepted standards are: (1) for water, the isotopic composition of standard mean oceanic water (SMOW), and (2) for carbon, the carbon isotopic composition in the fossil Pee Dee belemnite (PDB).

Many environmental processes separate ("fractionate") the lighter isotopes from the heavier ones. For example, the isotopes of hydrogen and oxygen are separated when water evaporates or condenses (e.g., Hoefs, 1980; Krouse, 1980). Usually, the light isotopes of water and carbon are separated and concentrated into gas phases, such as water vapor and methane. For example, the methane produced by methanogenesis in a landfill will have a much larger proportion of the light carbon isotope (^{12}C) than the original carbon-bearing source.

At the Fresh Kills landfill, the isotopic content of leachate itself should be different than that of groundwater and seawater because methanogenesis and sulfate-reduction in the landfill distinctively separate the heavy isotopes from the light isotopes of water and carbon compounds (Baedeker and Back, 1979 a,b). This isotopic separation can clearly and effectively "fingerprint" leachate contamination from other water mixtures.

- ***Radiogenic Isotopes***

For this project, the radiogenic isotope of hydrogen (tritium), and the radiogenic isotopes of strontium and lead were investigated. It should be noted that these analyses involved measurement of naturally occurring radiogenic isotopes, and did not entail introduction of radioactive tracers into the environment.

Tritium is produced by nuclear reactions, and one-half of a given amount of tritium will be lost by radioactive decay in about 12.3 years. Between 1952 and 1969, nuclear weapons tests introduced a large amount of tritium to the atmosphere and the world's waters (Drever, 1988).

Figure 7.503 shows the change in tritium activity in tritium units (TU) in precipitation over the northern hemisphere from the early 1950's to present (Robertson and Cherry, 1989).

The isotopic composition of lead (Pb) and strontium (Sr) in natural materials strongly depends upon their chemical composition and time history. Thus, Pb has three radiogenic isotopes, ^{208}Pb, produced by radioactive decay of ^{232}Th, ^{207}Pb, produced by radioactive decay of ^{235}U; and ^{206}Pb, produced by radioactive decay of ^{238}U. ^{204}Pb is a stable isotope and is used as the index isotope (e.g., $^{206}Pb/^{204}Pb$). Similarly, ^{87}Sr is produced by radioactive decay of ^{87}Rb. ^{86}Sr is stable and is used as the index isotope. The abundance of the radiogenic isotopes of strontium and lead depend on both parent isotope concentration and the age of the sample.

Natural materials in which the Rb Sr ratio has been relatively high for a long time will have $^{87}Sr/^{86}Sr$ ratios significantly greater than the ratio in the earth's mantle (about 0.702). Similarly, the isotopic abundance ratios $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ in natural materials depends upon the bulk U/Pb ratio and the age of the sample. The $^{87}Sr/^{86}Sr$ ratio in seawater (about 0.709) is effectively constant because Sr is introduced into the oceans from the weathering of an average of continental rocks world wide, has a long residence time in the marine environment, and is abundant. The isotopic composition of Pb in seawater is more variable because Pb is much less abundant in seawater than is strontium, it is derived from continental sources with variable source U/Pb, and it has a shorter marine residence time than does strontium.

Because the isotopic compositions of Sr and Pb in the natural environment are variable, they are useful to identify the sources of waters and the extent to which water may have mixed. The isotopic compositions of Pb and Sr in waters from the Fresh Kills Landfill have been analyzed to characterize leachate and seawater, and the extent to which leachate and seawater may have mixed with groundwater in bedrock and unconsolidated deposits beneath the landfill. Seawater or sea spray can particularly be identified in very dilute waters by strontium isotopes because the analytical technique (mass spectrometry) can produce excellent results with less than a microgram of strontium.

The isotopic composition of Pb is highly variable in the natural environment, reflecting the U/Pb ratio and age of the source. Pb from sediment or bedrock sources might be expected to be more radiogenic (i.e. higher $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$) than Pb from the earth's mantle because of the higher U/Pb and Th/Pb in crustal rocks, but this relationship is quite variable.

Similarly, seawater Pb has variable isotopic ratios because Pb is present in low concentrations and does not have a long residence time in seawater. Pb from certain kinds of industrial materials, such as automobile batteries, commonly have anomalous radiogenic isotopic ratios because they have been manufactured from Pb ores of the midcontinent (Missouri, Illinois, Iowa, Wisconsin) region (the so-called 'J-leads').

7.3.2 Conceptual Model for Landfill Geochemistry

Landfill leachate forms when chemical byproducts of degrading organic matter are mobilized, and inorganic solids and minerals in the landfill and underlying soils are dissolved by landfill-derived organic and inorganic acids. Organic degradation is accelerated and enhanced by bacteria, which use the organic matter as a nutrient source. Freshly deposited waste is first biodegraded in the presence of oxygen (oxic). This process is identical to the biodegradation of organic matter in shallow soils. As oxygen is depleted, the landfill waste biodegrades in the absence of oxygen (anoxic). This process mostly involves fermentation reactions identical to those occurring in human digestive tracts and in tidal flat muds (Baedeker and Back, 1979b). Depending upon the waste stream and age, individual landfill cells can generate different types of leachate.

Landfills generally have an anoxic, methane-producing core and an oxygenated surface. Consequently, landfill leachate is oxygen depleted and has low Eh (a measure of how effectively elements lose or gain electrons in chemical reactions). The low Eh of landfill leachate mobilizes many metals and generally causes leachate to have high concentrations of organic carbon, iron, manganese, ammonia, hydrogen sulfide, and alkalinity (Baedeker and Back, 1979).

When leachate infiltrates to the water table, groundwater under a landfill also becomes oxygen depleted. This anoxic zone of leachate-impacted groundwater may extend downgradient of the landfill, depending upon groundwater flow velocity, rate of leachate discharge, and age of the landfill. A transition zone commonly occurs between the anoxic zone and the oxygenated native groundwater. In this transition zone, some of the trace metals in solution may precipitate out when they come into contact with small amounts of oxygen. Figure 7.504 shows schematically how the geochemistry of an active landfill evolves.

The geochemical process approach study of the Fresh Kills landfill must be placed in the context of the natural geochemical setting and the types of groundwater that would be found in the underlying geologic formations. Four different lithologic units underlie or are proximate to the landfill: (1) Ordovician-age serpentinite (Staten Island Serpentinite); (2) Newark Group Triassic sandstone/shale (Stockton and Lockatong Formations), (3) Quaternary unconsolidated (mostly glacial) sediments, and (4) Cretaceous-age silts, clays and sands. Seawater and landfill leachate may influence groundwater in all of these lithologic units.

- ***Staten Island Serpentinite***

The unaltered, interior portion of the Staten Island Serpentinite is composed of iron and magnesium-rich silicate minerals, olivine and orthopyroxene, with a lesser amount of the chromium-rich mineral picorite. The outside edge of the rock body has been altered ("serpentinized") by heat and pressure to a complicated mixture of asbestiform minerals, including amphibole, chrysotile, and talc. Some of the original iron is now magnetite, an iron-oxide. When the minerals in serpentinite dissolve in groundwater, they contribute large amounts of magnesium compared to calcium and sodium. Typically, the groundwater is a magnesium-bicarbonate type (White, et al., 1963). This natural Mg-HCO3 signature from the Staten Island Serpentinite is expected for groundwater at the Fresh Kills site that has been primarily in contact with that formation.

- ***Stockton Formation***

The Triassic-age Stockton Formation is a classic "redbed" sequence of rocks, consisting of arkosic sandstones, siltstones, and shales. The formation is red from the oxidation of iron to hematite and goethite (Savage, 1968). Feldspar and quartz are the major minerals in the sediments, which were deposited in an alluvial or fluvial environment. There are few carbonate minerals. Several analyses of groundwater from aquifers in the correlative Newark Super group (White, et al., 1963) show that its water is similar to that found in limestone aquifers, a calcium-magnesium-bicarbonate-type water probably due to dissolving carbonate cements.

- ***Quaternary Deposits***

Quaternary deposits at the Fresh Kills site consist primarily of glacial till, glaciolacustrine silts and clays, and glacial and Recent sands. Glacial till typically consists of recycled material from underlying geologic deposits. This means that till often exhibits considerable mineralogical variability, complicating the characterization of water type. As a generalization, however, groundwater from glacial tills in New York is often of calcium-sodium-bicarbonate or calcium-magnesium-bicarbonate type.

- ***Lower Cretaceous Sediments***

The Cretaceous sediments on Staten Island are part of a complex sequence of deltaic sediments deposited on the Atlantic Coastal Plain. The sedimentological facies (individual strata reflecting a local environment of deposition) are complex and vary with depth and in areal extent (Allen, 1965; Broughten, 1966; Owen, et al., 1968). The lithology of the formation, both regionally and at the Fresh Kills site, consists of interbedded sand and clay units. Lignite and pyrite are common (Ohan, Kureshy and Kaarsberg, 1975, and references cited within), as well as the clay minerals glauconite, illite, and kaolinite (Pucci and Owens, 1989). The coarse-grained sediments mostly consist of quartz and silicate rock fragments. There are few carbonate minerals.

Because of the relative absence of highly soluble minerals, it is expected that the dissolved solids concentrations in groundwater from the Cretaceous sediments on Staten Island will be small compared to that of other aquifer units at the site. However, the groundwater type may locally vary, depending upon the degree to which lignite (carbon source) and pyrite (iron-sulfide) are dissolved by oxygen (oxidized), and the extent to which clay minerals are ion exchangers or "water softeners".

The local or "micro" geochemical environment may significantly affect water quality in Cretaceous sediments on the Atlantic Coastal Plain. Substantial differences in both total dissolved solids content and type of groundwater can occur between confining beds and aquifer units over a vertical distance of only a few feet (Pucci and Owens, 1989).

Changes in water quality are related to how rapidly the minerals dissolve, ion exchange, and the extent to which groundwater is oxygenated (Pucci and Owens, 1989). Groundwater in the

Cretaceous sediments in the Fresh Kills area is expected to be cation-bicarbonate type where dissolved oxygen is absent; and perhaps a sodium-sulfate-bicarbonate type, where oxygen and pyrite naturally combine to form dilute sulfuric acid.

- ***Seawater***

Seawater intrusion has occurred in some areas of Staten Island (Soren, 1988) and the Fresh Kills landfill (Parsons Brinkerhoff-Cosulich, 1982; this investigation). The major elements in seawater are sodium and chloride. Surface water bodies, such as the Arthur Kill, have received an input of municipal and industrial waste for many years (New York State Department of Health, 1960), and there may be contaminants sorbed to the near-shore sediments adjacent to these surface water bodies. When seawater flows landward, these contaminants could be desorbed and be transported to the site by groundwater. Table 7.22 provides a summary of the major solutes and nutrients contained in seawater and their concentrations. These concentrations are reported in mg/l (parts per million), the standard practice for these solutes which is followed in the graphical presentation and discussion of all geochemical data in this report section.

- ***Leachate***

Leachates are very complicated solutions which vary in chemical composition according to the waste stream, extent of water infiltration, temperature and time. However, most landfill leachates are formed in an anoxic environment, leading to chemical reactions that produce solute proportions very different from that found in uncontaminated groundwater or seawater. In particular, organic degradation produces dissolved organic matter, consisting mostly of complex organic acids, at much higher concentrations than normally found in native groundwater.

- ***Natural Geochemical Water Types***

Figure 7.505 shows a Piper diagram summarizing the anticipated types of native groundwater at the Fresh Kills site, based on assumed ionic species produced from water-rock interactions. Briefly, this diagram consists of three parts. Data points that would plot in the low left-hand triangle show the relative reactive percentages (equivalent concentration) of the major positively charged solutes (cations): calcium, magnesium, and sodium+potassium. To obtain relative percentages, each relative concentration is divided by the sum of all the cation reactive

concentrations (milliequivalents per liter). The percentages (out of 100 percent of the total major cation concentrations as meq/L) are then plotted on the triangular diagram, each apex of which marks the location for a water which only has one major cation.

Similarly, the triangular plot on the lower right-hand side shows the relative reactive percentages of the negatively charged major solutes (anions): chloride, sulfate, and carbonate species. Note that carbonate species must be calculated from alkalinity data obtained from the laboratory. In this investigation, the assumption was made that carbonate species were the primary contributors of alkalinity to groundwater. This assumption is generally valid for moderate pH, moderate to high alkalinity waters such as those common at the site.

Finally, the data points in the two triangles are extrapolated upwards into the diamond-shaped diagram which effectively presents the proportions of all seven major ions in a single region. Additional information on Piper diagrams can be found in any standard textbook on groundwater hydrology (e.g., Freeze and Cherry, 1979).

The Piper diagram in Figure 7.505 shows the fields or zones wherein groundwater from the different natural rocks and soils in the Fresh Kills area might be expected to fall. The fields were drawn assuming that the water chemistry in the units evolved only by the chemical reactions between precipitation and the minerals in the rocks. If the regional bedrock recharge area upgradient from the landfill site is overlain by glacial drift, the character of water in the bedrock will partly reflect the water chemistry of the drift. Note that seawater plots near the extreme right area of the diamond, documenting that most of the dissolved solids in seawater are sodium and chloride. In contrast, the anticipated groundwater chemistry of the serpentinite and Stockton Formation plots on the extreme left-hand side of the diamond, where more bicarbonate, calcium, and magnesium-rich waters would be found. Water chemistry in the glacial drift is expected to be far more variable, depending upon local variations in the mineralogical composition of the drift. For example, drift with substantial cation exchange capacity will exhibit water chemistry that is more sodium rich (because of natural "water softening"), compared to that found in drift with a low cation exchange capacity.

7.3.3 Geochemical Analysis

In the ensuing specific discussions of each landfill section, a series of graphical analyses of water chemistry and isotope data are provided to describe and differentiate the groundwaters associated with the Fresh Kills Landfill and underlying geologic units. Background information regarding these data presentations is provided below. This discussion is followed by a description of the chemical/isotopic database collected for this investigation, including an overview of analytical protocols and uncertainties associated with the measurement of chloride and the isotope parameters. It should be noted that, as a supplemental component of the overall water chemistry characterization program at Fresh Kills, the database for the geochemical investigation is not as comprehensive as that compiled for the regulatory agency specified 6 NYCRR Part 360 program. With the exception of Landfill Section 1/9, all wells were not sampled under the geochemical program (Section 4.7), and the list of major ions and isotopes analyzed at each well periodically varied in accordance with the defined scope of each phase of the investigation (as a minimum, a subset of hydraulically up and down gradient well clusters were analyzed for the full suite of geochemical analytes at each landfill section). Consequently, the various presentations of geochemical data (e.g., solute scatterplots) do not necessarily include all monitoring wells within a landfill section, or may include a specific well only in certain presentations where adequate analytical data is available.

- ***Solute Scatterplots***

The proportions of many dissolved solutes in leachate and natural groundwater (freshwater) should be different because the composition of landfill waste and its associated geochemical reactions are different than the mineral-water reactions in the underlying geologic materials. The proportions of solutes in seawater, which have evolved through geologic time, should be different from those in either native groundwater or leachate. Consequently, scatterplots of dissolved ion concentrations in leachate, groundwater, and seawater should exhibit distinct linear relationships that reflect mixing of the different water types (the equilibrium water chemistry associated with each water type is referred to as its "end member" chemistry).

In particular, because of the biodegradation of landfill waste material, leachate from a site of recent waste disposal should exhibit a higher concentration of total and dissolved organic carbon than seawater or groundwater. In contrast, the chloride concentration in seawater of about 20,000

mg/l should be much higher than that found in either groundwater or leachate, both of which are associated with relatively chloride-poor solids. Scatterplots of dissolved organic carbon (DOC) versus chloride concentration should differentiate groundwater that has mixed with seawater from that which has mixed with leachate. Similarly, a plot of dissolved sodium versus chloride can be used to distinguish leachate from seawater mixed with groundwater if the ratio of sodium to chloride in the leachate is different from that of seawater. It should be noted that the results of leachate anlaysis from other landfills indicates that the molar sodium/chloride ratio of leachate is variable and overlaps that of seawater. However, the molar sodium/chloride ratio of water sample from well 1W89:XW-5 (chosen to represent leachate in the geochemical mixing models described in Section 7.3.6) is approximately 1.7. This is much different than seawater, which has a molar ratio of 0.9. Thus, assuming the data from well XW-5 is representative, leachate from the Fresh Kills landfill has a molar sodium/chloride ratio about twice that of seawater.

The freshwater-seawater mixing line plotted on the sodium-chloride scatterplots is important because it defines a mixing trend. In most of the landfill sections, there is some scatter about this trend that could be the result of analytical error, uncertainty associated with chloride analysis, ion exchange reaction involving sodium, or the natural variability of the chemical composition of groundwater. The important feature of this scatterplot is that the data appear to form two different groups. One group follows the trend that suggests a possible seawater mixture (primarily intermediate depth wells), and the second group generally plots well above the mixing line suggesting a possible leachate mixture.

Boron can also be used to effectively distinguish freshwater-seawater mixtures from freshwater-leachate mixtures. A scatter plot of boron versus sulfate will show a distinct mixing line between freshwater and seawater. Freshwater samples which have anomalously high boron concentrations are considered to be contaminated with leachate (Ulman, 1991).

Landfills are noted for their distinct chemically reducing environment. In a reducing environment, sulfide is formed by the chemical transformation (reduction) of sulfate, coupled with the chemical oxidation of organic matter to dissolved carbon dioxide (usually as bicarbonate) and organic acids (Stumm and Morgan, 1981). A general equation showing this chemical reaction is:

$$SO_4^{-2} + 2CH_2O = 2\ HCO_3^- + H_2S_{(g)}$$

The net effect of this chemical reaction is that landfill leachate is often characterized by high dissolved alkalinity (mostly bicarbonate at pH from 6.4 to 10.3) and negligible sulfate concentrations. Consequently, a scatter plot of dissolved alkalinity (as bicarbonate) versus sulfate can be also used to distinguish leachate from native groundwater. Similarly , under the reducing conditions within a landfill, nitrogen is primarily present as ammonium (commonly referred to as ammonia), a reduced nitrogen species formed either through ammonification or nitrate reduction, as indicated below:

$$NO_3^- + H_2O + 2CH_2O = NH_4^+ + 2\ HCO_3^-$$

Therefore, a scatterplot of ammonium versus alkalinity should indicate leachate influenced groundwater. Similarly a plot of ammonium versus DOC can be used to characterize leachate.

- ***Environmental Isotopes***

A scatterplot of the ratios of the common environmental isotopes of water, $^2H/^1H$ (δD) versus $^{18}O/^{16}O$ ($\delta^{18}O$), can also be used to distinguish between leachate contamination and naturally poor quality groundwater. Most precipitation in the world falls near a well-known linear "water line" (global meteoric water line, or GMWL) defined by the equation (Hoefs, 1987):

$$\delta^2H = 8\delta^{18}O + 10$$

However, when methane or hydrogen sulfide are produced, the "light" hydrogen is preferentially extracted from the leachate, which is then left with proportionally more "heavy" hydrogen. Leachate or groundwater affected by methanogenesis and sulfide production will therefore plot on a vertical line above the meteoric water line and intersecting it at a point documenting the average isotopic content of infiltrating precipitation (e.g., Figure 7.541). Similarly, when methane is produced, bacteria extract the lightest carbon (^{12}C) from organic matter, resulting in proportionally heavier carbon left in the dissolved bicarbonate produced in the chemical reaction. Therefore, a plot of the isotopic ratio $^{13}C/^{12}C$ ($\delta^{13}C$) versus the concentrations of dissolved bicarbonate can be used to distinguish leachate from native groundwater. The isotopic fractionations of water and carbon associated with anoxic environments are also observed naturally in peat bogs and tidal flats. Because the Fresh Kills landfill was placed on a tidal marsh, any identification of leachate from its isotopic character must be confirmed by other

chemical parameters or by a particular site's hydrogeologic setting. For example, the dissolved inorganic carbon (DIC) isotopic content of a shallow groundwater sample collected from within an elevated region of the landfill leachate mound would not reflect geochemical processes associated with previous tidal sediments and peats underlying the landfill. In contrast, enriched δD in water and $\delta^{13}C$ of DIC in groundwater obtained from a semi-confined sand unit at depth might reflect natural geochemical processes.

Tritium was used to determine where groundwater might predate atmospheric atomic weapons testing, which began about 30 years ago and introduced large amounts of tritiated seawater into the atmosphere. During the height of atomic weapons testing, precipitation had a tritium content ranging from 1,000 to 3,000 tritium units (TU). Once this water infiltrated into aquifers and landfills, its tritium content decreased by half every 12.3 years. For example, water with a 2,000 TU that entered a flow path in 1960 will have about 1,000 TU in 1972, 500 TU in 1984, and 250 TU in 1996. In contrast, the global water cycle has diluted the tritium in the atmosphere such that modern precipitation has only a few tens of TU (Robertson and Cherry, 1989). Because it is known how long it takes for tritium to break down through radioactive decay, groundwater age can be directly measured if the water infiltrated to the water table after nuclear testing began 30 years ago (Robertson and Cherry, 1989). Leachate produced by the Fresh Kills landfill 30 years ago should be distinguishable from more recently generated leachate by its anomalously high tritium content.

The isotopic composition of Pb is highly variable in the natural environment, reflecting the U/Pb ratio and age of the source. Pb from sediment or bedrock sources might be expected to be more radiogenic (i.e. higher $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$) than Pb from the earth's mantle because of the higher U/Pb and The/Pb in crustal rocks, but this relationship is quite variable. Similarly, seawater Pb has variable isotopic ratios because Pb is present in low concentrations and does not have a long residence time in seawater. As noted earlier, Pb from certain kinds of industrial materials, such as automobile batteries, commonly exhibit anomalous radiogenic isotopic ratios. The radiogenic isotopes of Sr and Pb were investigated to determine their potential applicability to characterize contamination at landfills. Consequently, the data sets for these analyses are small relative to the other more standard chemical and isotopic analyses, and they will be discussed subsequently for the entire landfill rather than on a landfill section by section basis.

7.3.3.1 *Analytical Methods and Uncertainties*

The geochemical analysis for the Fresh Kills project was designed to determine what geochemical methods are most useful to characterize and distinguish leachate from seawater (or seawater influences) and native groundwater. To this end, a representative subset of all samples of groundwater was collected to test each method. This approach of analysis is the most cost-effective means of determining which method or methods would be most useful to use in future monitoring efforts. Probable indicator parameters for leachate were measured in samples from all wells (i.e., total dissolved solids, alkalinity, bromide, chloride, sulfate, total organic carbon, ammonia). Water was also analyzed for a comprehensive suite of dissolved solutes and isotope analyses on filtered samples collected from a subset of monitoring well clusters located within the refuse mounds and hydraulically up and downgradient (relative to the deep bedrock aquifer) of landfill sections. The geochemical sampling program was described in detail previously in report Section 4.7. A summary of all geochemical data collected during this investigation is contained in Appendix M, which also includes the chemical equivalence concentrations of the dissolved inorganic ion species.

Water quality data are discussed from all monitoring locations with the exception of those obtained from deep piezometers installed within the refuse mounds. These installations were installed in the central areas of the landfill sections as temporary monitoring points, primarily for water level data collection. Limited water quality data collected from them is not considered to be representative of deep aquifer chemistry because: (1) the depth, small diameter, and method of construction of these installations precluded optimal development for water quality sampling purposes; and (2) shifting of landfill materials resulted in damage to the piezometer riser pipes at several installations, compromising the integrity of the annular seal at these locations.

Standard analytical techniques were used to determine concentrations of dissolved and total chemical parameters and environmental isotopes in accordance with the Quality Assurance Project Plans (QAPjP) for the project analytical laboratory and hydrogeological investigation. The isotopic analysis of lead (Pb) and strontium (Sr) in water represents a fairly unique procedure and was performed in the geochemical laboratories of Syracuse University. A brief discussion of the analytical procedures, especially designed for measuring the isotopic composition of Pb and Sr in organic-rich leachate, is given below.

7.3.3.1.1 Lead and Strontium Isotopic Method Analysis

Lead: A 300 ml aliquot of the sample was evaporated to less than 100 ml. 1.5 ml of this liquid was transferred to a pre-cleaned microcentrifuge tube and 0.1 ml of concentrated HBr was added to make the solution 0.6M. The sample was then centrifuged at 5000 rpm for 5 minutes and the centrate loaded onto an ion exchange column with 35 microliters of Dowex AG 1 8X anion exchange resin which had been equilibrated with 0.6M HBr. The column was eluted with 0.6M HBr to remove elements other than Pb, and then Pb was removed with one column volume of 6M HCl. The Pb sample was evaporated to dryness with 1 drop of distilled HNO_3 and examined. If the volume of salt suggested that the Pb was not sufficiently purified, the column procedure was repeated until a clean sample resulted. The Pb sample was loaded onto a Re filament with 2 microliters each of 0.25N H_3PO_4 and silica gel, and analyzed in a VG Sector 54 multicollector mass spectrometer.

Strontium: A 300 ml aliquot of the sample was placed in a teflon beaker and evaporated to dryness. 5 ml of 2.5M HCl was added to the dried sample and the sample agitated to promote solution. 1.5 ml of the HCl solution was transferred to a microcentrifuge tube and centrifuged at 5000 rpm for 5 minutes. The centrate was loaded onto an ion exchange column containing about 30 ml of Dowex AG50 cation resin that had previously been equilibrated with 2.5M HCl. The column was eluted with 71 ml of 2.5M HCl , then Sr was removed in an additional 30 ml of 2.5MHCl. The sample was evaporated to dryness, re-dissolved in 2 ml of 2.5MHCl, and passed through the column again. The final sample was evaporated to dryness, loaded onto a Ta filament in 5 microliters of 0.25N H_3PO_4, and analyzed in a VG Sector 54 multicollector mass spectrometer.

7.3.3.1.2 Analytical Uncertainties

The quality of analyses of dissolved solutes in water samples was checked by electrochemical charge balance. Water should be electrochemically neutral; therefore, any samples which have an imbalance of greater than 20 percent are suspect and must be carefully examined. The balance calculation uses the milliequivalents per liter of total chloride, dissolved bicarbonate, dissolved organic carbon, and dissolved sulfate for anions, and dissolved sodium, dissolved

magnesium, dissolved calcium, dissolved potassium, and total ammonia for cations. For dissolved organic carbon, an average organic molecule is used (CH_2O, formula weight of 30g per mol) with the assumption that most organic molecules are negatively charged. This method of charge balance calculation is somewhat different than the standard charge balance calculation (Freeze and Cherry, 1979) because it includes an organic molecule with the anions, and ammonium with the cations. The equation for calculation, [(sum cations (meq/L)-sum anions (meq/L)/(sum cations (meq/L) + sum anions (meq/L))] x 100, remains the same. DOC and ammonium were added to the charge balance calculation because their addition resulted in a better charge balance. The attempt to account for DOC and ammonium in the charge balances requires several assumptions. First, this method assumes that organic acids have no effect on the alkalinity titration. Second, it is assumed that the average formula weight for an organic molecule is 30 grams per mol and the average valence charge is -1. It is also assumed that the pH of the water samples does not vary enough to significantly affect quantification of the ammonium concentration. All electrochemical charge balance data for samples obtained during this investigation are contained in Appendix M.

- ***Chloride***

For this study, total chloride was used in the calculations as a conservative compromise because concentrations of total chloride and dissolved chloride did not agree for some analyses of groundwater collected during the July 1991 and January 1992 sampling quarters. Electrochemically, the same samples often did not adequately balance (Appendix M). The lack of agreement between total and dissolved chloride is especially unusual because it is extremely unlikely that highly soluble chloride compounds (such as halite) could possibly exist as part of particulate material in the total sample. The potential exclusion of chloride from the dissolved sample during filtering was examined in the laboratory as follows: 50 ml of 500 mg/L chloride solution was mixed with 1 gram of smectite-rich soil from landfill soils and then filtered through a 0.2 micron filter. The chloride concentrations (measured by the mercuric nitrate method) before and after the experiments were identical, precluding filtration as a cause of the disparate analytical data.

To determine if the analytical methods had interferences not reported in the literature, five samples of leachate were collected from selected monitoring wells in Landfill Section 2/8 and 6/7 during January 1993 that exhibited discrepancies between total and dissolved chloride

concentrations in the July 1991 and January 1992 sampling rounds. Chloride concentrations of unpreserved filtered and unfiltered samples, and nitric acid preserved filtered and unfiltered samples were measured by the mercuric nitrate method used to generate the original data, with results provided in Attachment 32.

In the analytical method, mercuric nitrate is added to the leachate until all the chloride combines with mercury. The presence of excess mercuric ions causes a color change from clear to violet in the presence of an indicator reagent. Obtaining consistent values was extremely difficult for the unpreserved samples because the color change was typically indistinct. Often, the apparent color change was immediate, indicating less than 20 mg/L of chloride. For one sample, the color changed to violet and then reversed back to clear. Overall, it was very difficult to obtain reproducible results when the mercuric nitrate method used with unpreserved samples. It is possible that mercuric ions added to the sample do not stay in solution as ions but are complexed by organic acids in leachate . The complexes could unsystematically degrade during the analysis to produce the analytical imprecision and inaccuracy. Another possibility is that the organic acids somehow inhibit color development.

Chloride was also analyzed using the common argentometric method, which uses silver instead of mercury. The results were equally poor as for the mercuric nitrate method for the unpreserved samples. Additional replicate analyses of the filtered and unfiltered sample (Attachment 32) routinely indicated order of magnitude differences between the mercuric nitrate and argentometric methods, with no significant variation within method for filtered and unfiltered samples. These replicate analyses showed marked decreases in measured chloride concentrations with time, perhaps as a response to chemical or biological processes affecting the organic acids in the unpreserved samples. This latter finding may explain the discrepancy between chloride analyses during the July 1991 and January 1992 sampling rounds, as filtered samples were shipped off-site for analysis which was performed subsequent to the unfiltered analyses performed locally within a day of sample collection. Both filtered and unfiltered groundwater samples collected at Section 1/9 during the July 1992 sampling quarter were analyzed simultaneously within one day of collection, and do not exhibit significant variance between total and dissolved concentrations.

In contrast to the results of the mercuric nitrate titrations on the un-preserved samples, chloride concentrations measured in sets of unfiltered and filtered samples preserved with nitric acid were identical. Substitution of these chloride values into charge balances resulted in satisfactory

electrochemical balances. Nitric acid is an oxidizing agent which destroys many of the organic acids that might participate in forming mercury and other metal complexes. The analytical uncertainties associated with chloride determinations in some of the Fresh Kills leachate represents a phenomenon unreported in the literature. The reason why the chemical interferences mostly occur in the unpreserved samples is unknown, but may be related to organic substances present in the leachate.

Given the uncertainty in the dissolved, unpreserved, chloride analyses, unacidified total chloride data was used in the geochemical interpretations. The total chloride concentrations are higher than dissolved concentrations, and result in better electrochemical balances in most cases. As noted above, in the July 1992 sampling quarter at Landfill Section 1/9, total and dissolved chloride concentrations were equivalent, and most samples balanced electrochemically.

- ***Isotopes***

With the exception of tritium, the precision of instrument detection is generally not provided on a unit sample basis for the stable and radiogenic isotope analytical data. Based on the instrumentation and methods used to provide these data, associated error in reported values is: Pb (+/- 0.5%), Sr (+/- 0.05%), $\delta^{13}C$ (+/- 0.1 o/oo), $\delta^{18}O$ (+/- 0.1 o/oo), δD (+/- 1.0 o/oo). It should be noted that lead and strontium isotopes are reported as dimensionless ratios, and therefore error is reported as a percentage of the ratio. Carbon, oxygen, and deuterium isotopes are reported in "del" notation (parts per thousand), and error is reported in the same units.

7.3.3.2 Landfill Section 6/7

A scatterplot of total Cl versus DOC for Section 6/7 (Figures 7.506 - 7.507) shows that the data generally separate into two sets. Deep and intermediate monitoring well data plot on a horizontal trend reflecting relatively low concentrations of dissolved organic carbon (<25 mg/l) and relatively high concentrations of chloride. The chloride in the deep and intermediate monitoring wells may reflect a very small portion of connate water (seawater) mixing from below. In contrast, leachate-affected groundwater and water from most shallow wells plot on a trend having moderate chloride concentration and concentrations of organic carbon higher than that in the intermediate and deeper wells (50-3,000 mg/l) and likely reflect mixing of leachate and shallow gorundwater. Some wells exhibit DOC greater than about 100 mg/l and chloride concentrations

greater than about 800 mg/l. The water in these wells could possibly reflect: (1) a mixture of leachate with seawater; (2) a mixture of leachate with sea salt that was deposited on the landfill during storms or as dry particulates; (3) different (higher chloride) leachate composition; or (4) the influence of contamination in the Arthur Kill with subsequent influx into shallow groundwater.

A plot of dissolved sodium versus chloride suggests that some of the leachate exhibits a component similar to that of seawater. Figure 7.508 - 7.509 shows that the data separate into two fields: one approximately defined by the proportions of sodium and chloride in seawater (e.g., 6W91:IT152S, and 6W89:YW2 and YW10), and the other defined by leachate with high sodium and moderate to low chloride content (e.g., 6W91:IT160S, 151S and 6W89:YW1). The prior data support the hypothesis that the chlorinity in these wells may be derived from sea salt. No deep wells exhibit a leachate signature.

Figure 7.510, a plot of dissolved boron versus dissolved sulfate shows that all but one of the shallow wells plot along the horizontal boron axis, indicating a predominant freshwater source. Those samples that exhibit boron concentrations greater than 3 mg/l (average composition of freshwater) may indicate a borate source, such as detergents, in the landfill.

Figures 7.511 - 7.512, plots of dissolved sulfate versus dissolved bicarbonate, show that deep and intermediate groundwaters have measurable sulfate and minor alkalinity compared to the leachate-freshwater mixtures, which have little or no sulfate and bicarbonate concentrations up to thousands of mg/l. Well 6W91:IT152S exhibits an elevated sulfate concentration compared to that observed in other shallow wells. The water from this well appears to be primarily sea salt-affected and has little leachate character. This finding correlates with the results of the boron-sulfate and sodium-chloride ratio analyses. The value for dissolved alkalinity in water from well 6W91:IT155D may be too high, based on an electrochemical imbalance of more than -20 percent. Correction of the alkalinity concentration to achieve electrochemical balance would result in a concentration approximately 200 mg/l less than observed, consistent with the alkalinity reported for uncontaminated waters from serpentinite elsewhere (e.g., White, 1962). Alternatively, due to the shallow depth to bedrock in the area of this well (and well 6W91:IT154) water chemistry may be influenced by shallow infiltration associated with the area of the Richmond Avenue berm.

Figures 7.513 - 7.514, plots of dissolved ammonium versus dissolved bicarbonate concentrations, indicate that leachate-freshwater mixtures exhibit elevated ammonia and bicarbonate concentrations, predictable from anticipated ammonification in the anoxic leachate environment. In contrast, samples from deep and intermediate depth water bearing zones exhibit negligible ammonia, and bicarbonate concentrations up to about 350 mg/l.

- ***Piper and Stiff Diagrams***

Figures 7.515 and 7.516 show Piper and Stiff diagrams for those samples for which dissolved major solute analyses are available. As mentioned earlier, the Piper plot is a synthesis of the proportions of all major solutes in water. First, note that the radius of the circles defining the data points is proportional to the total dissolved solids content of the water, and that seawater is considerably more concentrated than any other sample at the site. Sample from deep well 6W91:IT160D completed in the Stockton Formation is a mixed cation-chloride-bicarbonate type water and very dilute (Figure 7.515). In contrast, leachate exhibits a distinctive sodium-bicarbonate water signature with TDS concentrations in the thousands of mg/l. The deep well completed in the Stockton Formation exhibits no influences from leachate contamination, based on its extremely dilute character. (Note that insufficient major ion data (e.g., sulfate, bicarbonate) was available for deep wells 6W91:IT153D, 163D in the July 1991 sampling quarter to include them on the Piper plot presented on Figure 7.515).

Perhaps the easiest method to visualize the distinctive chemistry of various groundwaters is through examination of Stiff diagrams (Figure 7.516 and 7.516A). These "star"-shaped diagrams consist of six horizontal lines, each graduated in concentrations expressed as equivalent concentrations, the same units used to construct Piper diagrams. Different water types are readily observed by comparing the shapes of the "stars". Note on Figure 7.516 that leachate (e.g., 6W89:YW9) exhibits a distinctive signature, with a sharp point extending to the upper left and a point oriented midway to the right, reflecting high sodium and bicarbonate concentrations. In contrast, as noted at the bottom of the figure, seawater would appear T-shaped, because both sodium and chloride concentrations are very high. The signature exhibited by groundwater in the deep wells is difficult to discern, a function of the low dissolved solids content of these waters, and is significantly different from that observed in the leachate.

It should be noted that the scale of the Stiff diagram is normally not adjusted or expanded to accommodate very dilute water chemistry (as is indicated in many of the scatter plot diagrams)

because the distinctive shape of the diagram, including lack of a distinct pattern due to very low TDS, represents the fundamental basis for discriminating between water types with this data presentation. However, keeping a constant scale results in loss of information regarding the chemical composition of dilute freshwaters (TDS<1000 mg/L) when compared with the brackish and saline waters under the Fresh Kills landfill. To compensate for this, expanded Stiff diagrams were prepared for the two most dilute water samples observed at Section 6/7 (Figure 7.516A). 6W91:IT160S, which is screened in refuse, has a sodium-bicarbonate water composition and likely reflects a leachate-groundwater mixture. 6W91:IT161S has a sodium-chloride water composition and may reflect a very dilute seawater mixture.

- ***Environmental and Radiogenic Isotopes***

If leachate has undergone methanogenesis and sulfate reduction, a ratio plot of δD vs. $\delta^{18}O$ will exhibit a series of lines trending vertically above the point on the meteoric water line indicating the isotopic content of the infiltrating precipitation. Figure 7.517 shows this to be the case for the leachate influenced wells at Section 6/7. These wells plot vertically above the GMWL at a $\delta^{18}O$ in the range of -7.0 to -8.0 o/oo, bracketing the value for precipitation in southern New York of -7.5 o/oo. Leachate is thus clearly defined by the isotopic content of the water. The $\delta^{18}O$ of the intermediate and deep wells essentially define the GMWL and are plotted on it.

Similarly, a plot of the carbon isotopic content of dissolved inorganic carbon versus bicarbonate concentrations (Figure 7.518), clearly shows that leachate bicarbonate is heavier (larger $\delta^{13}C$), and thus distinct from bicarbonate-poor deep groundwater at Section 6/7. The heavier isotopic content of the leachate inorganic carbon is consistent with what is expected from methane production; methane produced in the landfill removes the lighter carbon from the dissolved carbon pool, which is consequently left with a higher concentration of the heavier carbon isotope. The carbon isotopic content of bicarbonate in deep wells, about -20 o/oo, is close to -25 o/oo, the value for natural organic matter associated with sedimentary rocks and soils (Hoefs, 1987).

Figure 7.519, the tritium activity for selected wells in Section 6/7, shows that the deep groundwaters exhibit a tritium content generally <10 TU; they have not been affected by leachate during the past 30 years. In contrast, the tritium content of shallow leachate ranges from a modern value of about 50 TU to about 200 TU, a value consistent with what would be predicted from radioactive decay since the early 1960s. One exception to the tritium relationship exhibited in the deep wells occurs at location 6W91:IT153D, where a value of approximately 30 TU is

observed. As noted earlier relative to the dissolved sulfate/bicarbonate plot, this well is located in an area where the bedrock surface rises to an elevation of approximately -10 ft, and may be influenced by a shallow flow system.

7.3.3.3 Landfill Section 1/9

As for Section 6/7, native groundwater and leachate and seawater influences can be identified by solute ratio plots. Seawater influence is much more pronounced at Section 1/9, primarily in the intermediate depth wells completed in the Cretaceous sand unit in the western and southern areas of the landfill. Plots of dissolved organic carbon (DOC) versus total chloride (Figures 7.520 - 7.522) for Section 1/9 (July 1992 sampling quarter data) exhibit a clear distinction between leachate influenced and seawater influenced groundwater. Native groundwater (freshwater) that has not mixed with either seawater or leachate plots near the origin. Native groundwater that has mixed with seawater exhibits a low DOC and high chloride content, and plots along the horizontal axis. Native groundwater that has mixed with leachate plots along the vertical axis and exhibits high DOC and low chloride. From these figures, monitoring wells that exhibit elevated DOC (leachate mixing) are the shallow monitoring wells 1W91:IT001S, 002S, 003S, 007S, 008S, 009S, 010S, 011S, 012S, and 013S. Also, the intermediate wells screened in Recent/glacial sands (1W91:IT010I, 011I, and 1W92:IT016I) exhibits water with elevated DOC concentrations, although they do not plot in the freshwater leachate mixing zone.

Most intermediate depth wells exhibit groundwater containing more than 3000 mg/L of chloride, and plot near the seawater mixing line defined by Na and Cl (Figures 7.523 - 7.524). These wells are adjacent to the Arthur Kill on the west side of Section 1/9 and are screened in Cretaceous sand deposits 28 ft to 100 ft below sea level. The remaining intermediate and deep monitoring wells in Section 1/9 exhibit native groundwater chemistry, or native chemistry with a slight seawater mixture.

The plots of dissolved sodium versus total chloride for Section 1/9 (Figures 7.523 - 7.524) also suggest that water mixed with leachate exhibits a greater proportion of sodium than found in seawater, and thus plot above the line defining seawater -freshwater mixtures. The data distribution on the Na-Cl plots agree with the conclusions drawn from the DOC-chloride plot: only water from shallow wells, and intermediate depth wells screened in Recent/glacial sands, exhibit leachate mixtures.

Figures 7.525 - 7.526 are plots of boron versus sulfate for Landfill Section 1/9. Because of the different sulfate/boron ratios of seawater and freshwater, these scatterplots represent a very effective means to distinguish seawater mixtures. As mentioned earlier, landfill leachate commonly contains higher concentrations of boron than seawater or groundwater because of boron sources, usually detergents, in the landfill. The boron-sulfate plot becomes even more useful, considering the analytical uncertainties associated with the measurement of chloride noted earlier. Most of the data for Section 1/9 form a mixing line between freshwater and seawater compositions along the vertical axis. Water in many of the intermediate depth wells (1W91:IT007I, 008I, 010I1, 010I2, 011I2, 011I3, 012I2 and 1W92:IT009I2, 016I2) have clearly mixed with seawater. Of the deep wells, only 1W91:IT010D and 1W92:IT015D exhibit a seawater mixture. A series of the shallow wells exhibit a freshwater/leachate mixing signature (1W91:IT003S, 007S, 008S, 009S, 010S, 011S, 012S, 013S).

Figures 7.528 and 7.529 plot sulfate versus bicarbonate for Landfill Section 1/9 groundwaters. In non-carbonate terrains, natural groundwater will generally contain low concentrations of both sulfate and bicarbonate relative to either leachate or seawater. Seawater exhibits a high concentration of sulfate, and a low concentration of bicarbonate. A freshwater-seawater mixing line therefore would plot along the horizontal axis. Figures 7.528 - 7.529 indicate that water from most of the intermediate wells and two deep wells (1W91:IT010D and 1W92:IT015D) have mixed with seawater, consistent with the relationship observed previously on Figures 7.525 - 7.526. In contrast, freshwater mixed with leachate plots along the vertical axis, indicating the elevated bicarbonate and low sulfate signature typically produced by sulfate reduction. All of the shallow monitoring wells are mixed with leachate to some degree. Most of the deep intermediate and bedrock wells plot along the horizontal axis showing no leachate mixing. However, wells 1W91:IT012I1, and 1W92:IT016I1, 016I2 all show elevated bicarbonate concentrations, indicative of leachate mixing. Well 1W91:IT004S is probably affected by both leachate and seawater and plots between the two axes. Water from well 1W91:IT008S has a poor electrochemical balance, and it is difficult to evaluate the influences on its chemistry.

Figures 7.530 - 7.531 plot ammonium versus bicarbonate for Landfill Section 1/9. Groundwater mixed with leachate exhibits high ammonium and bicarbonate concentrations, consistent with ammonification and coincident sulfate reduction. Water from several wells contain anomalous concentrations of bicarbonate and ammonium. Well 1W91:IT004S exhibits a high bicarbonate concentration but lower ammonium concentrations than other water samples that exhibit leachate mixing. Water from wells 1W91:IT008S and 013S exhibit a poor electrochemical balance.

- ***Piper and Stiff Diagrams***

Figures 7.532 through 7.535 are Piper diagrams for those samples from Landfill Section 1/9 that exhibit acceptable electrochemical balances. As shown in Figure 7.505, seawater and native groundwater will plot in separate areas of the diagram. Seawater, with a chemistry dominated by sodium and chloride, will plot on the right-hand side of the central diamond with total dissolved solids (TDS) concentrations in the thousands of mg/l. Native groundwater will have low TDS and will generally plot in the upper left area of this central diamond. Leachate from the Fresh Kills landfill typically exhibits a sodium-bicarbonate chemistry, and will plot near the lower point of the diamond, with TDS in the hundreds to several thousand mg/l. Wells that exhibit mixtures of water types will plot along lines connecting the water types in the central diamond.

The relationships previously identified on the dissolved ion scatterplots are supported by the Piper diagrams. As indicated on Figure 7.532, most of the shallow wells plot in the region of the Piper diagram indicative of leachate mixing and exhibit a high to very high TDS content. Figures 7.533 and 7.534 indicate that, with the exception of wells 1W91:IT001I, 004I, 005I1, 005I2, 005I3, 006I, and 1W92:IT044I2 (located to the east or southeast of the landfill), all intermediate depth wells exhibit a strong seawater signature. Deep (bedrock) wells indicate native (freshwater) groundwater chemistry with a weaker seawater signature, notably 1W92:IT015D.

The Stiff diagrams indicated on Figures 7.536 through 7.540A clearly support the previously defined influences on water chemistry. On Figure 7.536, wells 1W91:IT007S, 009S, 010S, 011S, and 012S exhibit the characteristic leachate signature (previously identified in wells 6W89:YW2, YW9, and 6W91:IT151S at Section 6/7). Shallow wells 1W91:IT004S and 013S exhibit both seawater and leachate mixing: high sodium, bicarbonate, and chloride. As noted in the Piper plot analysis, Figures 7.537 - 7.539 indicate that all intermediate depth wells exhibit a notable seawater component except for those located to the east or southeast of the landfill (1W91:IT001I, 004I, 005I1, 005I2, 005I3, 044I2, 044I3). With the exception of well 1W92:015D (seawater influence), all deep wells exhibit dilute native groundwater chemistry.

The shape of the Staff diagram reflects composition and the size of the diagram reflects total dissolved solids when the scale remains constant. While the scale of the Stiff diagram is not normally adjusted for comparative analysis, keeping a constant scale results in loss of information regarding the chemical composition of dilute freshwaters (TDS<1,000 mg/L) when compared with

the brackish and saline waters under the Fresh Kills landfill. To compensate for this, expanded Stiff diagrams were prepared for the eight most dilute water samples from Section 1/9 (Figure 7.540A).

Of these eight samples, only 1W92:IT044I2 has a sodium-bicarbonate chemical composition associated with the typical landfill leachate. Sample 1W92:IT044I2 is a freshwater and exhibits a TDS concentration less than 200 mg/L. The source of the observed dilute sodium-bicarbonate composition is equivocal, and can be evaluated generally, in terms of natural freshwater geochemistry, and specifically, in terms of the full suite of geochemical indicator parametes analyzed at this well. The predominant source of sodium in groundwater is plagioclase; nephenline, sodalite, and glaucophane are other possible sources of sodium in many igneous and metamorphic rocks (Davis and DeWiest, 1966). Cation exchange of calcium for sodium in sedimentary rocks frequently results in a sodium-bicarbonate water type (Freeze and Cherry, 1979). As a result, sodium-bicarbonate water types are common in igneous ricks (both granitic and basaltic), schists, and shales and sandstones, especially where carbonate minerals are rare (Walton, 1985). Further, sodium-bicarbonate water types are the major hydrogeochemical facies in Cretaceous and Paleocene rocks of the northern Atlantic Coastal Plain (Back, 1961, 1966). Clearly, sodium-bicarbonate water types are a common, naturally-produced, chemical composition of freshwater aquifers.

Chemically, the 1W92:IT044I2 water sample is characterized by low DOC (<15 mg/L), low sulfate (<100 mg/L), low bicarbonate (100 mg/L or less), low tritium (<5 T.U.), and negative $\partial^{13}C$ (<-10‰). At these levels, these parameters suggest neither recharge with "young" water, nor mixing with leachate or seawater (perhaps the most convincing parameter is $\partial^{13}C$, as a 1% leachate mixture would result in a $\partial^{13}C$ of approximately 1‰.) These data, coupled with the more generic evaluation of dilute freshwater geochemistry, indicate that the probability of leachate mixing in this sample is extremely low.

- ***Environmental and Radiogenic Isotopes***

Figure 7.541 - 7.542 plot δD versus $\delta^{18}O$ for Section 1/9. Nearly all shallow wells, form a trend that distinctly moves away and upward from the meteoric water line. This trend reflects deuterium (^2H) enrichment from sulfate reduction and methanogenesis, indicative of leachate contamination. The intermediate and deep monitoring wells plot along the meteoric water line

with the exception of 1W92:IT009I and 1W91:IT013D. Water plotting on the meteoric water line reflects the composition of precipitation when the water originally infiltrated into the ground. This water has not mixed with leachate and therefore does not exhibit enrichment of deuterium.

Figures 7.543 - 7.544 plot $\delta^{13}C$ in dissolved inorganic carbon versus bicarbonate concentration. These figures again indicate a clear separation between leachate mixtures enriched in ^{13}C with high bicarbonate concentrations, and intermediate depth and deep monitoring zone water depleted in ^{13}C with low bicarbonate concentrations. Well 1W91:IT012I1 (screened in Recent sands) exhibits a mixture between leachate and natural sources of bicarbonate.

Tritium activity is elevated only in shallow wells influenced by leachate mixing, indicating they were recharged after the early 1960's (Figure 7.545). The very low tritium content exhibited in most deep and intermediate wells (<10 TU) indicates that the water in these wells is greater than 30 years old and has not mixed with leachate. Several intermediate depth and one deep well (1W92:IT009D) exhibit a slightly elevated tritium content (≤20 TU), and may reflect limited mixing with the shallow flow system.

7.3.3.4 Landfill Section 3/4

The plots of dissolved organic carbon versus total chloride for Landfill Section 3/4 (Figures 7.546 - 7.647) indicate data grouping into two general trends . Water from shallow monitoring wells (3W91:IT401S, 402S, 403S, 404S, 405S, 406S, and 407S) lie well above the horizontal axis, defining high concentrations of DOC and exhibit elevated concentrations of chloride. Water from most of the deep wells plot near the origin, exhibiting low concentrations of chloride and little or no DOC, representative of native water chemistry. Most of the intermediate depth wells exhibit elevated chloride and DOC, indicative of leachate and/or seawater mixing.

A plot of dissolved sodium versus total chloride (Figure 7.548) for Landfill Section 3/4 helps distinguish between seawater mixing and leachate mixing. Similar to the plot of DOC versus total chloride, water from the shallow wells in Section 3/4 exhibits high sodium concentrations with relatively low chloride concentrations. The proportions of sodium and chloride in water from the deep and intermediate wells (3W91:IT404I, 406I, 406D, and 407D) suggest possible mixing with seawater. Water from well 3W91:IT406I, plots anomalously and likely reflects a leachate mixture. Water from wells 3W91:IT403D and 404D do not appear to be mixed with either

seawater or leachate. Similarly, a scatterplot of sulfate versus boron clearly shows that mixing with seawater has occurred only in the deep and intermediate wells (Figure 7.549).

A plot of sulfate versus bicarbonate (Figure 7.550) distinguishes the different water types in Section 3/4. Water from all the shallow wells plots along a line with very low sulfate concentrations and high bicarbonate concentrations, consistent with alkalinity generated during sulfate reduction in a landfill. Water from all the deep monitoring wells fall along the horizontal axis, characteristic of seawater or native groundwater. Water from the intermediate depth monitoring wells 3W91:IT404I, 405I1, and 406I appears to plot along mixing lines between seawater and leachate-freshwater mixtures.

Figures 7.551 - 7.552 plot ammonium versus bicarbonate for Landfill Section 3/4. Again, water from all the shallow wells exhibits elevated ammonium and bicarbonate concentrations, characteristic of leachate mixing. The deep (bedrock) wells exhibit no leachate signature. Water from the intermediate wells 3W91:IT404I, 405I1 and 406I exhibit elevated bicarbonate, suggesting leachate mixing, although their ammonium concentrations are very low.

- ***Piper and Stiff Diagrams***

Figures 7.553 is a Piper diagram for Landfill Section 3/4 indicating those wells for which complete electrochemically-balanced major dissolved ion chemistry was available. As for Landfill Section 1/9, shallow wells exhibit a leachate signature, and are clearly distinguishable from the seawater influenced well, 3W91:IT405I1. Water from deep monitoring wells is more variable in composition, reflecting local mineral-water reactions. Figures 7.554 and 7.554A present the Stiff diagrams for each of the monitoring wells included on the Piper diagram. The shallow wells 3W91:IT403S, 404S, and 407S exhibit water with the composition typical of leachate mixing. Water from shallow well 3W91:IT406S shows characteristics of both leachate and seawater. Water from intermediate well 3W91:IT405I1 clearly exhibits a seawater mixture; this is possibly indicated in wells 3W91:IT404I and 407D. Deep monitoring wells 3W91:IT403D, 405D, and 406D exhibit water with neither a leachate or seawater signature.

The shape of the Stiff diagram reflects chemical composition, and the size of the diagram reflects total dissolved solids when the scale remains constant. However, keeping a constant scale results in loss of information regarding the chemical composition of dilute freshwaters (TDS<1,000 mg/L) when compared with the brackish and saline waters under the Fresh Kills landfill. To

compensate for this, expanded Stiff diagrams were prepared for the three most dilute water samples from Section 3/4 (Figure 7.554A). Of these three samples, only 3W91:IT403D has a sodium-bicarbonate chemical composition associated with the typical landfill leachate. 3W91:IT405D has a natural mixed cation-bicarbonate composition, and 3W91:IT406D indicates a possible very dilute seawater mixture. Water from 3W91:IT403D is characterized by low DOC (<15 mg/L), low sulfate (<100 mg/L), low bicarbonate (~ 100 mg/L), low tritium (<5 T.U.), and negative $\partial^{13}C$ (<-10‰). Thus, for the reasons outline previously (Landfill Section 1/9 discussion of well 1W92:IT044I2), the probability that this water composition reflects leachate mixing is very low.

- ***Environmental and Radiogenic Isotopes***

Figure 7.555 is a plot of δD versus $\delta^{18}O$ for Landfill Section 3/4. Water from the shallow monitoring wells 3W91:IT403S, 404S, 406S, and 407S, as well as intermediate depth well 404I, plot above the meteoric water line indicating enrichment in deuterium (^2H). As discussed in earlier sections, the generation of methane and hydrogen sulfide within a landfill causes enrichment of deuterium in leachate by preferentially removing lighter hydrogen atoms. Similarly, during formation of methane, the methanogenic bacteria preferentially remove the lightest carbon from the organic matter, resulting in a higher proportion of heavier carbon in dissolved bicarbonate in leachate. Figure 7.556, a plot of $\delta^{13}C$ to bicarbonate, shows a clear distinction between shallow monitoring wells (leachate mixing) and deep monitoring wells (no leachate mixing). Water from intermediate depth monitoring well 3W91:IT404I plots midway between these two populations, likely indicating a leachate mixture.

Tritium activity in water from wells completed in refuse is consistent with recharge since 1960. With the exception of well 3W91:IT404I, tritium activities in intermediate and deep wells are very low or non detectable, indicating no mixing with leachate (Figure 7.557).

7.3.3.5 Landfill Section 2/8

The plots of dissolved organic carbon versus total chloride for Landfill Section 2/8 (Figures 7.558 - 7.559) exhibit less discrimination between shallow and deeper data, mostly because the total dissolved solids concentrations in the shallow water is significantly lower than elsewhere in the landfill complex. Compared with other sections of the landfill, there is very little dissolved

organic carbon (<125 mg/L). The low concentrations of solutes in shallow water samples is probably a function of well location; of the shallow wells installed prior to the January 1992 sampling event, only well 2W91:IT306S is located adjacent to the primary landfill mound.

Plots of dissolved sodium versus total chloride (Figures 7.560 - 7.561) for Landfill Section 2/8 is similarly equivocal, with no clear distinction of the data along separate trends as found in the other landfill sections. This result can be interpreted to reflect only slight mixing of seawater with freshwater in this section of the landfill. The scatterplot of sulfate versus boron (Figure 7.562) confirms this interpretation. Plots of sulfate versus bicarbonate (Figures 7.563 - 7.564), and ammonium versus bicarbonate (Figures 7.565 - 7.566), also suggest limited leachate mixing from the available data. Compared with other sections of the landfill, the concentrations of bicarbonate and ammonium are low. Elevated concentrations of bicarbonate and ammonium at wells 2W91:IT308I1 and 308I2 suggest leachate mixing with these groundwaters.

- ***Piper and Stiff Diagrams***

Figure 7.567 is the Piper diagram for Landfill Section 2/8 wells with complete electrochemically-balanced major dissolved ion chemistry. As observed, water composition is substantially different than that exhibited in the other landfill sections. In Section 2/8, water from shallow wells ranges from a Ca-Mg-HCO_3 to a mixed cation-mixed anion type water with low TDS and no clear solute preponderances. In the other landfill sections, leachate influenced water is generally of the Na-HCO_3 type. As noted earlier, this finding is likely due to the location of the wells available for sampling and geochemical analysis during the January 1992 sampling quarter. Stiff diagrams for each of the monitoring wells (Figure 7.568) prepared at the same scale as those for the other landfill sections, shows the dilute concentrations of the shallow, intermediate, and deep groundwaters at Section 2/8.

The shape of the Stiff diagram reflects chemical composition, and the size of the digram reflects total dissolved solids when the scale remains constant. However, keeping a constant scale results in loss of information regarding the chemical composition of dilute freshwaters (TDS<1,000 mg/L) when compared with the brackish and saline waters under the Fresh Kills landfill. To compenate for this, expanded Stiff diagrams were prepared for the seven most dilute water samples from Landfill Section 2/8 (Figure 7.568A). Of these seven samples, only 2W91:IT302D has a sodium-bicarbonate chemical composition associated with the typical landfill leachate. The other water compositions are primarily calcium-bicarbonate (2W91:IT306I1, 306I2, 306D, 308D).

One sample has a calcium-sulfate composition (2W91:IT306S) and one sample has a mixed cation-chloride composition (2W91:IT304D). Water from 2W91:IT302D is characterized by low DOC (<15 mg/L), low sulfate (<100 mg/L), low bicarbonate (<100 mg/L), low tritium (<5 T.U.), and negative $\partial^{13}C$ (<-10‰). Consequently, the probability that this water composition reflects leachate mixing is extremely low.

- ***Environmental and Radiogenic Isotopes***

Figure 7.569 is a plot of δD versus $\delta^{18}O$ for Landfill Section 2/8. This figure shows that leachate mixing in sampled wells is minimal. All of the wells plot slightly higher than and along the meteoric water line. Carbon-13 is enriched in water from wells 2W91:IT302S, 308S, 308I1, and 308I2 suggesting that these water samples may be reflective of a leachate mixture (Figure 7.570). However, concentrations of other leachate indicators elsewhere in the landfill, such as ammonia and DOC, are low.

Tritium activities in water from wells in Section 2/8 are consistent with the stable isotopic data (Figure 7.571). Tritium activity in water from deep wells is near the detection limit, indicating that the water is older than 30 years. In contrast, tritium activity ranges from about 25 TU to 325 TU in water from shallow wells and two intermediate depth wells that have likely mixed with leachate (2W91:IT308I1, 308I2).

7.3.3.6 Spatial Distribution of Selected Geochemical Solutes and Isotopes

Areally, the data base for the dissolved concentrations of solutes in water from bedrock and the Cretaceous sediments is sparse. Samples are exclusively from wells located at the margins of each landfill section: no samples are from the interior of the landfill sections. Typically, sampling points located on opposite sides of a landfill section are separated by distances in excess of 2,500 ft; individual wells are typically separated by more than 750 feet. Any extrapolation of solute concentrations over such great distances without intervening data to constrain the configuration of isopleths can lead to very large errors, especially for rocks and sediments as chemically and physically heterogeneous as those under the Fresh Kills Landfill. Detailed field studies have shown that isopleths of solute concentration are seldom equidistant, even in homogeneous porous media, and often solute concentration gradients are greatest immediately adjacent to source areas (Domenico and Schwartz, 1990; Fetter, 1993). As a result,

all isopleth maps are contoured as dashed lines to show the high level of uncertaintly associated with the areal distribution of solute concentrations.

- ***Intermediate Depth (Cretaceous Sand) Monitoring Zone***

Dissolved Organic Carbon

The isopleth map for dissolved organic carbon in Cretaceous sediments (Figure 7.572) indicates little systematic pattern except for increasing concentrations towards the southwestern corner of Section 1/9. The higher concentrations of DOC at this corner of Section 1/9 may reflect the release of natural organics in localized reducing conditions, organic matter associated with seawater intrusion from the Arthur Kill, or dilute mixing with leachate.

Dissolved Bicarbonate

The isopleth map for dissolved bicarbonate in the Cretaceous sand (Figure 7.573) shows concentrations of less than 200 mg/L bicarbonate except along the western margin of Section 1/9 where seawater mixing has occured. Elevated bicarbonate concentrations in this area are likely the result of sulfate reduction in the presence or organic matter where seawater has mixed with freshwater; as well as a dilute leachate mixture.

Dissolved Sulfate

The isopleth map for dissolved sulfate in the Cretaceous sand (Figure 7.574) clearly documents that seawater has mixed with groundwater along the western and southern margins of landfill Secton 1/9. Concentrations of sulfate in this region can exceed 1,500 mg/L, compared to less than 100 mg/L in the rest of the Cretaceous sand.

$\partial^{13}C$ of Inorganic Carbon

The isopleth map of $\partial^{13}C$ in the Cretaceous sand shows a gradual increase from -18‰ to -4‰ in along the northwestern margin of Section 1/9 and an increase to -2‰ along the southern margin (Figure 7.575). The values for $\partial^{13}C$ are consistent with the mixing of seawater ($\partial^{13}C$=0‰) and/or very dilute leachate (less than 1%) with native groundwater ($\partial^{13}C$=-18‰). Mixing of more than 1% leachate with groundwater would result in a positive $\partial^{13}C$. This suggests that the source of the bicarbonate is primarily associated with seawater. Note that the highest $\partial^{13}C$ values (1W92:IT012I2 and 015I) do not correlate with the highest concentrations of bicarbonate (1W92:IT009I2 and 016I2).

Tritium Activity

The isopleth map for tritium activity in Cretaceous sand (Figure 7.576) shows the effects of seawater and/or dilute leachate mixing with groundwater. On the western margin of Landfill Section 1/9, tritium activity is as high as 23 (1W92:IT008I). Note however, that the youngest water (1W92:IT008I and 016I2) does not correlate with the highest $\partial^{13}C$ values (1W92:IT012I2 and 015I). The waters that have the highest bicarbonate concentrations (1W92:IT009I2 and 016I2) are relatively young, however.

- ***Deep (Bedrock) Monitoring Zone***

Dissolved Organic Carbon

The isopleth map for DOC in water from bedrock indicates that DOC concentrations exceed 10 mg/L only at three isolated locations in Sections 2/8 and 6/7 (2W91:IT303D, 307D and 6W91:IT158D; Figure 7.577). The source of the DOC is unknown, but it is unlikely related to leachate. No other leachate parameters were elevated in water from these wells.

Dissolved Bicarbonate

The isopleth map for dissolved bicarbonate in bedrock (Figure 7.578) indicates that the highest concentrations occur in the east-central and southern region of Section 6/7 and the north-central region of Section 2/8. The elevated concentrations of bicarbonate in this area is consistent with water composition controlled by the natural weathering of serpentinite minerals (e.g., Drever, 1988). Elsewhere in the bedrock under the landfill, dissolved bicarbonate concentrations are less than 100 mg/L.

Dissolved Sulfate

The isopleth map for dissolved sulfate in bedrock documents the almost complete absence of sulfate except for the southeastern regions of Section 1/9 and Section 6/7 (Figure 7.579). The elevated sulfate concentration in these regions is probably due to localized mixing with seawater.

$\partial^{13}D$ of Inorganic Carbon

The isopleth map of $\partial^{13}C$ in water from bedrock (Figure 7.580) shows a gradual increase from about -18‰ to -6‰ towards the southern margin of Section 1/9. Such a change in $\partial^{13}C$ is consistent with the mixing of seawater ($\partial^{13}C$=0‰) and native groundwater ($\partial^{13}C$=-20‰).

Tritium Activity

The isopleth map for tritium activity suggests that modern water (>10 T.U.) has entered the bedrock only along the eastern side of Section 6/7 and two isolated locations along the western margin of Section 1/9 (Figure 7.581). The occurance of groundwater post-dating 1960 in these places is consistent with recharge to the northeastern region of the aquifer in Section 6/7 and minor mixing of seawater with groundwater along the Arthur Kill.

In summary, the isopleth maps are useful for three reasons. First, they clearly show that leachate mixing in the bedrock aquifer is negligible. Second, they clearly show that seawater has mixed with groundwater along the western and southern margins of Section 1/9. Third, the maps show the difficulty of resolving dilute leachate mixtures in areas where seawater has intruded the aquifer, such as in Cretaceous sand along the western margin of Section 1/9. The distribution of geochemical parameters suggest that reduction of intruded seawater has resulted in elevated bicarbonate concentrations. Leachate does not appear to represent an important influence because $\partial^{13}C$ values remain negative. Alternately, a complex mixture of seawater, groundwater, and a very small percentage of leachate could provide the same results. No definitive, unique solution exists for this problem.

7.3.4 Strontium and Lead Isotopic Analysis

The strontium and lead isotopic composition data measured for groundwater are contained in Appendix M. The raw results for the radiogenic isotopic compositions are reported as ratios (dimensionless numbers), which is the standard form for reporting isotopic results. Strontium is reported as $^{87}Sr/^{86}Sr$, and lead is reported as $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$. The $^{87}Sr/^{86}Sr$ ratio varied from 0.708852 to 0.713676; $^{206}Pb/^{204}Pb$ ratios varied from 19.6779 to 17.9228; $^{207}Pb/^{204}Pb$ ratios varied from 16.2924 to 15.3753; and $^{208}Pb/^{204}Pb$ ratios varied from 39.6079 to 37.0802. These variations are well outside the range of analytical uncertainties, which for $^{87}Sr/^{86}Sr$ are at most +/- 0.0187% (0.0001 absolute uncertainty), and for the Pb isotopic ratios are at most +/- 1.72% and mostly about +/-0.5%.

The possible sources of water in the landfill and environs are (1) groundwater residing in the bedrock and the sediment immediately above it; (2) seawater, intruding as a lense into both the sediment and bedrock; and (3) landfill leachate. It is expected that strontium in water from sediment and bedrock would have $^{87}Sr/^{86}Sr$ ratios "elevated" (i.e. greater than about 0.7090)

because the waters would have equilibrated with more radiogenic Sr that developed in the rock minerals through the decay of ^{87}Rb over time. Water from all but one of the deep wells exhibit $^{87}Sr/^{86}Sr$ greater than 0.710 and most exhibit $^{87}Sr/^{86}Sr$ greater than 0.711, consistent with that expected from native groundwater.

The isotopic composition of Sr in modern seawater is well known (Faure, 1986) and has a value of 0.7088; one might expect Sr in a restricted seawater environment such as New York Harbor to be slightly more enriched in the radiogenic isotopic ^{87}Sr, because of introduction of strontium from surface waters draining surrounding land areas. Strontium in water from all of the shallow wells exhibits $^{87}Sr/^{86}Sr$ between 0.70885 and 0.70995, consistent with a seawater or sea salt source. Strontium in water from the intermediate wells exhibit ratios that range from 0.70934 to 0.71368, but most samples have ratios greater than 0.711, similar to that in the strontium from water in the deep wells.

Figure 7.592 is a plot of $^{87}Sr/^{86}Sr$ vs $^{206}Pb/^{204}Pb$ for the samples studied. It is clear that the water from the shallow wells exhibit Sr isotopic ratios characteristic of seawater whereas water from most of the deep and intermediate wells has more radiogenic Sr, characteristic of sediment or bedrock sources. Some of the deep and intermediate wells, however, exhibit Sr with isotopic compositions intermediate between the elevated values typical of the deep sources and seawater; this may suggest mixing between these sources. Pb isotopic ratios on the other hand, are variable for water from all wells, irrespective of depth, and are unfortunately not useful to discriminate among the sources of the water samples.

The strontium isotopic data agree with the results of the geochemical and statistical analyses. Water sampled in the shallow wells, which has mixed with leachate from the landfill, is also affected to some extent by seawater introduced from the surrounding estuarine system. The $^{87}Sr/^{86}Sr$ ratios of the samples were plotted against several other chemical parameters considered to be characteristic of either leachate from the landfill or seawater to evaluate the extent to which leachate has mixed with intermediate and deep wells. These include NH_4^+ (high concentrations typical of leachate), Sr (high values typical of seawater), and boron (high concentrations typical of leachate).

Figure 7.593, a plot of $^{87}Sr/^{86}Sr$ versus boron, identifies the seawater impacted wells. The strontium isotope signature normalizes the data such that the usefulness of boron as a leachate indicator is enhanced. Water from the shallow wells all exhibit a meteoric/leachate boron

signature. The three intermediate depth wells with a seawater isotopic signature also have a boron signature that indicates mixing with meteoric/leachate derived water. The deep wells with a seawater signature have very low boron indicating little contact with meteoric water.

Figure 7.594 shows Sr isotopic composition vs. Sr concentration. The three intermediate wells with water exhibiting dissolved $^{87}Sr/^{86}Sr$ less than 0.710 all have Sr concentrations greater than 2.5 mg/liter, consistent with groundwater mixing with seawater. In contrast, all of the shallow wells, the deep wells, and the rest of the intermediate wells have Sr concentrations less than 2 mg/L regardless of their Sr isotopic composition. Water from these wells cannot have mixed with very much seawater.

Collectively, the strontium isotopic data are consistent with the following model:

- The deep wells sampled exhibit freshwater sources in the bedrock substrate. They show no evidence of leachate mixing in their Sr isotopic compositions.
- The Sr isotopic signature of strontium in water from shallow wells indicates that there is a seawater component, but Sr concentrations indicate that the seawater component is usually small. This would be the case if the water in the shallow wells is mostly meteoric water with a small seawater component from sea spray during storms. In this case, the isotopic composition of the Sr in water from the shallow wells would have the signature of seawater, even if the Sr concentrations in the water were in the ug/l range.,
- The intermediate depth wells screened in sand units overlying the bedrock are variably mixed with seawater.
- The leachate does not have a distinctive Sr isotopic signature derived from the refuse; rather, it has inherited the isotopic signature from seawater or sea salt.

7.3.5 Multivariate Statistical Analysis of Geochemical Data

The geochemical process approach was applied in this investigation to examine water quality trends and possible mixtures of water types. The trends shown by scatterplots used in the geochemical process approach suggest that water quality beneath the Fresh Kills landfill is the result of mixing of three distinct water types: dilute freshwater, seawater, and leachate. However, the geochemical process approach does not classify the samples into distinct groups, especially in the case of dilute groundwaters where the fields of freshwater-leachate mixtures,

freshwater-seawater mixtures, and freshwater all overlap. Multivariate techniques were used to independently classify the water samples into distinct water types. The multivariate approach does not statistically compare solute concentrations to allowable contaminant levels or determine whether solute concentrations exceed water quality standards and criteria. Rather, it provies a basis for determining where any exceedances of standards and criteria represent a logical reflection of water chemistry, and where they do not (i.e., reflect natural geochemical variability, or interferences in analytical measurements).

The multivariate approach has two advantages compared to other classification methods. First, it makes no *a priori* assumptions about sample data. Second, it compares many variables at the same time, rather than just two variables (such as in scatterplots). Three multivariate methods were used in this investigation (for a review of multivariate statistical techniques and data standardization procedures see Davis, 1986). Cluster analysis was applied to classify the samples into groups. Discriminant function analysis was applied to determine if the derived cluster groups were significantly different. Principal components analysis was applied to indicate which variables were responsible for the groupings. Cluster analysis and principal components analysis were performed using SYSTAT 5.0; discriminant function analysis was preformed using SAS 5.0.

The first step in the multivariate analysis was to identify an appropriate data set for the statistical analysis. Thirteen water chemistry parameters were chosen based on the results of the geochemical process approach: total dissolved solids (TDS), dissolved organic carbon (DOC), total chloride, dissolved sulfate, dissolved bicarbonate, dissolved calcium, dissolved magnesium, dissolved potassium, dissolved sodium, total ammonium, dissolved boron, $\delta^{13}C$, and calculated δD. Calculated δD is the difference between the observed δD and the value for δD predicted by the meteoric water line equation ($\delta D = 8\delta^{18}O + 10$). δD could be calculated from this equation because none of the geochemical processes occurring within the landfill fractionate oxygen isotopes (sulfate reduction and methanogenesis fractionate hydrogen isotopes). A water sample was chosen for multivariate analysis if data for all thirteen water chemistry parameters were available and if the data exhibited a reasonable electrochemical charge balance (+/-20%). Using these criteria, water chemistry samples from sixty-three wells were selected for multivariate analysis (Table 7.23). Raw analytical data from these wells are summarized in Table 7.24 (Section I).

The second step in the multivariate analysis was to transform and standardize the raw data (Table 7.24; Sections II and III). The data set was logarithmically transformed ($Y_i = \ln X_i$) because most

geologic data, especially geochemical data, exhibit lognormal distributions (USEPA, 1989; 1992; Davis, 1986). Although normality is not a prerequisite for multivariate analysis, normal or near normal distributions improve the linearity of the data set and the efficacy of the analysis of derived correlation matrices. All data were logarithmically transformed except for $\delta^{13}C$ and calculated δD, which could not be logarithimically transformed due to the presence of negative values. The results of the probability plot correlation coefficient test (Filliben, 1975) indicate that the lognormal distribution better describes the data for all variables (Table 7.25). The majority of the logarithmically transformed data sets have a lognormal distribution at the 0.01 level of significance, with the correlation coefficient increasing for all data sets relative to the untransformed (raw) data. Following transformation, the data were standardized by Z-score. The equation for Z-score standardization (Z_i) is:

$$Z_i = (y_i - Y) / s$$

In this equation, y_i is the logarithmically transformed value for sample *i*, Y is the logarithmically transformed variable mean, and s is the standard deviation of the variable. Standardization results in new values which have a mean of zero and are measured in units of standard deviations (Table 7.24 - Section III). Standardization makes the data distribution independent of measurement units and scale of measurement because all the variables are "weighted" equally. For example, after standardization, the distribution of a trace solute, such as boron, can be directly compared with that of a major solute, such as sodium, or an isotopic value such as $\delta^{13}C$.

The third step in the multivariate analysis was cluster analysis. For the cluster analysis, a mean euclidean distance matrix was calculated from the standardized, logarithmically transformed data set. The data were then clustered using the unweighted pair group method (UPGM). UPGM minimizes the distortion between the dendrogram (Figure 7.582) and the distance matrix. The results of the cluster analysis confirms the hypothesis that three distinct water types occur beneath the Fresh Kills Landfill, as follows:

Group A: 1W91:IT001S, 002S, 003S, 007S, 009S, 010S, 011S, 012S, 013S; 1P89:XP5; 6W89:YW1, YW3, YW9; and 3W91:403S, 404S, 406S, and 407S.

Group B: 1W91:IT004S, 007I, 008I, 009I1, 009I2, 010I1, 010I2, 011I1, 011I2, 011I3, 012I1, 012I2, 013I, 015I, 016I1, 016I2, 011D, 015D, 016D; 6W91:IT160S: and 3W91:IT406I.

Group C: 1W91:IT001I, 004I, 005I1, 005I2, 005I3, 006I, 044I2, 002D, 008D, 009D, 010D, 012D; 2W91:IT302S, 306S, 308S, 306I1, 306I2, 308I1, 308I2, 308D; 3W91:IT404D, 406D, 407D, 404I; and 6W91:IT160D.

The clusters are consistent with results of the geochemical process approach. Group A consists of shallow water samples that are interpreted as leachate-freshwater mixtures. Group A is characterized by the highest means for bicarbonate, ammonium, boron, $\delta^{13}C$, and δD. Group B consists of shallow, intermediate, and deep water samples that are interpreted as seawater-freshwater mixtures. Group B is characterized by the highest means for total dissolved solids, chloride, sulfate, calcium, magnesium, and sodium. Group C consists of intermediate and deep water samples that plot near the origin of the ion scatterplots and are interpreted as very dilute groundwaters (the freshwater end-member). Group C is characterized by having the lowest means for all the variables. Two exceptions in Group C are samples 308I1 and 308I2, which have characteristics of a freshwater-leachate mixture, but exhibit extremely low ammonium concentrations. Samples 308I1 and 308I2 are from Section 2/8, which is the only landfill section that does not show a linear trend between bicarbonate and ammonium (Figures 7.565 and 7.566). The strontium isotopes from these two wells clearly show a "deep" water signature, implying no mixing with shallow water or seawater. The cause of this anomalous chemical composition is unknown but, as noted in Section 7.2.2, may reflect surface water leakage through damaged well seals.

The fourth step in the multivariate analysis was discriminant function analysis. The purpose of discriminant function analysis was to determine whether the derived clusters are significantly different. Discriminant function analysis tests a null hypothesis that states that the three groups are not significantly different. The alternate hypothesis states that the three groups are significantly different. The discriminant functions were calculated using Wilks' lamda to approximate the F statistic. The hypothesis was tested at the 0.0001 level of significance; as indicated in Table 7.26, the test results show that groups A, B, and C are all significantly different from one another.

Finally, principal components analysis (PCA) was preformed to determine which of the thirteen variables were most important in separating the three clusters. PCA gives insight into the structure of the data matrix (Davis, 1986). A covariance matrix was calculated from the transformed, standardized data set, from which principal components (eigenvectors) were derived. The eigenvectors can be thought of as lines in multidimensional space that separate the data. In

the case of PCA, the eigenvectors (Table 7.27) are all at right angles to one another, and form the axes of a scatterplot. The percent of the total variance explained by each eigenvector is calculated from the eigenvalues (Table 7.27). Scatterplots of the principal component scores (Table 7.28) for each sample show the separation of the three groups along the principal component axes (Figures 7.583 and 7.583A).

The groupings for these figures correlate to cluster analysis groups A, B, and C. Leachate-impacted samples correspond to Group A, seawater-impacted samples correspond to Group B, and native groundwater (freshwater) samples correspond to Group C. Results of the PCA indicate that only two eigenvectors are most important in separating the data. A third eigenvector provides a small amount of additional separation and brings the total reduction in variance achieved by the first three eigenvectors to the 85% level (Table 7.27). The first principal component (eigenvector) accounts for nearly 50 percent of the variance. The important variables that characterize this component are total dissolved solids, potassium, sodium, magnesium, and chloride. Thus, this component consists of the "seawater parameters". The second principal component accounts for nearly 31 percent of the variance. The important variables that characterize this component are bicarbonate, ammonium, and to some degree, $\delta^{13}C$. This component is characterized by the "leachate parameters." The third principal component accounts for 5% of the variance; the variables that characterize this component are calcium and magnesium.

Figures 7.583 and 7.583A clearly show that the three principal components separate the three groups. They also show that the Group C samples (freshwater) are very different from group A samples (seawater-freshwater mixture). The figures indicate that even though the three groups are significantly different (as shown by discriminant function analysis), there is some overlap between the groups, especially at low TDS where distinguishing between dilute freshwater, dilute mixtures of leachate with freshwater, and seawater with freshwater becomes difficult.

7.3.6 Geochemical Mixing Models

The probable effects of mixing leachate with native groundwater was evaluated through the use of conservative geochemical mixing models. The variables used in the models are the same variables that successfully distinguish leachate influenced water samples (e.g., TDS, sodium, ammonia, bicarbonate, chloride, DOC, sulfate, boron and $\delta^{13}C$). The models are based on

application of mixing equations presented earlier in Section 7.3.1.1. The mixing equation was modified for use with $\delta^{13}C$ because the source of the $\delta^{13}C$ signature is bicarbonate. As a result, the shape of the $\delta^{13}C$ mixing curve is non-linear and dependent on the concentrations of bicarbonate in each end member, as follows:

$$\delta^{13}C_{mix} = \left[\left(\frac{C_1^{HCO_3} X_1}{C_{mix}^{HCO_3}} \right) * \delta^{13}C_1 \right] + \left[\left(\frac{C_2^{HCO_3} (1 - X_1)}{C_{mix}^{HCO_3}} \right) * \delta^{13}C_2 \right]$$

It is assumed in this analysis that chemical reactions that might occur when leachate, seawater, and freshwaters mix do not significantly decrease the concentrations of solutes of interest. This assumption appears reasonable because the scatterplot distributions among the indicator solutes generally fall on straight lines consistent with a non-reactive mixing hypothesis. Additional discussion of the assumptions and limitations inherent in the mixing models is contained in Attachment 36. Some of the problems are outlined below.

To model mixing, the characteristics of typical "geochemical end members" must be identified. A geochemical endmember represents water exhibiting equilibrium water chemistry characteristic of its environment as a result of a long residence time within that environment. Endmembers applicable to this investigation are seawater, leachate, and native groundwater chemistry associated with the Recent/glacial/Cretaceous sand units and the bedrock. Of these three, seawater represents the end member most easily defined due to the extensive literature regarding its characteristics (e.g., Table 7.22).

It is difficult, however, to clearly identify the characteristics of a "type" leachate, because leachate is diluted by precipitation. While all available leachate data is from shallow wells, the most concentrated leachate would occur at the base of the landfill where temperatures are highest, anaerobic processes are most intense, and the residence time of the water in contact with the refuse is the longest. Consequently, leachate sample from shallow wells likely does not reflect the characteristics of the purest leachate produced in the landfill. Regardless, a "representative leachate" endmember signature was selected from a well installed in the refuse mound (1W89L:XW-5, TDS=15 000 mg/l), which is typical of the higher strength leachate observed in

the shallow samples. For a further discussion of the spatial and temporal variation of leachate chemistry, refer to Section 7.1.

The proportions of solutes in XW-5 make it a conservative choice for the leachate end-member. Although XW-5 may be more dilute than leachate at the base of the landfill, the proportions of solutes clearly indicate that XW-5 is representative of an evolved leachate. Sulfate has almost been completely removed by sulfate reduction, bicarbonate and ammonium are orders of magnitude higher than that associated with freshwater, the boron concentration is twice that of seawater, and $\partial^{13}C$ is near the maximum observed at Fresh Kills. Comparison of the mixing model results to observed water chemistry suggests that the concentration of ammonium in XW-5 is lower than that of the average leachate (Attachment 36). It is important to note that use of diluted leachate for this analysis adds a degree of conservatism to the mixing calculations; for example, a 10 percent mix of this leachate with freshwater may actually represent the chemistry associated with a 5 percent mix of the higher strength leachate presumed to exist at the base of the landfill, which represents the source for vertical migration and mixing.

Similarly, the concentrations of dissolved solutes in water from the native Cretaceous and bedrock aquifers are highly variable. There are many possible mixtures, depending on the initial composition of the groundwater, which varies considerably on a local scale (see the Piper diagrams). Following review of background or "native" water chemistry data compiled from water supply wells in New Jersey (Appendix N), and geochemical data procured during this investigation, the water chemistry from well 2W91:IT306I2 (TDS = 200 mg/l) was selected to represent the natural freshwater endmember for this analysis. Water sample from this well exhibits no chemical signature of either leachate or seawater. The freshwater sample was mixed with leachate to show how concentrations of selected constituents might change as mixing progressed. To estimate a seawater-freshwater-leachate mixture, the freshwater sample was first mixed with seawater until values approximated that of the seawater influenced wells. This "seawater-freshwater mixture" was then mixed with leachate (i.e., well 1P89:XW5) to evaluate the effect of a three component mixture. The table below summarizes the assumed endmember chemistry applied to the geochemical mixing analyses:

Analyte	Assumed Leachate Endmember Chemistry (mg/l) Well 1W89:XW-5 [a]	Assumed Freshwater Endmember Chemistry (mg/l) Well 2W91:306I2 [a]	Assumed Seawater Endmember Chemistry (mg/l) [b]
TDS	15,000	200	34,951

Analyte	Assumed Leachate Endmember Chemistry (mg/l) Well 1W89:XW-5 [a]	Assumed Freshwater Endmember Chemistry (mg/l) Well 2W91:306I2 [a]	Assumed Seawater Endmember Chemistry (mg/l) [b]
Sulfate	11	16	2,630
Bicarbonate[c]	8,800	140	138
Total Chloride	4,480	17.5	18,790
DOC	1,200	2.2	1
Sodium	4,820	12.4	10,450
Total Ammonium	387	0.05	0
Boron	7.5	0.04	4
$\partial^{13}C$	24.3	-17	0

[a] January 1992 sample data (Appendix M)
[b] Drever, 1988
[c] Measured alkalinity converted to bicarbonate (HCO_3) through the relationship: HCO_3=Alkalinity/0.8202.

The results of these mixing analyses are shown in the series of curves presented in Figures 7.584-7.590. Attachment 36 contains a series of charts that compare observed water chemistry at all shallow intermediate depth and deep wells in the geochemical sampling program with the chemistry predicted from the freshwater leachate mixing models. The effort of seawater mixing is also evaluated. An example of this analysis for the freshwater - leachate bicarbonate mix is illustrated on Figure 7.591. For the three component mix, only a 10 percent initial seawater - freshwater mix is plotted on Figures 7.584 - 7.590. A tabular summary of alternative initial mixtures (based on the July 1992 chloride data for each individual well) is contained in Attachment 36.

The results of the freshwater - leachate mixing analysis consistently indicate leachate influence at only three of the intermediate and deep wells analyzed under the geochemical sampling program: 2W91:308I1, 308I2, and 3W91:406I. Due to variability in the mixing results for each individual analyte, and the previously described uncertainty regarding the chemistry of the leachate endmember, it is difficult to quantify the magnitude of the leachate mix. For the three identified wells, this mix would appear to be on the order of 10+ percent. With several exceptions on an analyte specific basis, all other wells in the freshwater - leachate mixing

analysis group exhibit less than a 5 percent mix, which in practical terms represents the limit of resolution for this technique.

Additional uncertainty is exhibited in the three component mixing analysis, where inherent imbalances between indicator analytes are noted in definition of the seawater mixture component on a specific well basis (refer to figures, tables and discussion in Attachment 36). The results of this analysis suggest a leachate influence in excess of 5 percent within most of the intermediate depth wells screened in Recent/glacial sands at Section 1/9 (1W91:009I1, 010I1, 011I1, 012I1, 016I1), as well as one well screened in the Cretaceous sands (1W91:008I). However, the $\delta^{13}C$ of this well does not indicate more than a 1% leachate mixture. Remaining intermediate depth wells and deep wells do not exhibit a consistent leachate mixing signature.

In closing, it is important to note that the mixing analyses rely on the same data set as explored in prior scatter plot and isotope analyses, but encompass an added degree of variability in their interpretation due to the definition of endmember chemistry. Consequently, results of these analyses should be considered as a single component of the unified investigation of all data, as presented in summary form in Section 7.3.8.

7.3.7 Clay Mineral Composition and Sediment Cation Exchange Capacity

X-ray diffraction patterns of oriented clay mounts were analyzed for 123 clay samples obtained from on-site test and well borings. When used in conjunction with measurements of cation exchange capacity, information on the clay mineral composition can be used to determine the ability of the soils under the landfill to naturally attenuate metal contamination from leachate. Sample preparation followed the standard method reviewed in Moore and Reynolds (1989). Semi-quantitative analysis of the proportion of each clay mineral was based on the normalized ratios of the 15Å (smectite 001), 10Å (illite 001), and 7Å (chlorite 002/kaolinite 001) peaks. Because both chlorite and kaolinite have 7Å (angstrom) peaks, the presence of chlorite was determined by the presence of a 4.7Å peak (chlorite 003).

The strategy for this investigation consisted of the collection of two samples from each selected test boring. One sample was collected directly below the refuse, and one sample was collected from the base of the unconsolidated overburden deposits, above bedrock.

The samples collected reflect most of the unconsolidated sediments present beneath the Fresh Kills Landfill: weathered bedrock, residual clay, Cretaceous clay, Cretaceous clay and silt, Cretaceous sand, glacial sand, glacial till, glaciolacustrine silt and clay, Recent sand, Recent silt and clay, peat, and refuse/fill. Most of the shallow samples consist of the Recent and glacial sands, peat, and refuse/fill. The deep samples represent primarily the residual clay and weathered bedrock.

The results of the x-ray analyses indicated that there are three distinct clay assemblages under the landfill: an illite-dominated assemblage, a kaolinite-dominated assemblage, and a smectite dominated assemblage (Attachment 33). Illite-dominated samples are the most abundant.

There was little clay mineral variation in the shallow samples and great variation in the deep samples. Based on descriptive statistics of the clay mineral peak height ratios (Attachment 33), the variability of the clay assemblage in the soil types can be assessed quantitatively. Several of the soils have been combined due to similarity in clay assemblages. The degree of variability is based on the standard deviation of the peak height ratio.

The Cretaceous facies are kaolinite-dominated with little variability. The refuse/fill materials are some what more variable, but are also kaolinite-dominated. The peat represents an illite/chlorite assemblage with low variability. The Recent sediments are primarily an illite/chlorite assemblage with some variability due to samples which are either smectite- or kaolinite-dominated. The glaciolacustrine silt and clay represents a combination of illite- and kaolinite-dominated samples, probably reflecting the variability of rocks in glacial source areas; however, most of the samples are illite-rich. Both the residual clay and weathered bedrock exhibit extremely variable clay mineral composition, which probably reflects the variation in underlying bedrock composition.

- ***Cation Exchange Capacity***

The cation exchange capacity for the sediments beneath the Fresh Kills landfill was determined for 110 samples (Attachment 33), obtained from the test boring and well boring sample archive.

The cation exchange capacity was determined by the standard method, using sodium acetate as the primary exchange reagent and ammonium acetate as the secondary exchange reagent (Eslinger and Pevear, 1988). In the first step, sodium cations displace the cations sorbed to the clay surfaces. Sorbed cations balance charge imbalances caused by structural defects associated with

ion substitution within the clay mineral. In the second step, ammonium cations displace the sodium sorbed during the first step. The concentration of sodium is measured and the cation exchange capacity (CEC) is reported as meq Na per 100 g of sample.

The only minerals that exhibit high cation exchange capacities are zeolites, manganese oxides, and clay minerals (Carroll, 1959). Of these, only clay minerals are abundant in most natural sedimentary environments. Therefore, it is assumed that the cation exchange capacity of the Fresh Kills landfill samples is a function of the clay minerals present in each sample. The cation exchange capacity is important because it is used to calculate the retardation factor for metal ion transport (Domenico and Schwartz, 1990):

$$\frac{V_w}{V_c} = 1 + \frac{\rho_s (1-n) K_s \ CEC}{n \ \tau}$$

where v_w / v_c describes how many times faster the groundwater is moving relative to the contaminant being sorbed, ρ_s is the density of the solid (usually 2.65 g/cc), *1-n/n* is the inverse of the void ratio, K_s is the selectivity coefficient, *CEC* is the cation exchange capacity (meq/mass), and τ is the total competing cation concentration in solution (meq/mass).

Analysis of the Fresh Kills samples indicates that greater than 90 percent of the samples exhibit a CEC less than 15 meq/100g. These data imply that there is little cation exchange in the sediment beneath the landfill. This conclusion is supported by the clay mineral compositions of the sediment - most of the samples have clay mineral compositions with high percentages of illite or kaolinite which typically exhibit CEC less than 20 meq/100g.

In general, the data suggest a relationship between grain size and CEC. For example, samples from the Recent sand tend to exhibit low CEC. This is logical because samples that contain more silt and sand will contain less clay sized material, and therefore less clay minerals. As a result, grain size may exert a more important control over CEC, and therefore contaminant retardation, than does clay mineral composition.

Clay mineralogy does have an effect on the CEC for samples from the same sediment facies. Kaolinite-dominated samples typically exhibit CEC values less than 10 meq/100g. Illite-dominated samples ranged from 5-20 meq/100g. Smectite is the clay which has the highest

cation exchange capacity (up to 100 meq/100 g). However less than five percent of the samples analyzed had smectite as a clay mineral; therefore CEC's greater than 30 meq/100 g would not be expected for many of the sediments underlying the Fresh Kills landfill. It should be noted, however, that of all samples analyzed, smectite is associated primarily with the residual clay and weathered bedrock, indicating that significant attenuation capacity is afforded by the sediments immediately overlying bedrock.

One of the major problems of the standard method for CEC determination is that the ratios of the major exchangeable species (Mg, Na, Ca, and K) cannot be measured, because sodium acetate is used as an exchange reagent, precluding determination of exchangeable sodium. Fourteen samples were re-analyzed for CEC using the lithium-cesium method (Neal, 1977) which allows for the measurement of all of the exchangeable species. The calcium/sodium ratio (which measures the interaction of meteoric water with the samples) was then compared (Attachment 33). Samples that have interacted with meteoric water tend to have high calcium/sodium ratios because of the natural water softening calcium/sodium exchange process. The three shallow samples exhibit an average Ca/Na ratio an order of magnitude lower than the average of the 11 deep samples selected for analysis. This low ratio implies that sodium bearing leachate has penetrated into the underlying shallow soils. Although these data are limited, they agree with water chemistry analyses that indicate sodium-bicarbonate leachate influence in the shallow wells.

7.3.8 Summary and Conclusions

The "geochemical process approach" (GPA) was used to assess the water chemistry data obtained at the Fresh Kill landfill. The GPA was used both to determine the types of groundwater occurring naturally under the landfill and to determine which groundwater samples have been affected by landfill leachate. Shallow groundwater heavily affected by leachate usually has a sodium-bicarbonate water type, very low sulfate, tritium values reflecting precipitation between 1960 and the present, and high organic carbon content. Leachate influenced samples also generally contain ammonium, and are enriched in deuterium and ^{13}C due to ammonification, methanogenesis, and sulfate reduction. Wells that clearly show leachate impact are screened in refuse or shallow unconsolidated overburden sediments. Seawater influence is clearly exhibited in a series of intermediate depth wells, primarily at Section 1/9. There are also a few instances of apparent sea salt or seawater influence on groundwater chemistry in shallow wells around the perimeter of the landfill sections.

The results of the full suite of geochemical analyses, including multivariate and mixing analyses, are summarized in Tables 7.29 - 7.32 for each of the four landfill sections. Application of the geochemical process approach detailed in Sections 7.3.2 and 7.3.3 was the basic method used to prepare the summary tables. The scientific reasoning in this approach limits the choice of potential solutes and parameters that can be used to clearly distinguish among mixtures of leachate, seawater and freshwater, and identifies: (1) differences in the chemical composition of the possible "end member" solutions (seawater, leachate and freshwater), and (2) chemical reactions typically found in the landfill environment. The geochemical process approach shows that, at dilute concentrations where seawater-freshwater and leachate-freshwater trends intersect, it is difficult to distinguish between the two types of mixtures. Thus, limits for significant mixtures of leachate were selected based on the information provided by the scatterplots, along with a knowledge of solute concentrations found in natural groundwater (freshwater).

In addition to the geochemical process approach, strontium isotopes were used to identify seawater mixing, Stiff diagrams were used to characterize water types, tritium plots were used to indicate if the "age" of the water was young enough to indicate a leachate mixture, cluster analysis statistics were used to identify the natural groupings of the water samples, and theoretical mixing calculations were applied to indicate the probable level of leachate mixing. In summary, Tables 7.29 through 7.32 were prepared through establishment of a series of criteria, based on the relationships observed in the plots of the geochemical data, defining: (1) clear leachate and/or seawater mixing, (2) possible leachate mixing, and (3) no leachate mixing. Several examples of criteria development are discussed below; these examples reference Section 1/9 (as the data set for this landfill is most extensive), although the cited relationships apply to the analysis of data from all of the landfill sections.

- ***Dissolved Organic Carbon versus Chloride***

The two sources for chloride concentrations greater than 100 mg/L in the landfill environment are leachate and seawater. In contrast, seawater exhibits less than 2 mg/L DOC (Drever, 1988), compared to leachate DOC concentrations from hundreds to thousands of mg/L. Thus, scatterplots of DOC versus chloride clearly distinguish freshwater - seawater and freshwater - leachate mixtures (e.g., Figure 7.521). Water clearly exhibiting a leachate influence will have a DOC concentration > 100 mg/L, hundreds of times greater than that of seawater or native groundwater. Water exhibiting 10- 100 mg/L DOC may possibly be influenced by leachate. It should be noted that groundwater associated with fluvial and marine deposits, such as at the

Fresh Kills landfill, can have a natural DOC concentration up to 100 mg/L (Thurman, 1985). Therefore, DOC alone up to that concentration may not be indicative of leachate contamination.

- ***Sulfate versus Boron***

The two sources for boron at the Fresh Kills landfill are seawater and leachate. The concentration of boron in seawater is about 4.5 mg/L (Drever, 1988), as high as 12 mg/L in the leachate, and less than 2 mg/L in the native groundwater. In contrast, the concentration of sulfate in seawater is about 3,000 mg/L, less than 50 mg/L in leachate, and less than 20 mg/L in native groundwater. Thus, scatterplots of sulfate versus boron can distinguish between freshwater - leachate and freshwater - seawater mixtures (e.g., Figure 7.525). Waters with less than 50 mg/L SO_4 and more than 3 mg/L B were considered as mixed with leachate. Boron versus sulfate scatterplots were not used to qualitatively determine possible leachate mixture, because the range in boron concentrations is too small.

- ***Bicarbonate versus Sulfate***

Reduction of sulfate to sulfide produces elevated concentrations of bicarbonate in leachate and in some natural waters under reducing conditions. As a result, leachate typically has high concentrations of bicarbonate (>1000 mg/L) and low concentrations of sulfate (<20 mg/L). Bicarbonate concentrations in natural freshwater are generally on the order of 100 mg/L, about the same as that for seawater. Thus, scatterplots of sulfate versus bicarbonate clearly show freshwater - seawater and freshwater - leachate mixtures (e.g., Figure 7.528). Water exhibiting a clear leachate influence will have a concentration of bicarbonate greater than 1000 mg/L; water samples with bicarbonate concentrations of 100-1000 mg/L represent possible leachate mixtures. The value of 1000 mg/L, about ten times greater than that associated with in native groundwaters, was conservatively chosen to define leachate mixing because natural groundwater may have bicarbonate concentrations of hundreds of mg/L (Freeze and Cherry, 1979; Drever, 1988).

- ***Bicarbonate versus Ammonium***

Ammonium (NH_4^+) is produced by the ammonification of nitrate under anoxic conditions. These are the same conditions that result in sulfate reduction. Thus, a leachate - freshwater mixture typically should have high concentrations of both ammonium and bicarbonate (e.g., Figure 7.530). Water clearly exhibiting a leachate mixture will have a NH_4 concentration > 100 mg/L, whereas

10-100 mg/L NH_4 indicates a possible leachate mixture. The value of 100 mg/L was conservatively chosen for this distinction because it is at least ten times greater than the concentration of ammonium expected in native groundwaters. The ammonium concentration of seawater is zero.

- ***Stiff Diagrams***

The shapes of Stiff diagrams were qualitatively used to determine the presence of leachate in groundwater (e.g., Figures 7.536 and 7.537). A sodium-bicarbonate water type was used to characterize leachate, whereas a sodium-chloride type water defines seawater.

- ***Stable Isotopes of Water and Dissolved Carbon***

The processes of methanogenesis and sulfate reduction removes isotopically light hydrogen in methane and hydrogen sulfide, leaving isotopically heavy hydrogen in water. Thus, water samples with a δD value that plot well above the meteoric water line are considered to indicative of a leachate mixture (e.g., Figure 7.541).

Carbon associated with leachate has a positive $\delta^{13}C$ value due to the removal of light carbon during methanogenesis. In addition, sulfate reduction in anoxic conditions will result in the production of bicarbonate. Thus, on a plot of bicarbonate versus $\delta^{13}C$, a leachate mixture is identified by a positive $\delta^{13}C$ value and high bicarbonate concentrations (e.g., Figure 7.543). In contrast, native groundwater (freshwater) exhibits a negative $\delta^{13}C$ value and low bicarbonate concentrations.

- ***Radiogenic Isotopes***

Tritium activity > 25 TU was used to indicate leachate mixing in groundwater. Tritium activity from 10-25 TU was used to indicate possible leachate mixing, and tritium activity < 10 TU to indicate no leachate influence (e.g., Figure 7.545). $^{87/86}Sr$ values between 0.709 and 0.710 were used to indicate a seawater mixture (e.g., Figure 7.593).

- ***Cluster Analysis***

Application of multivariate statistical techniques were successful in grouping water samples into three categories of leachate mixtures, seawater mixtures, and native groundwater (Figure 7.582). Group A samples were interpreted as leachate mixtures, Group B samples were interpreted as seawater mixtures, and Group C samples were interpreted as native groundwaters.

- ***Mixing Analysis***

The mixing analysis indicates the levels of possible leachate mixing that would result in the concentrations of important solutes found in water samples from the Fresh Kills landfill (e.g., Figure 7.591). Samples that consistently exhibited a leachate mixture greater than 10 percent were considered to be clearly representative of leachate mixing. Samples that consistently exhibited a 5-10 percent leachate mixture were considered to be possibly influenced by leachate. The lower limit of resolution of the mixing analyses is believed to be on the order of about 5 percent.

Significant findings identified through application of the geochemical process approach to this investigation include:

1. Scatterplots of relatively nonreactive solutes, such as total chloride, dissolved sodium, and dissolved organic carbon show that leachate can generally be distinguished from groundwater and from seawater-impacted groundwater at the landfill perimeter in Landfill Sections 1/9, 6/7 and 3/4. In general, leachate is a Na-HCO_3 type water with more organic carbon and less chloride relative to sodium than other water types at the site. Leachate in Sections 2/8 is generally more dilute than found elsewhere in the landfill, and has a chemical composition dominated by Ca and Mg, rather than Na. Solute plots at section 2/8 do not clearly identify the extent of groundwater contamination by leachate. This discrepancy is probably due to the location of shallow wells relative to the refuse mound available for sampling during the January 1992 sampling quarter.

2. Scatterplots of solutes affected by oxidation-reduction reactions also generally show clear distinctions between leachate and other water types for Landfill Sections 1/9, 6/7 and 3/4. In particular, leachate mixtures exhibit high concentrations of dissolved bicarbonate and ammonia and low concentrations of dissolved sulfate relative to native groundwater (freshwater) and seawater. These differences in concentrations are caused by the production of alkalinity during sulfate reduction and the production of ammonium during

ammonification and nitrate reduction. Ammonium, alkalinity , and sulfate are not as useful to distinguish leachate in Section 2/8, based on available data.

3. Piper diagrams of the wells for which major element data are available allow dilute, native groundwater types to be differentiated from leachate and seawater influences.

4. Stiff diagrams provide an easy visual distinction between water types and overall dissolved solids content of groundwater and leachate. On a Stiff diagram, the sodium-bicarbonate water type of leachate influenced samples is easily distinguished from the sodium-chloride chemistry of seawater and the very dilute water from deep wells.

5. Stable environmental isotopes provide independent support of the observations discussed above. The isotopes of oxygen and hydrogen in groundwater indicate that leachate isotopic composition has been influenced by methanogenesis and sulfate reduction in the landfill. Similarly, methanogenesis has left the leachate bicarbonate enriched with "heavy" carbon (^{13}C), distinct from the "lighter" bicarbonate present in deep, native groundwaters. The stable environmental isotopes provide an excellent supporting tool to identify leachate influence in groundwater . Most shallow groundwater and leachate is isotopically enriched in deuterium (δD) in every landfill section, as is the dissolved bicarbonate in $\delta^{13}C$.

6. The radioactive isotope tritium often could be used to collaborate the identification of leachate from the other geochemical methods. Where leachate mixes with groundwater, tritium activities are generally greater than 10 TU. However, this method must be used with care because in situ radioactive sources can be another source for tritium in the water, and leachate isolated from the major flow system may exhibit nondectectable tritium activity.

7. Multivariate analysis independently identified leachate and seawater mixtures, consistent with the findings of scatterplots, Piper and Stiff diagrams, and isotopic analyses.

8. Strontium isotopic ratios clearly define groundwater from bedrock, and groundwater mixed with seawater. The isotopic data, when plotted against inorganic solutes, supports the hypothesis that several shallow wells exhibit a seawater component; this component is probably the result of sea spray derived from storms.

9. With the exception of the residual clay and weathered bedrock, the clay mineralogy and grain size of the sediments beneath the Fresh Kills landfill results in a low cation exchange capacity. As a result, independent of hydraulic conductivity controls, most of the overburden sediments would exhibit limited attenuation of metal ions in solution. The Ca/Na ratio of a selected sample of shallow sediments appears to agree with water chemistry analyses that indicate leachate influence within wells in the shallow/refuse monitoring zone.

7.4 Numerical Solute Transport Analysis

In order to evaluate the potential for vertical leachate migration from the refuse to underlying sediments, a series of solute transport simulations were performed with the calibrated two dimensional (cross-sectional) numerical flow models developed for each of the landfill sections. These simulations were run simultaneously with the steady state flow analyses performed during sensitivity analysis (Attachments 18, 22, 26; 20 year period identified for solute transport), as well as the final transient simulations performed for each cross-section (Attachments 20, 24, 28).

As noted in earlier Section 6.0 discussions relative to sensitivity analysis, leachate is expressed as a scaled mass fraction value that varies from 0.0 to 1.0. The maximum value of 1.0 is assumed to be a constant source at the base of each of the refuse units. Several processes are simulated in the solute transport simulations, namely diffusion, advection, and dispersion. Diffusion is the process by which chemical species dissolved in water move from areas of higher concentration to areas of lower concentration. Advection is the process by which moving groundwater carries with it dissolved solutes. The process of dispersion acts to dilute the solute and lower its concentration, and consists of components both longitudinal and transverse to the direction of flow.

An additional component of the transport process consists of sorption or retardation, which represents chemical, physical, and biological activities within the soil matrix that interact with the solute and further act to reduce its concentration in solution. The most common retardation mechanisms are represented by the chemical reactions of adsorption-desorption, cation exchange, precipitation-dissolution, and oxidation-reduction. For example, many of the heavy metals are readily adsorbed onto solid surfaces or trapped by clays through ion exchange (as per the discussion in Section 7.3.7). Similarly, organic chemicals in solution can be adsorbed by the organic carbon content of the soils. Due to the wide range of retardation processes associated with the suite of solutes normally present in contaminant source areas, a conservative or non-reactive solute is often used to simulate the transport process (retardation factor $[R_d]= 1$). Under this approach (applied in this investigation) the processes of diffusion, advection, and dispersion fully control solute transport, and matrix interactions are ignored. Consequently, simulated mass distributions are conservative (high) relative to those that would be expected for any of the reactive solutes.

With the exception of the Section 6/7 cross-section, the transient solute transport simulations were run in five year increments for the period of time assumed to represent the approximate current age of each landfill section, based on review of historical aerial photography (Section 1/9: 30 years, Sections 2/8 and 3/4: 40 years, Section 6/7: 25 years). Leachate head in the landfill refuse mounds was varied over time from sea level to current observed leachate mound elevations.

At Sections 1/9 and 2/8 - 3/4, two solute transport scenarios were simulated: (1) a base simulation reflective of limited or marginal interconnection between shallow sand units and lower Cretaceous sands, and (2) a simulation within which shallow sand layers were inserted to provide enhanced or direct interconnection with lower Cretaceous sands. At Section 6/7, only the base scenario was run, and output provided only at the 25 year time interval, since sensitivity analyses had previously indicated that potential vertical sand interconnection at depth is not a salient consideration at that landfill.

Supporting material for these simulations contained in Attachments 20, 24, and 28 consist of grid cell by cell outputs followed by summary output grouped by stratigraphic unit for each five year increment, for both the base and sand interconnection simulations. For the final simulated time increment, detailed output is provided for both head and solute. As noted earlier, for Section 6/7 data is provided only for the final (25 year) base simulation.

Consistent with earlier discussions regarding the distribution of groundwater flux, the results of these analyses indicate that the majority of solute mass is associated with the refuse and shallow sand units underlying the landfills, ranging from 76-95 percent across the landfill sections. Solute migration to the Cretaceous sand unit is noted under both Landfill Sections 1/9 and 2/8. Interestingly, little variation in the mass distribution is observed between the base and sand interconnection simulations in this unit, notably at Section 2/8. The latter is the result of a fairly direct conduit into the Cretaceous sands incorporated into the base simulation at Section 2/8 (Sheet 6.38). Very little or virtually no mass is distributed into the weathered bedrock or bedrock units underlying the landfill sections.

- ***Predicted and Observed Solute Concentration***

Solute transport analysis allows for an independent means of evaluating the accuracy of numerically computed groundwater flux, through comparison of simulated solute distribution with observed solute concentrations measured in monitoring wells. As noted earlier, an important

consideration in this investigation is that the scaled mass fraction represents a conservative (non-reactive) substance, and will exhibit a concentration higher than that which would be expected from the suite of solutes associated with the migration of landfill leachate. Consequently, the comparative analysis is essentially a qualitative procedure, and is most appropriately applied to the examination of a conservative solute, such as chloride.

Unfortunately, the seawater influence in several of the monitoring zones underlying the Fresh Kills Landfill precludes use of chloride for this purpose in this investigation (even a very dilute seawater influence, on the order of several percent, results in a chloride concentration that exceeds median concentrations observed in the refuse mounds). For this reason, alkalinity has been identified as a reasonably non-reactive solute for comparative analysis; within the pH ranges of the groundwaters underlying the landfill, alkalinity is represented primarily by bicarbonate anion (HCO^-_3).

Figures 7.595, 7.596, and 7.597 summarize the percentage mass distributions associated with the transient solute transport simulations performed for the Landfill Section 1/9, 2/8 - 3/4, and 6/7 cross-sectional models. The plotted data represent the final simulated time increments (Section 1/9: 30 years, Sections 2/8 - 3/4: 40 years, Section 6/7: 25 years). The cross-sections at Sections 1/9 and 2/8 - 3/4 indicate the mass distributions for both the base and sand interconnection simulations.

Table 7.33 provides a comparative assessment of observed versus simulated percent solute distribution in monitoring wells located along the cross-sections identified in Figures 7.595-7.597. Mean solute (corrected alkalinity) concentration at each monitoring well location is expressed as percentage of the median alkalinity concentration measured within the shallow/refuse monitoring zone at each landfill section. As indicated in Table 7.33, the mean alkalinity concentration at each well is corrected by an estimated background concentration (Table 8.3) to account for the natural freshwater concentration of this solute, prior to performance of the percentage calculation. This percentage is compared to the simulated scaled mass fraction associated with both the base and sand interconnection simulations (where performed) at each landfill section. Given the limitations of the analysis described earlier, the observed and simulated concentration distributions generally agree well from a qualitative perspective. In addition, several insights into the simulated mechanisms of lateral and vertical flux are also observed.

With the exception of well 6W91:IT154D, virtually no solute is observed within the weathered bedrock/bedrock monitoring zone under simulated and observed conditions. As noted in Section 7.2.4, the shallow depth to bedrock along the eastern margin of Landfill Section 6/7 allows the potential for leachate or shallow groundwater mixing within the bedrock unit; this is observed in both the results of well sample analysis, and in the solute transport simulation.

Leachate mixing within intermediate depth sand units is observed in well sample data and the solute transport simulations at Landfill Sections 1/9 (1W91:IT008I), 2/8 (2W91:308I1), and 3/4 (3W91:IT406I). At Section 1/9, the solute transport analysis suggests that field conditions are more accurately represented by the base simulation rather than the sand interconnection simulation, relative to the observed versus predicted concentration distribution in the Cretaceous sand unit at location 1W91:IT008I. In addition, model computed vertical flux in the vicinity of location 1W91:001I appears excessive given observed data.

At Section 2/8, leachate mixing within the glacial sands associated with well 2W91:IT308I1 is observed in both well sample data and the transient simulations. Vertical flux to the deeper glacial sands as simulated by the cross-sectional model are at variance with the observed relationship, although it should be noted that the full suite of chemical analysis associated with well 2W91:IT308I2 is inconclusive regarding leachate mixing. The model predicted solute distribution is excessive relative to observed data at well location 2W92:IT309I. This suggests that, even under the base simulation, the hydraulic connection between the base of the refuse and the Cretaceous sand unit is more direct than warranted by field conditions. Alternatively, the head distribution simulated by the model may be excessive relative to field conditions, resulting in a solute flux scenario that may not be realized for some time.

At Section 3/4, leachate influence in well 3W91:IT406I is observed both in well sample data and the model simulations. Leachate mixing observed in the alkalinity data at well 6W91:IT162I is not simulated by the model.

Several processes may act to increase the modeled rate of vertical flux (and associated solute transport) beyond that believed to be associated with field conditions. For the two dimensional simulations, flow perpendicular to the cross-section (as noted above at location 2W91:IT308I1) represents one process that can affect the solute distribution. Additionally, as noted in Sections 6.2 through 6.4, considerations such as the elevation of the saturated leachate mound, and the

basal hydraulic conductivity distribution of the refuse, can affect vertical flux and the distribution of solute. These considerations have been partially evaluated within the context of the sensitivity analyses performed for the Landfill Section 1/9 and 2/8 - 3/4 cross-sectional models (Attachments 22 and 26). A more focused sensitivity analysis of the effect of unsaturated zones within the refuse was performed for the cross-sectional simulations at these landfill sections, and is contained in Attachment 35. These simulations indicate that the percentage of vertical leakage can be reduced by as much as 13 percent assuming a widespread areal distribution of unsaturated zones within the leachate mound. The effects of these processes on the migration of leachate will be evaluated more extensively through three dimensional solute transport analyses conducted in support of the Consent Order Appendix A-4 Leachate Mitigation Investigation.

- ***Three Dimensional Numerical Solute Transport Analysis***

As discussed in Section 6.6.2, solute transport analyses were performed using the calibrated three dimensional groundwater flow model of the project area. Very little data are available concerning the history and potential leachate distribution over time for the area beneath the landfill. Therefore, an attempt to simulate a know historical migration pattern is not feasible. Rather, the results of the solute transport simulation were used to observe potential migration pathways of leachate from the landfill mounds to and through underlying transmissive units. Such an analysis is useful for the integration of all components of the hydrogeological investigation (i.e., stratigraphic and hydrostratigraphic interpretations with observed water chemistry).

Based on the data contained on Map Sheet 6.71 (advective solute transport only), areas exhibiting potential leachate migration were schematically combined with the findings of the water quality and geochemical assessments to allow for direct comparison between the results of the two analyses (Figures 7.599-7.601). On these figures, data from the flow model Layer 4 were used to indicate areas of simulated solute transport on Figure 7.599 (Recent/glacial sands), and data from model Layer 6 (Cretaceous sand Unit 1) were used to indicate areas of simulated solute transport on Figure 7.600.

With the exception of the Cretaceous sand unit in Section 2/8, the model computed results closely simulate areas of observed leachate migration in the intermediate depth monitoring zone horizons. The discrepancy at Section 2/8 may represent potential future areas of leachate migration, the results of excessive leachate mound head applied over the flow model simulation period, or model boundary condition effects (resulting from a thinning of model layers) in that area.

Figure 7.601 indicates the results of the advective solute transport simulation in the bedrock, indicating several small regions of potential leachate migration. With the exception of Section 2/8, such migration is simulated within areas where Cretaceous sediments are not present between Recent/glacial deposits and bedrock. No migration to bedrock was observed when dispersion and sorption were incorporated into the solute transport simulation. Model simulated solute within the bedrock at Section 2/8, not observed in field data, may result from any of a series of factors, as noted above.

7.5 Summary

Leachate contamination occurs throughout the shallow/refuse monitoring zone at all of the landfill sections at Fresh Kills. The strength of the leachate (as measured by the concentration of chemical indicator parameters) is highest in Landfill Sections 1/9 and 3/4, relative to Sections 2/8 and 6/7 (Figures 7.241 - 7.246). These figures also indicate that leachate mixing in the intermediate depth monitoring zone is most pronounced at Landfill Section 3/4 in Recent sand deposits. Leachate mixing also is observed in Recent sands in Section 1/9 and glacial sands in Section 2/8 within the intermediate depth monitoring zone. Dilute mixing of leachate is noted in the Cretaceous sands at the southern tip of Section 1/9; a seawater influence and corresponding water quality degradation is observed in the western and southern areas of Section 1/9 in both the Recent and Cretaceous sand deposits. Little or no evidence of leachate migration to the deep (bedrock) monitoring zone is indicated in the analytical data.

Tables 7.3 through 7.14 and 7.29 through 7.32 provide a summary assessment of wells within which leachate influences on groundwater chemistry is observed, or potentially observed, by landfill section and monitoring zone. These assessments were based on a comparison of observed data with water quality standards/criteria, background/literature water quality data or data derived from similarly screened wells within a monitoring zone, or characteristic geochemical relationships identified for leachate affected waters. This assessment process

entailed the use of common indicator parameters, metals, dissolved solutes, and stable and radiogenic isotopes to define leachate influences. These analytes are routinely observed in measurable concentrations at all monitoring wells, and provide data that are generally not sensitive to qualification through data validation and usability review. Consequently, they represent a consistent data base amenable to qualitative and quantitative analysis relative to groundwater quality assessment.

Organic compounds (volatiles, semivolatiles, pesticides/herbicides/PCBs) were not used in these assessments, as they represent poor indicators of leachate contamination at the Fresh Kills landfill due primarily to: (1) the generally low concentration, sporadic occurrence, and lack of consistency in the detection of these compounds in all monitoring zones, (2) the questionable identification of many of these compounds near the detection limit range of concentration in the intermediate depth and deep monitoring zones, as observed through the data usability process, and (3) ongoing data usability review of organic compound data for the April, July, and October 1992 sampling events.

Outside of the shallow/refuse monitoring zone, only one instance of organic compound contamination is observed in the analytical data. This concerns a pattern of occurrence of two volatile organic compounds (2-Butanone and toluene) at low concentrations in a series of wells completed in the deep (bedrock) monitoring zone. The source of these compounds is unknown but is not believed to be associated with vertical leachate migration, due to: (1) the absence or low concentration of these compounds in overlying (source) intermediate depth and shallow/refuse monitoring zones, (2) upward vertical hydraulic gradients observed from the bedrock in most locations, (3) natural water chemistry characteristics exhibited by the results of general chemistry and geochemical analysis in the bedrock wells, and (4) the results of numerical groundwater flow and solute transport analysis. NYCDOS is currently investigating the potential for an upgradient, off-site source for this contamination.

Figures 7.598 through 7.601 graphically summarize the results of the groundwater quality and geochemical assessments, indicating well locations at which degraded or potentially degraded water chemistry has been observed (refer to Figures 4.23 - 4.26 for well identification numbers), with comparison to the results of conservative (advective transport only) three dimensional solute transport simulations. These figures segregate the results of these assessments by monitoring zone, and indicate seawater as well as leachate influences, where appropriate. A distinction has

been drawn in the intermediate (confined sand) monitoring zone, with relationships identified for the shallower Recent/glacial sands appearing on a separate figure (Figure 7.599) from the generally deeper Cretaceous sands (Figure 7.600). Seawater influences are noted primarily in the intermediate depth zones and, to a lesser degree, in the bedrock. Within the Cretaceous sand unit, the mapped extent of seawater influence is inferred primarily from geochemical analysis, although downhole geophysical logs were used to provide data in the central area of Section 1/9 where water chemistry information is not available. Geochemical inferences regarding seawater influences in wells screened within the shallow/refuse zone are sporadic, and have not been mapped.

The presence of the seawater influence increases the difficulty in evaluating leachate migration within sand units underlying the western and southern areas of Landfill Section 1/9, as observed through comparison of Tables 7.4 and 7.29, and discussions associated with the three component mixing analysis contained in Section 7.3.6. As noted in earlier text, the presence of seawater in Cretaceous sediments is noted in the literature for Staten Island (Soren, 1988), and is known to extend to the south of Landfill Section 1/9 in the vicinity of the South Shore Golf Course. The source of the seawater in the Cretaceous unit is not known, but is believed to associated either with: (1) residual (connate) seawater derived from the last eustatic high that has not yet been flushed from the sediments (Meisler, et al., 1984), (2) density driven migration through overlying Recent/glacial sediments in hydraulic communication with the Arthur Kill (possibly enhanced through channel dredging), (3) historic pumping activity in the bedrock or Cretaceous unit, resulting in localized areas of induced recharge from overlying sediments and the Arthur Kill channel, or (4) some combination of the above. Based on the results of a solute transport analysis performed for a Cretaceous unit pumping well scenario (Attachment 39), the most likely explanation for its presence is the historical pumping of an irrigation supply well at the South Shore Golf Course, located to the south of Section 1/9.

Assuming limited mixing of leachate with seawater influenced groundwater, as presumed from the results of the numerical flow analyses presented in Section 6.0 (and solute transport analyses discussed previously in Section 7.4), ultimate decision-making regarding the scope of appropriate remedial action in the Cretaceous unit needs to be evaluated against the existing, naturally degraded nature of groundwater in this area (chloride concentrations in excess of 250 mg/l are considered excessively salty for consumption, while observed concentrations in the seawater influenced Cretaceous unit range from about 3,000 to 13,000 mg/l).

8.0 Environmental Monitoring Plan/Site Analytical Plan

8.1 Introduction

This Environmental Monitoring Plan (EMP) and Site Analytical Plan (SAP) is presented in compliance with Appendices A-4, A-6, and A-7 of the Consent Order. Under Appendix A-6 and A-7, the New York City Department of Sanitation (NYCDOS) is required to submit "recommendations" for a long term monitoring program. This document exceeds the requirements of the Consent Order in that it goes beyond recommendations, and defines in detail a long term monitoring program that is in compliance with 6NYCRR Part 360-2.11(c) and (d). This document is suitable as a submission for permitting under Part 360, as specified in Appendix A-2 of the Consent Order. Also, under Appendix A-4 of the Consent Order, NYCDOS is required to submit an Engineering Report that is in compliance with 6 NYCRR Part 360-2.7. Subdivision (c) of that section requires a conceptual closure plan including a post closure monitoring plan that is in compliance with 6 NYCRR Part 360-2.11 and 2.15. This document also fulfills that requirement.

All monitoring activities, including preconstruction characterization to establish existing site water quality, operational monitoring (including operational, closure and post closure monitoring) and contingency monitoring are specified in 360-2.11 (c). Given the special circumstances of Fresh Kills as an existing unlined landfill, the specifications of Section 2.11 (c) require examination relative to their application to this project, to insure that the intent of the regulations are satisfied, and a clear set of objectives are established specifically for long term monitoring at Fresh Kills.

Elements of the Site Analytical Plan specific to 6 NYCRR Part 360-2.11(d) are presented in Section 8.3 and Appendix 41 of this document. However, many of the elements are incorporated into the Groundwater Contingency Monitoring Program detailed in Sections 8.2, and the following referenced documents which are not duplicated in Section 8.3, namely the Quality Assurance Program Plan (QAPP) for the Fresh Kills Landfill Leachate Mitigation Project, Department of Sanitation, New York City, New York; Revision 2, dated September 5, 1991 and the Analytical Quality Assurance/Quality Control Project Plan (QAPjP) Revision 3, January 16, 1992. These documents, and subsequent modifications are incorporated into the SAP by reference.

It is intended that the EMP and SAP will be "living" documents that will be subject to modification as conditions at Fresh Kills change during the life of the landfill, and during the closure and post closure monitoring period.

8.1.1 Objectives of Environmental Monitoring Plan/Site Analytical Plan

The objectives of the Environmental Monitoring Plan (EMP)/Site Analytical Plan (SAP) are to specify all of the requirements for monitoring the Fresh Kills Landfill to:

1. Determine the effects of leachate releases on the surrounding groundwater and surface water resources;

2. Characterize the existing conditions at Fresh Kills Landfill by establishing a data base to be used in the design of potential leachate mitigation corrective measures to protect the public health and the environment;

3. Monitor the effectiveness of the corrective measures in protecting the public health and the environment during operation, closure and post closure; and

4. Meet all of the requirements of the Fresh Kills Consent order and 6 NYCRR Part 360-2.11(c), 360-2.11(d) and 360-2.15, effective October 9, 1993.

8.1.2 Elements Of The Environmental Monitoring Plan/Site Analytical Plan

The elements of this EMP/SAP address the requirements of 6 NYCRR Part 360-2.11(c) and (d), and references to Section 2.11 in 360-2.15. The EMP describes all proposed on-site and off-site monitoring of groundwater, surface water and sediments, leachate and water supply wells that will occur at the Fresh Kills landfill. The relationship between the elements of the EMP and the SAP are illustrated in Figure 8.1.

8.1.2.1 Groundwater Sampling

Groundwater sampling described in 6 NYCRR Part 360-2.11(c)(1) describes the groundwater sampling program and stipulates that groundwater monitoring wells must be capable of detecting

landfill derived groundwater contamination within the critical stratigraphic section of the landfill. Additionally, this section sets forth the requirements for the placement and construction of monitoring wells.

These requirements were met in the design and implementation of the perimeter monitoring well program, as discussed in Section 4.3 of the Final Hydrogeological Report. These wells, including 1989 NYCDOS wells installed in Landfill Section 6/7, represent the monitoring array for the long term groundwater monitoring program required pursuant to the Consent Order. The details for groundwater monitoring, and the SAP for groundwater sampling, are presented as part of the contingency monitoring program in Sections 8.1.3.3 and 8.3 below.

8.1.2.2 Surface Water and Sediment Sampling

Sampling described in paragraph 360-2.11(c)(2) describes the surface water and sediment sampling program and stipulates that all surface water bodies which may be impacted by a contaminant release at the facility require sampling during the operational and contingency monitoring programs. As required by this paragraph, NYSDEC may require sampling of the surface water and sediments during the site investigation phase. In the case of flowing waters, a sufficient number of stations need to be located upgradient and down gradient to allow impact of the facility to be measured. The detailed analysis requirements at these sampling points must be specified in the contingency monitoring plan, and detailed sampling requirements must be specified in the Site Analytical Plan.

Appendix A-7 of the Fresh Kills Consent Order stipulated that a surface water and sediment investigation would be required for the site investigation phase. This requirement was met by the Final Surface Water and Sediment Report. The surface waters bordering Fresh Kills are classified as flowing waters; however, since they are tidal, they represent unique challenges in the siting of the sampling stations to conform to the "upgradient and down gradient" requirements of the contingency monitoring plan. Therefore, in both the characterization phase and in the contingency monitoring phase, the concept of near-field and far-field are substituted for the upgradient and downgradient requirements. In its simplest form, this concept is based on the fact that the impacts of the landfill to surface waters and sediments, if they exist, will be greater in closer proximity of the landfill, and will be driven by tidal fluctuations rather than continuous

flow in one direction. In recognition of the fact that there is a net outflow from the Fresh Kills waterway into the Arthur Kill, some sampling stations were situated above the tidal influence to measure the input of possible contaminants from upstream sources. In the case of the Arthur Kill, the modeling of the tidal fluxes indicates that there may be a slight net flow to the north; however this exists only during a very limited set of conditions. Changes in seasonal rainfall, winds, depth and location in the Arthur Kill cause this situation to change. Therefore, far-field stations were established to establish the "upgradient condition" as the base for the measurement of possible landfill impacts.

The details of the surface water and sediment sampling portion of the contingency monitoring plan are presented in the Surface Water and Sediment Report and meet the remaining requirements of 6 NYCRR Part 360-2.11(c)(2).

8.1.2.3 Leachate Sampling

Leachate sampling described in 6 NYCRR Part 360-211(c)(3) specifies that the environmental monitoring plan must specify leachate sampling points in order to obtain a representative characterization of leachate composition in the primary leachate collection and removal system. The intent of the leachate sampling is to monitor the constituents in leachate that are being removed for treatment, and that may escape from the landfill through a liner system. The analysis of the leachate is for expanded parameters, and is to occur semiannually.

For Fresh Kills, during the characterization phase of the Hydrogeological Investigation, sampling and analysis of the leachate at the Veterans Avenue Leachate Collection system has been performed and the data reported in the Hydrogeological Report. Also, wells screened in the refuse and just below the refuse have been monitored to establish the characteristics of the leachate. Therefore, an understanding of the nature and constituents of the leachate at Fresh Kills currently exists, and forms the basis for further evaluation. However, as the design of a leachate collection and containment system proceeds and the specific nature of this system is determined, a plan for monitoring leachate as mandated in 6 NYCRR Part 360-211 (c)(3) will be developed and included as an addendum to the Environmental Monitoring Plan.

8.1.2.4 Water Supply Well Sampling

Water supply well sampling described in paragraph 360-2.11(c)(4) is not applicable to Fresh Kills, as per the findings of the Supply Well Survey Report (IT Corporation, 1991a).

8.1.3 Water Quality Monitoring

6 NYCRR Part 360-2.11(c)(5) mandates a water quality monitoring program for groundwater and surface waters and sediments. The regulations require preconstruction monitoring to establish the "existing" water quality at the site, operational water quality monitoring to detect any change in water quality due to the filling activities and during the closure and post closure phases, and contingency monitoring if contamination is detected at the site.

8.1.3.1 Existing Water Quality

Existing water quality, as described in 6 NYCRR Part 360-2.11(c)(5)(i), is established during the preconstruction period as part of the initial hydrogeological study to characterize the site and establish the base against which the results of future monitoring programs can be measured. As necessary, these data become the basis for the development of site specific groundwater protection standards. Section 8.2.2.1.2 discusses the definition of existing water quality relative to the groundwater monitoring program.

As part of the Surface Water and Sediment Investigation the surface waters and sediments at stations in the vicinity of Fresh Kills were sampled and analyzed for expanded, baseline, and routine parameters over a period eight quarters. The results from these stations were compared to results from "far field" stations and reference stations to measure the impact of discharges from the landfill on the quality of the surface waters and sediments. In conjunction with this effort, a benthic invertebrate investigation was conducted to directly determine the effects of Fresh Kills on the indigenous aquatic communities in the Fresh Kills waterways.

The requirements for "existing" water quality monitoring, to the extent possible, have been met in the execution of the Hydrogeological Investigation and in the Surface Water and Sediment

Investigation, with the results reported in the Final Hydrogeological Report and the Final Surface Water and Sediment Report.

8.1.3.2 Operational Water Quality

The operational water quality monitoring described in 6 NYCRR Part 360-2.11(c)(5)(ii) was intended to occur during operation, closure, and post closure periods of the facility. The intent of operational water quality monitoring is to detect any landfill derived contamination of groundwater and surface waters. The operational water quality monitoring plan must contain trigger mechanisms for initiating contingency water quality monitoring. For a contingency monitoring program to be triggered, significant increase in concentration over "existing" water quality for one or more baseline parameters must occur.

In the case of Fresh Kills, initial water quality monitoring occurred during performance of the Hydrogeological Investigation. This monitoring identified the constituents and concentration distribution of contaminants in the landfill leachate and groundwater and revealed that many of the analytes exceeded regulatory agency water quality standards. Since a significant increase in some analytes is exhibited in groundwater, according to 6 NYCRR Part 360-2.11(c)(5)(ii)(f)(2), a contingency monitoring program that meets the requirements of subparagraph (iii) must be established for Fresh Kills. The Environmental Monitoring Plan herein represents a contingency monitoring program as defined in 6 NYCRR Part 360-2.11(c)(5)(iii).

8.1.3.3 Contingency Monitoring

An environmental monitoring plan must include a plan for contingency water quality monitoring as described in 6 NYCRR Part 360-2.11(c)(5)(iii). As indicated above, contingency water quality monitoring must take place when a significant increase over "existing" water quality is detected in one or more baseline parameters listed in the Part 360 Water Quality Analysis Tables. Once contingency monitoring is triggered, the owner/operator is required to execute a contingency monitoring program which involves analysis of upgradient and down gradient groundwater samples for the expanded parameter list in the Part 360 Water Quality Analysis Tables. In addition to various reporting requirements, if expanded parameters continue to be detected in the

groundwater, then the facility operator must establish site specific groundwater protection standards for those expanded parameters that were detected, as described in 6 NYCRR Part 360-2.11(c)(5)(iii)(f). If one or more of the expanded parameters are detected at or above the groundwater protection standards established for the site, then the owner operator must initiate an assessment of corrective measures required under 6 NYCRR Part 360-2.20. Lastly, if continued contingency monitoring shows that water quality falls below groundwater protection standards, or if the owner/operator shows that the source of contamination is from other sources, then the owner/operator may return to operational monitoring. Also, 6 NYCRR Part 360-2.11(c)(2) indicates that surface water and sediment sampling must take place, if appropriate, and a plan for surface water and sediment sampling is required as part of the contingency monitoring plan.

In the case of Fresh Kills, as indicated above, contamination has been detected in the groundwater at concentrations significantly above "existing" conditions for series of analytes. Therefore, Section 8.2 of this Environmental Monitoring Plan in fact represents the contingency monitoring program. The Leachate Mitigation System Investigation, which is currently underway under the requirements of Consent Order Appendix A-6, fulfills the requirement for a corrective measures assessment as required under 6 NYCRR Part 360-2.11(c)(5)(iii)(e)(4), and as described in 6 NYCRR Part 360-2.20.

8.2 Long Term Groundwater Monitoring Program (Contingency Groundwater Monitoring Program)

As discussed above, under the terms of the Consent Order, NYCDOS is required to develop a Long Term Groundwater Monitoring Program meeting the requirements of 6 NYCRR 360-2.11(c). These regulations specify that the program must be capable of distinguishing landfill-derived contamination from "existing" water quality at the site, and must identify trigger mechanisms to initiate contingency monitoring, as appropriate. As described above, the contingency monitoring program has already been triggered at Fresh Kills based on the currently observed water quality at the site, and development of corrective actions is ongoing.

The specific objectives of the Long Term Groundwater (Contingency) Monitoring Program are to:

1) Comply with 6 NYCRR Part 360-2.11(c) for the purpose of obtaining an operations permit for the Fresh Kills Landfill;

2) Monitor the effects of continued operations at Fresh Kills on groundwater quality;

3) Monitor the effectiveness of the leachate mitigation system (once constructed) on groundwater quality; and

4) Monitor the continued effects of Fresh Kills on groundwater quality during the closure and post closure period.

8.2.1 Monitoring Program

The monitoring program consists of three major components: identification of analytical parameters, identification of monitoring zones and sample locations within the critical stratigraphic section, and definition of sample frequency.

8.2.1.1 Monitoring Parameters

In this section, a continuum in the analyte list is established for application to various components of the monitoring program. Detected (critical) parameters are identified within the comprehensive analyte list, and a series of effective leachate indicator parameters are defined that include a subset of these analytes, as well as a suite of geochemical parameters.

8.2.1.1.1 Expanded Parameters and Data Quality Objectives

As the Fresh Kills Landfill is currently in the contingency monitoring phase, the basis for water quality analysis is the expanded parameter analyte list specified under 6 NYCRR Part 360-2.11(d)(6). The expanded parameters consist of nine field parameters (including measurement of static water level and notation of field conditions), 15 leachate indicators, 27 inorganic parameters (metals and trace elements), and 197 organic compounds (including volatile, semivolatile, and pesticide/herbicide/PCB compounds and groups of compounds).

Table 8.1 summarizes these analytes, and differs from 360-2.11(d)(6) only in terms of one field parameter (floaters and sinkers), one organic compound (Kepone) and two categories (groups) of organic compounds (polychlorinated dibenzo-p-dioxins, and polychlorinated dibenzofurans). Testing for the presence of floaters and sinkers has been removed from the analyte list due to the current impracticality of such testing given the installation of dedicated pump systems in all monitoring wells. It should be noted that the routine performance of such testing during quarterly sampling in 1991 and 1992 did not identify the presence of nonaqueous phase liquids in any of the on-site monitoring wells. Kepone was removed from the analyte list during initial technical review and development of the project QAPjP due to a repeated lack of quantitation. Based on the results of dioxin and furan analysis performed during 1991, NYCDOS requested removal of these analyte groups from the project analytical program. Based on technical review of supporting analytical data, NYSDEC subsequently waived the requirement to analyze for these compounds.

A primary component of the Site Analytical Plan specified under 6 NYCRR Part 360-2.11(d) is the establishment of data quality objectives (DQOs) for the data generation activity. The process of DQO definition includes identification of the goals of the water quality monitoring program (as previously described), the identification of regulatory programs and standards applicable to the analytical programs, and minimum detection limits for each of the parameters listed in the 360-2.11(d)(6) Water Quality Analysis Tables (in this case, the expanded parameters).

Table 8.1 summarizes all relevant information applied to the development of data quality objectives for the Long Term Environmental Monitoring Program, and indicates the DQOs for the expanded parameter analyte list. Such relevant information includes applicable NYSDEC Water Quality Standards, criteria, and guidance values (6 NYCRR Parts 702.3(a), (b), 702.4, 702.5, 702.6, 702.7, 702.15(a)(1)(ii), 703.3, 703.5(a)(3); 10 NYCRR Part 170; 10 NYCRR Subpart 5-1), and analytical test method detection limits (MDLs) and Practical Quantitation Limits (PQLs) for all analytes, where applicable. The MDL is the minimum concentration of an analyte that can be detected under ideal conditions by a specific laboratory test instrument. The PQL is the lowest concentration of an analyte that can be reliably determined within specified limits of precision and accuracy by a specific analytical test method under routine laboratory operating conditions. The PQL is generally established as 3-5 times the MDL.

For the purpose of the Long Term Environmental Monitoring Program, data quality objectives were established on an individual analyte basis, and set equal to the analogous water quality standard or guidance value, unless the project specific PQL exceeded the regulatory agency criterion. In the latter case, the DQO was established as the PQL. The tabulation of all analyte specific water quality criteria with the project defined DQOs on Table 8.1 is intended to insure that the analytical laboratory quantifies detected analytes to the maximum extent practicable in the case where PQL based DQOs exceed the water quality criteria (i.e., as estimated "J" qualified data in the range between the analyte MDL and PQL).

8.2.1.1.2 Critical Parameters and Groundwater Protection Standards

Critical parameters represent those analytes that have been detected during the monitoring program, and therefore represent the basis for data analysis and decision making. Table 8.2 provides a list of these analytes. In the case of the field parameters, leachate indicators, and inorganic parameters, all analytes are routinely detected. This is not the case with the organic parameters, which vary significantly in terms of their spatial occurrence and frequency of detection. For this reason, organic critical parameters are segregated by landfill section on Table 8.2, and only those analytes that have been consistently detected are indicated. Compounds that have been consistently detected only as estimated values are indicated by the symbol "(J)". Organic compounds that have not been detected consistently are identified separately in Table 8.2A. As noted in Section 8.2.3, the critical parameter list will be reviewed, and as necessary revised, on an annual basis to accommodate the progressive findings of the analytical program. Organic compounds that were initially detected, but have not been detected subsequently for at least two sampling quarters, will be removed from the critical parameter list.

Definition of the critical parameters represents a central component of the Environmental Monitoring Program relative to the rotational well sampling strategy defined in Section 8.2.2.3. During sampling quarters for which baseline parameter analysis is prescribed, the analytical program must additionally include analysis of detected expanded parameter compounds contained on the critical parameter list.

Under the contingency monitoring component of 6 NYCRR Part 360-2.11(c)(5), groundwater protection standards are required to be defined for all detected analytes. These standards are

required to be either: (1) regulatory agency water quality standards (e.g., Table 8.1), (2) "existing" water quality, if no water quality standards have been established, or (3) "existing" water quality, if measured analyte concentrations exceed water quality standards. Existing water quality is defined as that representative of groundwater conditions in the landfill area prior to any deposition of waste. Such data are not available for Fresh Kills given the age of the facility. However, as discussed in Chapter 7.0, water quality within certain monitoring zones and locations within the project area clearly exhibits dilute fresh water chemistry, with no indication of leachate mixing. The most representative of these areas consist of the intermediate depth Cretaceous sand and deep (bedrock) monitoring zones within the eastern portion of Landfill Section 2/8, and the southern portion of Landfill Section 6/7.

Table 8.3 lists all critical parameters contained within the leachate indicator and inorganic analyte groups, and indicates associated water chemistry summary statistics from those wells for which existing water quality status is presumed. These wells are represented by 2W91:IT305I, 306I1, 306I2, 307I; 2W92:IT309I, 310I1, 310I2, 311I2 in the Cretaceous sand monitoring zone, and 2W91:IT304D, 306D, 308D; 2W92:IT309D, 310D; 6W91:IT157D, 158D in the bedrock monitoring zone. Organic compounds are not indicated on this table due to the presumption that, under existing (background) conditions, these compounds would not be detected; consequently, the groundwater protection standards for these analytes would be equivalent to the regulatory standards, criteria, and guidance values indicated in Table 8.1. A possible exception to this approach relates to the compounds 2-butanone and toluene identified in the bedrock monitoring zone. Pending analysis of groundwater obtained from upgradient monitoring wells currently being installed, "existing" water quality may require redefinition for these compounds.

Tables 8.3 and 8.3A indicate groundwater protection standards developed for the leachate indicator and inorganic analytes within the Cretaceous sand and bedrock water bearing units, respectively. Standards identified from data associated with the Cretaceous sand wells are considered applicable to the Recent and glacial sand units extant within the project area.

Groundwater protection standards were established as the median of the monitoring well data, where such data exceeded regulatory standards. This was the case only relative to turbidity, color, phenolic compounds, iron, and sulfide. In the case of phenolic compounds, exceedences are related primarily to interferences, and consequent variability in the method detection limit.

Naturally elevated concentrations observed in the inorganic constituents is not surprising given the literature and historical database (Sections 7.1.1, 7.1.2).

Several other analytes exceed water quality standards in terms of maximum measured concentrations (manganese, sodium, TDS, chloride, magnesium, hexavalent chromium, and antimony). In the case of the trace elements, these exceedences are related primarily to variation in the analytical method detection limit. Relative specifically to antimony, use of Graphic Furnace Atomic Absorption Spectrophotometry (GFAAS) as noted in Section 7.2.5.3, will act to improve the method detection limit, and is reflected in the groundwater protection standard identified for this element in Tables 8.3 and 8.3A. With the exception of the trace elements, exceedences observed relative to these inorganic constituents are representative of natural variability; such variability (which includes the dilute presence of seawater mixing in intermediate and deep monitoring zones) needs to be considered in subsequent data analyses, i.e., through the integration of geochemical analysis in the interpretation of site chemistry (as discussed subsequently).

8.2.1.1.3 Site Specific Indicator Parameters and Geochemical Analytes

As with any analytical data base, a subset of the analytes provide the majority of information to be gained through detailed review. This is the case at Fresh Kills, where a specific group of inorganic constituents and organic compound groups provide the clearest indicators of the presence of leachate and/or seawater mixing in groundwater. These parameters are represented by:

Alkalinity (as $CaCO_3$)
Ammonia (NH^+_4)
Biochemical Oxygen Demand (BOD_5)
Boron (B^{+++})
Chemical Oxygen Demand (COD)
Chloride (CL^-)
Sulfate (SO_4^{2-})
Total Dissolved Solids (TDS)
Total Organic Carbon (TOC)
Total Volatile Organic Compounds (VOCs)

In addition to the above, a suite of geochemical analytes have been identified to assist in the evaluation of both leachate and seawater mixing, and provide an independent assessment of the results of conventional water quality analysis. These analytes, including dissolved (filtered) solutes and isotopes are:

Sodium (Na^+)
Magnesium (Mg^{2+})
Calcium (Ca^{2+})
Potassium (K^+)
Sulfate (SO_4^{2-})
Chloride (Cl^-)
Bicarbonate (HCO_3^-)
Boron (B^{+++})
Ammonium (NH_4^+)
Dissolved Organic Carbon (DOC)
$\delta^{13}C$
Tritium

The constituents identified above play a central role in the interpretation and annual reporting of analytical data under the Fresh Kills Environmental Monitoring Program, as detailed in Section 8.2.3.

8.2.1.1.4 Hydraulic Monitoring

As a supplement to the analytical sampling and analysis program, hydraulic head will be monitored within deep (bedrock) and selected intermediate depth (Cretaceous sand) wells as a component of the Long Term Environmental Monitoring Program. The rationale for such monitoring is that changes in the hydraulic regime at the landfill (including effects of increasing refuse and leachate mound elevations at the active landfills and remedial actions), will be most quickly observed through examination of hydraulic head (water level elevation) data.

Monitoring of water levels in bedrock wells will be performed manually on a monthly basis; continuous water level monitoring will be performed in the Cretaceous sand wells through the use of dedicated pressure transducers and electronic data loggers. Monitoring well clusters to be instrumented with the continuous monitoring equipment are: 006, 007, 008, 015, and 044 at

Section 1/9, and well clusters 305, 306, 307, and 311 at Section 2/8. Manual and continuous water level data will be submitted with the annual water quality monitoring report (Section 8.2.3).

8.2.1.2 Monitoring Zones (Critical Stratigraphic Section)

The concept of the critical stratigraphic section was introduced in Section 6.1.4.6 relative to the regional conceptual model of groundwater flow, and was defined as representing those hydrostratigraphic units that exhibit a potential to be affected by the migration of landfill leachate. In addition to the shallow/refuse monitoring zone, it was noted that the majority of the unconsolidated overburden unit (consisting of Recent, glacial and Cretaceous sands within the intermediate depth monitoring zone) would be considered a component of the critical stratigraphic section. It was further noted that observed hydraulic head relationships throughout the project area did not generally support direct migration of leachate contamination to the bedrock. However, due to the potential for limited leachate mixing at depth, as observed in the results of two and three dimensional groundwater flow and solute transport analysis, the deep (bedrock) monitoring zone was incorporated into the critical stratigraphic section.

As noted in Section 4.3.3, the existing project monitoring well array installed under this hydrogeologic investigation in accordance with the requirements of Consent Order Appendix A-6 and 6 NYCRR Part 360, allows for comprehensive monitoring of the defined critical stratigraphic section. This full array includes several additional intermediate depth monitoring wells identified in Section 4.3.3 (scheduled for December 1993 installation) to supplement the existing well distribution.

8.2.1.3 Sample Location and Frequency

A sample location and frequency strategy for the Long Term Environmental Monitoring Program has been identified for the monitoring well array installed across the critical stratigraphic section at the Fresh Kills Landfill based on consideration of: (1) the lateral well spacing increment associated with the monitoring well array within each monitoring zone, (2) the results of the groundwater quality and geochemical assessment, (3) the results of the conceptual and numerical groundwater flow analysis, and (4) the ongoing status of corrective actions at the landfill, in

accordance with the requirements of Consent Order Appendices A-3 (final capping and closure of Landfill Sections 2/8 and 3/4), and A-4 (leachate capture and treatment at Landfill Sections 1/9 and 6/7).

The proposed monitoring strategy consists of a quarterly sampling rotation. Within each monitoring zone, wells are divided into several groups, with sample collection alternating by group over the course of the year for expanded parameters, or baseline (plus detected expanded) parameters. The number of groups identified within each monitoring zone dictates the frequency at which each individual well is sampled within any year. This strategy is illustrated on Figures 8.2, 8.3, and 8.4 for the shallow/refuse, intermediate depth, and deep (bedrock) monitoring zones, respectively, at Fresh Kills (refer to Figures 4.27 - 4.30 for well identification numbers). Table 8.4 provides a detailed tabulation of the monitoring well assignments by group for each monitoring zone. As indicated, monitoring wells within the shallow/refuse monitoring zone have been divided into four groups, with those in the intermediate depth and deep (bedrock) zones divided into two groups.

Wells within the shallow/refuse monitoring zone exhibit a high degree of perimeter control relative to water quality assessment as a result of the 500 ft lateral spacing specification associated with their installation. Quarterly sampling of this zone has been performed since January 1991 on a progressively increasing number of monitoring wells, and the characteristics of leachate have been well established through this sampling effort. The increased sampling frequency identified for the intermediate depth and deep monitoring zones is a reflection of the potential sensitivity of these units to the vertical migration of leachate from the refuse mounds.

Table 8.5 provides a detailed description of the sampling rotation associated with each zone, noting the frequency of sample collection as well as the time distribution of baseline and expended parameter sampling and analysis. With four well groups (shallow/refuse monitoring zone), all wells are sampled once per year, with three of the groups receiving baseline (plus detected expanded) parameter analysis, and one of the groups receiving expanded parameter analysis. Over a period of four years, all wells are sampled once for expanded parameters. Table 8.5 indicates the full range of sampling permutations for this well grouping strategy, covering a period of 16 years. With two well groups (intermediate depth and deep monitoring zones), all wells are sampled twice per year, with one group during one quarter receiving expanded parameter analysis; baseline (plus detected expanded) parameter analysis is performed

during the other quarters for both groups. Over a period of two years, all wells are sampled once for expanded parameters. Table 8.5 indicates the full range of sampling permutations for this well grouping strategy, covering a period of eight years.

In addition to the strategy identified above for the conventional (expanded and baseline) parameters, geochemical sampling and analysis is also incorporated into the Long Term Monitoring Program. As indicated on Table 8.5, such analysis is performed on all intermediate depth and deep (bedrock) wells once a year, and once every other year for wells within the shallow/refuse monitoring zone.

8.2.2 Reporting

Within 90 days of the completion of each sampling quarter, all analytical data (including data quality assessment reports prepared in accordance with Section 8.3.5) will be submitted to NYSDEC. The analytical data submission will be prepared in both paper and electronic format in accordance with deliverable specifications previously established for this project.

In addition, an annual report will be prepared that compiles all data and summarizes contravention of groundwater protection standards. The critical parameter list will be modified, as necessary, based on review of analytes detected during the monitoring period. Trends in data will be depicted through the use control charts for selected analytes at all wells.

A control chart represents a method for the evaluation of groundwater analytical data from a monitoring well over time. In its most common application, it is used as an alternative to prediction limits for testing intrawell comparisons during a groundwater detection monitoring program (USEPA, 1992). In such an application, a test statistic is derived from a series of background data from a monitoring well against which successive quarters of monitoring data from that well are compared, to determine if significant changes in water quality have occurred. A useful component of the control chart application is that, in addition to providing a comparative test statistic, the method yields a graphical presentation of the time series data, allowing for a straightforward assessment of data trends.

It is this latter feature, rather than test statistic development, which is applicable to annual reporting under the Long Term Environmental Monitoring Program. Since there is no available background data set available for individual monitoring wells at the landfill, and the facility is currently in the contingency monitoring phase, there is no utility in application of the test statistic "trigger" (analogous to the 3 standard deviation criterion specified in the 6 NYCRR Part 360 detection monitoring program).

Figure 8.5 provides an example of the combined Shewhart cumulative sum (CUSUM) control chart recommended by USEPA Interim Final Guidance on the statistical analysis of groundwater monitoring data at RCRA facilities (USEPA, 1989). Concentration data is plotted in standardized units, both as a standardized mean, Z_i (triangular data points on Figure 8.5), and as a cumulative sum of the standardized means, CUSUM (circular data points), for each sampling event. Rapid changes in constituent concentration are readily observed by changes in the plot of the standardized mean data, while gradual trends are noted by the plot of the CUSUM data. (The "H" and "SCL" values at the top of the chart represent control limits for the Z_i and CUSUM data, respectively, in a typical detection monitoring program.)

In the preparation of control charts for the Fresh Kills Monitoring Program Annual Report, all sample data will be logarithmically transformed prior to calculation of standardized mean and CUSUM values. Analytes proposed for control chart development and ongoing review are those conventional parameters identified in Section 8.2.2.1.3: alkalinity, ammonia, biochemical oxygen demand, boron, chemical oxygen demand, chloride, sulfate, total dissolved solids, total organic carbon, and total volatile organic compounds.

In addition to the above, the annual report will summarize the results of the geochemical analysis program through the preparation of a series of scatterplots, similar to those referenced in Section 7.3.3. Once sufficient data have been obtained to make the evaluation meaningful, $\delta^{13}C$ and tritium data will be plotted as a time series for intermediate depth and deep well locations.

8.3 Site Analytical Plan

Some the of the elements of the Site Analytical Plan described in 6 NYCRR Part 360-2.11(d) are presented in Appendix 41. However, many of the elements are incorporated into the contingency

monitoring program detailed in Section 8.2, and are not duplicated here. In addition, many of the elements of the SAP are presented in the Quality Assurance Program Plan (QAPP) for the Fresh Kills Landfill Leachate Mitigation Project, Department of Sanitation, New York City, New York; Revision 2, dated September 5, 1991 and the Analytical Quality Assurance/Quality Control Project Plan (QAPjP) Revision 3, January 16, 1992 and subsequent modifications are included in the SAP by reference.

8.3.1 Data Quality Objectives

The data quality objectives for groundwater described in 6 NYCRR Part 360-2.11(d)(1) were discussed in Section 8.2.1.1.1 and are tabulated in Table 8.1. Other data quality objectives associated with the PARCC parameters are discussed in the QAPP referenced above; objectives of the groundwater monitoring program were defined previously in Section 8.2.

8.3.2 Analytical Quality Assurance/Analytical Quality Control Plan

The analytical quality assurance/analytical quality control plan described in 6 NYCRR Part 360-2.11(d)(2) is included in the QAPjP referenced above.

8.3.3 Field Sampling Procedures

The field sampling procedures described in 6 NYCRR Part 360-2.11(d)(3) are presented in Attachment 41 of this document, with other elements of the procedures detailed in the previously referenced QAPP and QAPjP.

8.3.4 Laboratory Procedures

The Laboratory Procedures described in 6 NYCRR Part 360-2.11(d)(4) are provided in the previously referenced QAPjP.

8.3.5 Data Quality Assessment

As described in 6 NYCRR Part 360-2.11(d)(5), at the conclusion of each sampling event and the analysis of samples collected, data quality assessment will occur. The results of the data quality assessment will be submitted with the results of the sampling events (Section 8.2.2). The data quality assessment will occur in two phases:

- **Data Validation** as described in subparagraph 360-2.11(d)(5)(i) will be conducted on all analytical data for the facility an a rate of twenty percent of the data generated. For the Fresh Kills EMP, data validation will be performed by an independent contractor (H2M Laboratories).

- **Data Usability Analysis** as described in paragraph 360-2.11(d)(5)(ii) will be performed on all analytical data obtained under the EMP. The data usability evaluation will be conducted by IT Corporation in accordance with the methodologies previously established under the Landfill Leachate Mitigation System Project (Appendix O).

9.0 SUMMARY OF FINDINGS

This section discusses the primary findings of the hydrogeological investigation relative to geologic, hydrogeologic, and water quality/chemistry site characterization. Within each technical area, a general overview is provided, followed by landfill section specific discussions.

9.1 Geology

Literature review relative to the geology of Staten Island has indicated a limited availability of current and pertinent information compared to neighboring areas of New Jersey and Long Island. Consequently, in the development of the investigation and analysis program for this project, maximum use of the limited local data base was made, supplemented by prior site-specific subsurface investigations, and regional studies that include general reference to conditions within Staten Island.

The Fresh Kills Landfill occurs within two physiographic provinces (regional areas of characteristic or distinctive geology, topography, and climate): The Triassic Lowland portion of the Piedmont Province underlies the northern portion of the project area, and the Coastal Plain Province is represented to the south (Figure 2.2). The division between these regions is termed the "Fall Line", and has been mapped beneath the project site. The presence of this regional boundary within the area of investigation complicates the geologic and stratigraphic evaluation. Straight-forward analysis is further complicated by the effects of glaciation in the region, which modified the prior topography and deposited a sequence of highly variable soil materials. The Fresh Kills area is especially difficult to evaluate in this regard, due to its location near the terminal glacial advance, reflecting a range of subglacial, glaciofluvial, glaciolacustrine and ice contact, depositional environments.

Recognizing these complexities, conventional lithologic analysis was supplemented by a series of additional investigative techniques in the geologic analysis program. These included downhole geophysical logging (to assist in the definition of geologic contacts, and the evaluation of soil characteristics), microfossil analysis (to establish the age of sediments in support of lateral correlation), and piezo electric cone penetration testing (to allow for a higher level of definition of lithologic structure in shallow sediments).

Based on these analyses, the stratigraphic column for the project area is established, as follows:

Lithostratigraphic Units	Time Stratigraphic Units
Refuse/Fill (F) Peat (Qp) Silt and Clay (Qrc) Sand (Qrs)	Holocene (Recent)
Glaciolacustrine Silt and Clay (Qgl) Glacial Sand (Qgs) Glacial Till/Diamict (Qgt)	Pleistocene (includes Columbia Group)
Silt and Clay (Kc) Sand (Ks)	Cretaceous
Residual Clay (Tlc, Tsc, Osc, Shc) Weathered Bedrock (Tlw, Tsw, Jdw, Osw, Shw) Bedrock (Tl, Ts, Jd, Os, Sh)	Triassic/Jurassic; Ordovician

This stratigraphic column is very similar to that identified in previous investigations, although detailed knowledge of the vertical and lateral distribution of the deposits has been achieved only through this hydrogeologic investigation. The lithostratigraphic units represent the evolution of different geologic environments through time. Time stratigraphic units corresponding to the groups of lithostratigraphic units are also presented. The lithostratigraphic units do not always occur in the order listed above within the time stratigraphic unit (for example, peat may occur below Recent silt and clay). The time stratigraphic units, by definition, must always occur in sequence, although units may be absent due to nondeposition or erosion. Ages of the unconsolidated materials are defined by microfossil analysis, by geological perspective (i.e., till is distinctly glacial and therefore Pleistocene in age), and by correlation with previous investigations. A brief descriptive summary of the stratigraphic units is provided below:

- ***Recent Deposits***

Man made deposits are comprised of either refuse or clean fill. Refuse consists of man-made objects and plant/food materials. It is found at the ground surface or below clean fill, and above natural geologic strata or clean fill. Clean fill is found above natural geologic strata and below, within, or above refuse. It is composed primarily of varied amounts of silt, clay, sand, gravel, boulders, and cobbles.

Peat, dark brown to black in color, is composed of fibrous plant material or meadow mat. It is located below refuse/fill, and above or interbedded with other Recent Deposits.

Recent Silt and Clay is light gray to black in color with a textural predominance of silt and clay. It is located above glacial deposits and below refuse/fill.

Recent Sand is brownish to light gray to black in color with a textural predominance of sand. It is found at the ground surface or below refuse/fill, Recent silt and clay, peat, and above the glacial deposits. Due to the absence of glacial deposits in some portions of the western area of Landfill Section 1/9, positive identification of the Recent sand in that area is difficult through simple visual examination. Other methods, such as microfossil analysis, grain size distribution and color were utilized to identify Recent sand in that area.

- ***Pleistocene Deposits***

Glaciolacustrine silt and clay is red brown in color with a textural predominance of silt and clay. It is found below the Recent deposits or refuse/fill, and above or interbedded with glacial till/diamict.

Glacial sand is red brown in color with a textural predominance of sand. It is found below the Recent deposits and above, below, or within the glaciolacustrine silt and clay or the glacial till/diamict.

Glacial till/diamict is red brown in color with a textural predominance of silt and clay, with a greater frequency of sand and gravel than glaciolacustrine silt and clay. Occasionally a textural

predominance of gravel size fraction with a high sand, silt and clay content is seen. The glacial till/diamict is found below Recent deposits or refuse/fill, and above Cretaceous deposits, residual clay, or bedrock.

Columbia Group sediments are yellow to orange brown sands and silt/clay located in the southern portions of Landfill Sections 1/9 and 2/8. They are found above the Cretaceous deposits and below the glacial deposits.

- ***Cretaceous Deposits***

The Cretaceous silt and clay is light gray to black and/or variegated red brown and light gray in color with a textural predominance of silt and clay. It is located below refuse/fill, Recent, or glacial deposits and above residual clay or bedrock. In the southern portion of Section 2/8, other methods are necessary to differentiate between Recent and Cretaceous silt and clay. Silt and clay predominantly red brown in color that occurs below glacial deposits is differentiated from glaciolacustrine silt and clay by its firm, stiff nature and/or red brown/light gray mottled character.

Cretaceous sand is white to dark gray in color with a textural predominance of sand. It occurs below Recent or glacial deposits and above residual clay or bedrock. Due to the absence of glacial deposits in the western portion of Section 1/9, other methods were necessary to distinguish Cretaceous sand from Recent sand.

- ***Residual Clay***

Residual clay is red brown, light gray, yellow green, blue green, red purple, or blue gray in color with a textural predominance of silt and clay. It is found below the glacial deposits or Cretaceous deposits and above bedrock. It is differentiated from Cretaceous silt and clay by its often waxy lustre, or color association with the underlying bedrock.

- ***Bedrock***

Within the project area, bedrock consists of the Triassic Stockton Formation (shale, siltstone, and sandstone), the Triassic Lockatong Formation (shale and siltstone), schist, and the Staten Island serpentinite (highly mineralized metamorphic rock). Weathered bedrock consists of consolidated rock that is freshly to severely weathered, and exhibits fairly extensive to extensive fracturing based on the inspection of rock core. Unweathered (competent) bedrock consists of solid rock that is usually fresh to moderately weathered, and exhibits limited to fairly extensive fracturing based on the inspection of rock core.

9.1.1 Landfill Section 6/7

The refuse/fill at Section 6/7 (Sheets 5.28 through 5.30) lies predominantly upon a base of Recent silt and clay and peat materials (Sheets 5.31 and 5.33) deposited within a tidal marsh environment that was present prior to the initiation of landfilling activities. Recent sand may occur as isolated or transmissive channel deposits within this matrix, and in some areas may be in contact with the refuse/fill (Sheet 5.78). A laterally extensive unit of Recent sand occurs within the northwestern area of the landfill, and is correlative to a similar deposit underlying Landfill Section 3/4 to the west. Along the eastern border of the landfill, within a former upland area, the Recent deposits are absent, and glacial deposits occur below refuse/fill and above bedrock.

A glaciolacustrine silt and clay sequence (glacial lake bed deposit) underlies the Recent deposits across virtually the entire landfill area. This unit is underlain by an equally extensive layer of glacial till (Sheet 5.56). The glacial sands in the north west portion of the section were deposited in an ice marginal environment and are associated with the kame feature in Landfill Section 3/4. The potential exists for glacial sand present in the southern portion of the landfill section to be correlative with similar units on the other side of Richmond Creek in Landfill Section 2/8. Residual clay (soil derived from significant decomposition and consequent weathering of underlying bedrock) is the basal soil unit above bedrock within most of the northern half of the landfill section (Sheet 5.68).

The bedrock within Section 6/7 consists of the Stockton Formation (sandstone, shale, and siltstone) in the north, and ordovician serpentinite and associated schist to the south (Sheet 5.82). A zone of weathered bedrock occurs above the serpentinite and above portions of the Stockton Formation (Sheet 5.71). The bedrock surface generally rises to the east, resulting in a thinning of the Recent and glaciolacustrine deposits in that area. In the extreme southern portion of the landfill section, the weathered bedrock/bedrock surface slopes steeply to the southeast (Sheets 5.71, 5.74). Within this region, an interbedded sequence of Cretaceous silt/clay and sand occurs in the bedrock low area below Recent and glacial deposits. It is interpreted that these strata correlate with more areally extensive Cretaceous strata underlying Landfill Sections 1/9 and 2/8 to the west.

9.1.2 Landfill Section 1/9

The refuse/fill in Section 1/9 overlies Recent sediments of silt and clay, peat, and sand deposited within a prior tidal marsh environment that existed under most of the landfill section (Sheet 5.78). The Recent sand occurs as transmissive channel deposits or layers above, below, or within the confining silt and clay layer. When they occur above the silt and clay, they are in contact with the refuse. In the east-southeast portion of the landfill section, the Recent sediments are absent from a former upland area (Sheet 5.78). In this area, glacial or Cretaceous sediments occur below refuse/fill.

Beneath the Recent deposits in the northern and central portions of the landfill is a confining unit of glaciolacustrine silt and clay (Sheet 5.41). This unit is often underlain by a layer of glacial till that occurs as a fairly continuous layer in the eastern half of the landfill. Glacial sand mainly occurs with till in a kame deposit in the east central portion of the landfill section (Figure 5.13; "A").

Cretaceous deposits consisting of interbedded silt/clay and sand underlie the glacial and/or Recent deposits within the landfill (Sheet 5.80). Thickness of the sand members within the Cretaceous unit generally range from 2 to 20 ft thick, with a maximum observed composite thickness of approximately 80 ft in the south. A basal sand layer occurs across almost the entire extent of the Cretaceous sequence. The Cretaceous clay and silt is the predominant unit above this basal sand layer; however, sand interbeds are common. The most extensive of these interbedded sand

units occurs in the east central portion of the landfill. Age dating of Cretaceous sediments through microfossil analysis indicates that portions of these strata may not directly correlate with extensive Cretaceous deposits in New Jersey. The major implication of the findings of the microfossil analysis that Cretaceous strata in the Fresh Kills area are likely separated from primary water supply aquifers in New Jersey by thick, overlying confining beds of silt and clay. Seawater degradation of the Cretaceous sands at Section 1/9 mitigates against the potential effects of a dilute leachate influence in this unit on possibly correlative strata to the west and south.

A confining layer of residual clay underlies the Cretaceous sequence under the entire landfill section (Sheet 5.68). A generally transmissive weathered bedrock zone occurs between the residual clay and the competent bedrock, although this zone exhibits an extremely low hydraulic conductibility along the east-central area of the landfill. The bedrock underlying Section 1/9 consists of the Triassic Stockton Formation (sandstone, shale, and siltstone).

9.1.3 Landfill Section 2/8

Within this Section, the refuse/fill overlies Recent silt/clay, peat or sand in the north, and either glacial deposits or Cretaceous deposits in the south (Sheet 5.78). The Recent deposits are limited to former tidal marsh areas in the northern and southwestern areas of the landfill that was present prior to the placement of fill. The Recent sand is found in eastern and northern areas of the landfill, the latter being correlative to the site wide, laterally continuous sand unit.

A glaciolacustrine silt and clay unit underlies the Recent deposits where the latter are present. The glaciolacustrine silt and clay pinches out to the south as a former upland area is approached. A deposit of glacial till is present below most of the landfill. However, in an area within the south central portion of the Section, the till and/or glaciolacustrine silt and clay is absent and apparently was excavated during landfilling activities (Sheet 5.79). Most of the glacial sand is associated with the kame feature in Landfill Section 1/9. The glacial sand may extend under Richmond Creek and be correlative with sand in the southwest area of Landfill Section 6/7.

Cretaceous deposits consisting of interbedded clay/silt and sand layers occur below the glacial sequence under most of the landfill. There is a basal sand layer correlative over most of the landfill section. Above the basal sand layer, the clay and silt is dominant, but is interbedded with

sand units. Portions of the Cretaceous clay/silt and sand layers have been correlated westward into Landfill Section 1/9 and eastward into Landfill Section 6/7.

A confining residual clay exists in portions of the landfill (Sheet 5.68). Weathered bedrock also underlies most of the landfill, occurring between the residual clay and competent bedrock (Sheet 5.71). The bedrock within Section 2/8 consists of the Stockton Formation (sandstone, shale, and siltstone) in the north and west, and serpentinite and schist in the south and east (Sheet 5.82).

9.1.4 Landfill Section 3/4

Refuse/fill occurs above Recent sediments deposited within a former tidal marsh environment across most of the entire Section (Sheet 5.78). Above the kame feature in the east central portion of the landfill (Figure 5.13; "B"), Recent sediments are absent, and the refuse/fill is in contact with glacial deposits. Most commonly the refuse lies upon a Recent silt and clay/peat base; however, in the north and central portions of the landfill, the silt and clay/peat is absent, and the refuse/fill was deposited directly above the Recent sand. The Recent sand is laterally extensive beneath most of the landfill section (Sheet 5.37).

Section-wide deposits of glaciolacustrine silt and clay underlie the Recent deposits, except for a small area in the east central portion of the site (Sheet 5.42). Below the glaciolacustrine silt and clay, a continuous unit of glacial till occurs. Glacial sand occurs mostly within and associated with the kame feature located in the east central portion of the landfill. These sands extend westward in Landfill Section 3/4 and eastward under Main Creek into Landfill Section 6/7 (Sheets 5.46 and 5.47). Non-lodgement till and glaciolacustrine silt and clay is often interbedded with the glacial sand.

A relatively thick confining residual clay layer occurs below the glacial deposits across the entire landfill (Sheet 5.68). A weathered bedrock zone is present between the confining residual clay layer and competent bedrock (Sheet 5.71). The bedrock in Section 3/4 consists of the Lockatong Formation (siltstone) in the west-northwest, and the Stockton Formation (sandstone, shale, and siltstone) in the southeast (Sheet 5.82).

9.1.5 Three Dimensional Perspective

Three dimensional analysis of the distribution of sediments within the project area (Sheets 5.78-5.80, 5.6 - 5.27, and 5.85 - 5.92) indicate that laterally correlative strata of Recent, glacial and Cretaceous sands (Figures 5.32 - 5.34) are deposited in a manner that would suggest vertical continuity in portions of Landfill Sections 1/9, 2/8, 3/4, and 6/7. These findings have been incorporated into the development of the regional, three dimensional numerical flow model to assess implications regarding vertical groundwater flux and leachate migration.

9.2 Hydrogeology

Assessment of the groundwater flow system is achieved through definition of a series of basic elements that define area hydrogeology and form the basis for conceptual model development. These include: (1) hydrostratigraphic units, (2) hydraulic conductivity distribution and thickness, (3) hydraulic boundary conditions, (4) hydraulic head distribution, (5) temporal hydraulic head variations, and (6) groundwater flux analysis.

Based on the results of detailed geologic mapping, hydraulically transmissive and restrictive have been defined across the project area, resulting in the development of a series of hydrostratigraphic units. At the regional scale, these are represented by the refuse, unconsolidated overburden, and bedrock units. On a more local, landfill section scale, segregation of the unconsolidated overburden hydrostratigraphic unit into sub-units of transmissive and restrictive strata has been performed in support of more detailed evaluation (Sheets 6.11-6.29).

The hydraulic conductivity (K) distribution of most hydrostratigraphic units and sub-units has been defined through the performance of in-situ testing and laboratory testing of soil materials (Sheets 6.2-6.10). Adequate hydraulic conductivity data have been recovered to characterize soil materials (Tables 6.1 - 6.3). The thickness distribution of hydrostratigraphic units and sub-units is also fairly well established (Sheets 5.30, 5.32, 5.38-5.40, 5.44, 5.45, 5.52-5.55, 5.58, 5.61, 5.65-5.67, 5.70, 5.73, 6.30, 6.31).

Boundary conditions relate to hydraulic features or processes that are external to the hydrostratigraphic units (along their boundaries) and prescribe the means by which groundwater

flow is routed in and out of the physical system being evaluated or modeled. Broadly defined, boundary conditions include infiltration from precipitation, surface water/sea level stage (elevation), the base of the bedrock flow system, landfill alterations (grading), and local or regional hydraulic gradients.

Infiltration rate and the base of the bedrock flow system represent the two boundary conditions about which the least information is available. Analytical flux analysis suggests that recharge can vary from approximately 14 to 18 in./yr across the landfill, with an arithmetic average of 16.3 in./yr. Regional flux analysis indicates generally small vertical gradients within the bedrock, suggesting a more regional horizontal flow system within that unit.

The lateral and vertical hydraulic head (water level elevation) distribution defines the driving force for the groundwater flow system. The existing data base allows for an adequate definition of the lateral distribution of hydraulic head in the primary transmissive hydrostratigraphic units or sub-units identified in the project area (i.e., refuse, Cretaceous sand, and bedrock; Sheets 6.32, 6.38, 6.40). Limited data is also available to generally characterize hydraulic head and flow gradients in several of the smaller, discontinuous transmissive units (Sheets 6.33-6.37; 6.39). Based on available data obtained from test borings and shallow/deep cluster piezometers installed in the refuse, the elevations of the leachate mounds within the refuse units are not believed to be representative of full saturation. Unsaturated (dry) zones appear to be perching leachate 30-60 ft above the true saturated surface. Field data are sufficient to allow for numerical evaluation of the effects of such perched conditions on horizontal and vertical groundwater flux. The presence of a saline water influence in the Cretaceous sand unit within Landfill Section 1/9 necessitated correction of field measured salt water heads to equivalent fresh water heads for correlation with data obtained at individual monitoring locations (Table 6.6).

The vertical head distribution is well established at monitoring well (cluster well) locations (Table 6.7); while these point relationships generally cannot be extrapolated spatially with a high degree of precision, they do allow for quantitative assessment (Figures 6.48 - 6.50). Based on the available data, the following relationships are observed: Flow potential within the refuse mounds to adjacent surface water discharge areas, and vertically downward to overburden materials; upward gradients from the bedrock unit into overburden materials; lateral discharge from overburden units into adjacent surface waters or out of the project area along the regional hydraulic gradient. Upward gradients from the bedrock unit are not as characteristic within

Landfill Section 2/8 as in the other landfill sections, establishing a potential downward gradient to this unit through the overburden. This represents potential only, and not significant flux due to the overlying thickness distribution of low permeability strata.

Available data from within the bedrock units underlying the central portions of the landfills suggest areas of mounding in the bedrock piezometric surface (Sheet 6.40). Such mounding is believed to represent a pressure effect caused by depression/compaction of overburden strata due to the weight of overlying refuse, rather than a downward hydraulic loading (flux). This assessment is based on the thickness distribution of hydraulically restrictive materials underlying the landfills, as well as observed vertical gradient distributions, discussed above.

Temporal hydraulic head relationships (resulting primarily from tidal effects within the Fresh Kills estuarine system) have been recorded at most well installations and within surface waters through the use of continuous water level recorders (Figures 6.13, 6.14, 6.16-6.19; 6.23 - 6.31; 6.35 - 6.38; 6.41-6.44). Water levels within shallow/refuse wells screened in the unconfined (water table) water bearing unit are generally not tidally influenced. The influence of tidal fluctuation on water levels in wells screened in intermediate depth confined or semi-confined sand strata is mixed, dependent on spatial location and the continuity of the transmissive unit. Water levels in the bedrock wells generally exhibit tidal fluctuation, consistent with pressure induced effects. Based on data recorded through 1991 and 1992, it appears that the steady-state analyses of groundwater flow considered to date are consistent under transient conditions (Appendix J).

Barometric analysis of shallow/refuse wells suggests that groundwater within the refuse mounds may be flowing under semi-confined conditions as a result of the positive gas pressures observed in the unsaturated refuse (Figure 6.15).

9.2.1 Landfill Section 6/7

Conceptual model analysis of Landfill Section 6/7 suggests that low permeability Recent silt and clay, till or residual clay form the contact with the base of the landfill. Contours of water levels in both plan and profile indicate that the majority of groundwater within the refuse unit moves laterally toward the surrounding local surface water bodies (Sheets 6.32, 6.17-6.27). Analytical

flux analysis indicates that about one percent of recharge that enters the landfill can leave the refuse unit (and shallow, hydraulically interconnected sands) as vertical flux to deeper overburden units (Figure 6.20). Recharge was estimated through flux analysis to be approximately 13.73 in./yr. A two-dimensional, cross-sectional, numerical flow model was developed for Landfill Section 6/7 (Sheet 6.44) and calibrated with transient data (Table 6.10).

Calibrated two dimensional model results (Figure 6.21) indicate generally horizontal flow within the refuse to discharge zones within Main Creek to the west, and a perimeter tributary stream to the east. Below the central groundwater mound, a vertical downward gradient is evident, responsible for a flux of about one percent of infiltration into the overburden hydrostratigraphic unit, similar to analytical results. Flow within the overburden is primarily lateral and appears to be local to the landfill in nature, with the primary source of discharge being Main Creek. Beneath the landfill mound, a vertical downward gradient is evident within the upper portion of the unconsolidated unit; the magnitude of the gradient decreases with depth, but extends to the bedrock unit. With the possible exception of the eastern margin of the landfill, where silt and clay deposits thin and the bedrock surface rises, the potential for groundwater flux into the bedrock is negligible.

Steady-state sensitivity analyses (Table 6.11) performed on the cross-sectional model relative to flow and solute transport indicate the following:

- Variations in hydraulic conductivity and ratios of vertical to horizontal K in the refuse unit generally only affect the flow within the refuse unit. Solute transport to the underlying units was not significantly affected in terms of total distribution.

- The potential for high permeability sand lenses beneath the refuse can effect the distribution of solute, with more direct solute discharge to the surface water and less to the underlying units.

- High permeability sand lenses beneath the refuse do not significantly alter the refuse head distributions or mass flux exiting/entering the landfill.

- High permeability sand lenses within the lower permeability silt and clay units can effect the distribution of head within the lower permeability unit, but do not significantly change the distribution of solute.

- Increases in the hydraulic conductivity of the till unit increase the potential for solute to migrate into the bedrock unit on the eastern model boundary.

The results of the sensitivity analyses indicated that the regional three dimensional (areal) numerical model of this portion of the project area could be simulated with three layers representing the refuse, unconsolidated overburden, and bedrock hydrostratigraphic units.

9.2.2 Landfill Section 1/9

Conceptual model analysis of Landfill Section 1/9 suggests that in general, the base of the landfill is in contact with low permeability Recent silts and clays, glacial clays, till, and Cretaceous clays, although Recent and glacial sand deposits may be in direct contact with the refuse in the western and south western area. Plan and profile contours of water level elevations (Sheet 6.32) suggest that the majority of groundwater leaving the refuse unit leaves as lateral flow, although a vertical flow component has been noted beneath the landfill in some areas.

Analytical flux analysis suggests that approximately 14 percent of recharge that enters the landfill can leave the refuse unit (and shallow, hydraulically interconnected sands) as vertical flux to deeper overburden units (Figure 6.32). Recharge to Landfill Section 1/9 was estimated through net flux analysis as 17.10 in. per year.

A two dimensional, cross-sectional numerical groundwater flow model was constructed for Landfill Section 1/9 (Sheet 6.44), and calibrated with transient data (Table 6.14). The cross sectional model was designed to address the full range of complexities identified within overburden hydrostratigraphic units underlying the landfill; notably, the laterally extensive Cretaceous sequence containing thick, correlative units of transmissive sand.

Two-dimensional model results indicate generally horizontal flow within the refuse to lateral discharge boundaries (Figure 6.33). Beneath the groundwater mound, a vertical downward

gradient is evident into the overburden hydrostratigraphic unit. Unlike at Section 6/7, preliminary model results indicate that the flux associated with this gradient is large, representing about 37 per cent of infiltration from precipitation. Model results also indicate that higher permeability sand units can affect both the vertical and horizontal flow system; however, while a potentially significant vertical head loss is computed for low permeability materials beneath the landfill, horizontal flow is maintained within the higher permeability units. Potential flux to the bedrock unit is computed to be negligible.

Sensitivity analysis was performed on the steady-state two-dimensional numerical model similar to that performed at Landfill Section 6/7 (Table 6.15). Model sensitivity analysis results suggest that low permeability units of greater than 15 ft can significantly reduce the potential for leachate migration to lower, more permeable units. Model simulations also suggest that potential unsaturated zones within the refuse unit can reduce the water-levels at the base of the refuse unit and decrease the potential for vertical migration of leachate.

9.2.3 Landfill Sections 2/8 and 3/4

Conceptual model analysis for Landfill Section 2/8 indicates that the majority of the landfill is underlain by Recent silts and clays, glacial clays, till or Cretaceous clay. There is a potential for Recent sands to be in contact with the base of the refuse in the northern and western areas of the landfill, and possibly upper Cretaceous sands in the southeastern portion of the landfill. Plots of plan and profile water level elevation contours (Sheet 6.32) indicate a general horizontal direction of groundwater flow within the refuse unit with some potential for vertical flow in the sand contact locations described above.

Analytical flux analysis at Section 2/8 suggests that approximately five percent of recharge that enters the landfill can leave the refuse unit (and shallow, hydraulically interconnected sands) as vertical flux to deeper overburden units (Figure 6.39). A rate of 16.27 in. per year of recharge was calculated through flux analysis.

Conceptual model analysis for Landfill Section 3/4 suggests a high potential for the northern and western portions of the landfill to be indirect contact with a Recent sand unit. Beneath these sand units are fairly extensive units of glacial clay or till. Plots in plan and profile of water level

elevations (Sheets 6.32, 6.14-6.17; 6.20-6.27) indicate that, in general, groundwater leaves the refuse unit as horizontal flow either in the refuse unit itself or, where present, the underlying sand unit.

Analytical flux analysis indicates that approximately 11 percent of the total flux leaving the refuse and upper sand units exits as vertical flux to lower units beneath the landfill. Net flux analysis also suggests an average recharge rate of 18.25 in./yr.

A two dimensional (cross sectional) flow model was constructed that bisects both Landfill Sections 2/8 and 3/4 (Sheet 6.44). The cross-sectional model was designed to address the full range of complexities identified within the overburden hydrostratigraphic unit underlying these landfill sections, including a laterally correlative Recent sand unit at Section 3/4, and an extensive Cretaceous sequence at Section 2/8 exhibiting transmissive sand members.

As at the other landfill sections, flow within the refuse is primarily horizontal to lateral discharge boundaries, notably the Fresh Kills (Figure 6.47). Beneath the groundwater mounds, a vertical downward gradient is evident, responsible for a flux of approximately 10 percent into the underlying overburden hydrostratigraphic unit.

The pressure head beneath landfill Section 3/4 appears to affect the flow within the bedrock, although this is not noted at Section 2/8. Potential flux to the bedrock unit is negligible. Flow within the bedrock is generally horizontal with a discharge toward the model lateral boundaries. A small component of upward flow from the bedrock is evident beneath the Fresh Kills River, which outside the area affected by the mound within Section 3/4, is probably the dominant flow direction.

Sensitivity analyses performed on the Sections 2/8 and 3/4 cross-sectional model were similar to those performed at the other landfill sections (Table 6.20), and exhibited similar findings.

9.2.4 Regional Numerical Model

A regional numerical model was constructed to cover the entire Fresh Kills landfill complex. The model consists of seven layers representing the following: the refuse unit (two layers), an

upper Recent/glacial sand unit, a lower Recent/glacial sand unit, the upper Cretaceous sand, the lower Cretaceous sand and the bedrock (Figure 6.51). All model layers were designed to accurately reflect the distribution of high and low permeability units defined in the stratigraphic analysis (Sheets 6.55 - 6.59). High permeability "windows" were simulated between model layers to allow for vertical communication, where such interconnection was suggested in the stratigraphic model (Sheets 5.93 - 5.95).

Model computed results agree well with head data observed in the field, and flux estimates calculated with analytical methods (Figures 6.52 - 6.55). Model output indicates that the presence of low permeability dry zones within the refuse unit may be creating a perched water level elevations within central portions of the refuse mounds, and that the water level elevations at the base of the refuse are less than currently mapped. Model results indicate vertical flux to shallow Recent/glacial sand units in all landfill sections, and to the Cretaceous sands underlying portions of Landfill Section 1/9 and 2/8. Model results also indicate little potential for flux of groundwater to the bedrock unit and that observed mounding in the bedrock is probably due primarily to the added weight of the refuse increasing pressures within the bedrock.

9.3 Water Quality/Chemistry

Two groundwater sampling programs have been performed at the Fresh Kills Landfill. These include an ongoing, comprehensive quarterly water quality sampling program for 6 NYCRR Part 360 specified Expanded Parameters (indicator parameters, metals, and organic compounds), and a limited geochemical sampling program (filtered indicator parameters, metals and environmental isotopes) performed at Landfill Sections 1/9, 2/8, 3/4, 6/7. The results of an assessment of groundwater quality and geochemistry are summarized in Tables 7.3 - 7.14, and 7.29 - 7.32 and illustrated on Figures 7.598 - 7.601. Landfill section specific discussions are provided below.

9.3.1 Landfill Section 6/7

Concentrations of nitrogen and carbon series indicator parameters [ammonia, total Kjeldahl nitrogen (TKN), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC)] as well as alkalinity and metals parameters including barium, boron, lead,

iron, potassium, and zinc appear at elevated concentrations in the shallow/refuse (unconfined water table) water bearing zone (Figures 7.142 - 7.184). Regulated general water chemistry constituents are typically well in excess of water quality standards.

A series of organic compounds occur in the shallow/refuse monitoring zone at low concentrations, but only six occur with any consistency are detected consistently as non-qualified values, namely: chlorobenzene, chloromethane, total xylenes, naphthalene, 2,4-D and 2,4,5-TP (silvex). Within the intermediate depth and deep (bedrock) monitoring zones, the presence of organic compounds is very sporadic (Tables 7.19D - 7.21D). Two compounds, 2-butanone and toluene, occur repeatedly at low concentrations in several deep monitoring wells. The presence of these compounds is not believed to associated with leachate migration as observed hydraulic and general chemical/geochemical data do not support such a scenario. NYCDOS is currently investigating the potential for an upgradient source for these compounds.

The concentrations of leachate indicator parameters in intermediate depth or bedrock (confined or semi-confined) water bearing units are several orders of magnitude lower than those exhibited in the shallow/refuse zone (Figures 7.227 - 7.240). Exceedences of water quality standards in these zones are limited primarily to metals compounds. Elevated concentrations of these analytes are believed to represent the influence of mineral content of the soil and bedrock materials (Tables 7.2, 8.3, 8.3A), and the incidental, localized effects of turbidity (and acid sample preservation) on sample analysis.

Filtered sample has been collected from a subset of the monitoring well locations at Section 6/7 to allow for the geochemical analysis of groundwater. Filtered sample is necessary for this analysis in order to allow for quantification of the ionic forms of dissolved solutes, which allows for development of formation water characteristics that are distinctive between leachate affected, sea water affected, and natural groundwaters. Sample was also collected and analyzed for the stable and radiogenic forms of the environmental isotopes of carbon, sulfur, hydrogen, lead and strontium to supplement the conventional geochemical database. The results of these analyses provide a clear distinction between the inherent characteristics of the leachate affected shallow/refuse (unconfined) water bearing zone, and the deeper intermediate and deep bedrock zones (Table 7.32). Consistent with the assessment of indicator parameter data derived from the 6 NYCRR Part 360 sampling program, no evidence of leachate mixing at depth is apparent.

9.3.2 Landfill Section 1/9

As in Section 6/7, concentrations of nitrogen and carbon series leachate indicator parameters, as well as alkalinity and many metals parameters occur at elevated concentrations in the shallow/refuse water bearing zone (Figures 7.13 - 7.55). Regulated general chemistry constituents are typically well in excess of water quality standards. Organic compounds, while generally detected at a greater frequency than within Section 6/7, are limited to a small number of occurrences in excess of water quality standards; nearly half of the detected constituents are reported as qualified (estimated) concentrations below detection limits).

With the exception of a series of intermediate depth wells screened within the Cretaceous sand unit along the west and south of Section 1/9, the concentrations of leachate indicator parameters in intermediate depth or bedrock water bearing units are one to several orders of magnitude lower than those exhibited in the shallow/refuse zone (Figures 7.185 - 7.198). Exceedances of water quality standards in these zones is limited primarily to metals compounds (Tables 7.4 and 7.5). Elevated concentrations of these analytes are believed to represent the influence of the mineral content of the soil and bedrock materials, and the incidental, localized effects of turbidity (and acid sample preservation) on sample analysis.

The occurrence of organic compounds in the shallow/refuse monitoring zone is fairly widespread at Section 1/9, although the concentration distribution is low (Figures 7.399 - 7.401). Among the volatile organic compounds, chlorobenzene, ethylbenze, toluene and total xylenes are detected most often. 2,4-Dimethylphenol, naphthalene, and bis(2-ethylhexyl)phthalate are the most commonly detected semivolatile organic compounds with the phthalate routinely detected in QC blanks as a laboratory contaminant. 2,4,5-TP (silvex) is the most commonly detected compound in the pesticide/herbicide ground. With the exception of 2-butanone and toluene in several bedrock wells, the occurrence of organic compounds is sporadic in the intermediate depth and deep monitoring zones (Tables 7.19A - 7.21A). The volatile organic compounds identified in the bedrock wells are not believed to be derived from vertical leachate migration, as observed general chemical/geochemical and hydraulic data do not support such migration and organic contamination at depth.

Within the Cretaceous sand, significantly elevated concentrations of chloride are observed, as well as elevated concentrations of ammonia, TKN, hardness, and a series of metals parameters.

The chloride data is indicative of saline (seawater) mixing in this sand unit. Elevated concentrations of the other constituents reflect the water chemistry associated with this influence, vertical migration of leachate affected groundwater (as noted through performance of cross-sectional numerical solute transport analysis), or a combination of the above. The results of geochemical analysis (Table 7.29; Figures 7.537 - 7.539) clearly indicate the sea water influence within the intermediate depth monitoring zone along the west and south of Section 1/9, and suggest dilute leachate mixing at depth, primarily in the shallower Recent sand units.

9.3.3 Landfill Section 2/8

Similar to the above, concentrations of nitrogen and carbon series leachate indicator parameters, as well as alkalinity and many metals parameters occur at elevated concentrations in the shallow/refuse water bearing zone (Figures 7.56 - 7.98). Regulated general chemical constituents are typically in excess of water quality standards.

With one exception, the concentrations of leachate indicator parameters in intermediate depth or bedrock water bearing units are one to several orders of magnitude lower than those exhibited in the shallow/refuse zone. Exceedances of water quality standards in these zones is limited primarily to metals compounds (Tables 7.7 and 7.8). Elevated concentrations of these analytes are believed to represent the influence of the mineral content of the soil and bedrock materials, and the incidental, localized effects of turbidity (and acid sample preservation) on sample analysis.

The occurrence of organic compounds within the shallow/refuse monitoring zone at Section 2/8 is very limited and sporadic. Only the herbicide 2,4,5-TP (silvex) occurs with any consistency, and at low concentrations. The same pattern is observed in the intermediate and deep monitoring zones, with the exception of the repeated presence of: (1) 2,4,5-TP at low concentrations in one well screened in the glacial sands along the western area of the landfill, and (2) two volatile organic compounds (2-butanone and toluene) in several bedrock wells. As noted earlier, the volatile organic compounds are not believed to represent vertical leachate mixing, as observed general chemical/geochemical and hydraulic data do not support leachate migration and organic contamination at depth.

One intermediate depth well cluster located within glacial sands along the western margin of the landfill exhibits elevated concentrations of several leachate indicator parameters, and may be affected by lateral or vertical migration of leachate (Table 7.7; Figure 7.596). Geochemical analysis of water chemistry at Section 2/8 indicates generally dilute groundwater characteristics in all monitoring zones, including the shallow/refuse zone. This latter is due primarily to the spatial location of shallow wells relative to the refuse mound available for sampling during January 1992. Geochemical evidence of leachate mixing with groundwater is noted in the glacial sands along the western landfill margin (Table 7.30).

9.3.4 Landfill Section 3/4

As at the other Landfill Sections, concentrations of nitrogen and carbon series leachate indicator parameters (with the exception of BOD), alkalinity, and many metals parameters occur at elevated concentrations in the shallow/refuse water bearing zone (Figures 7.99 - 7.141). Regulated general chemistry constituents are typically well in excess of water quality standards. A number of organic compounds are present in the shallow/refuse monitoring zone at low concentrations, but only five occur with any consistency, namely: benzene, chlorobenzene, toluene, naphthalene, and 2,4,5-TP (silvex). Within the intermediate depth and deep monitoring zones, the presence of organic compounds is limited and sporadic (Tables 7.19C - 7.21C). 2-Butanone and toluene have been identified on several occasions in one bedrock monitoring well.

The concentrations of leachate indicator parameters in most intermediate depth (Recent sand) wells is elevated, indicating leachate mixing (Table 7.10). Concentrations in the bedrock water bearing unit are one to several orders of magnitude lower than those exhibited in the shallow/refuse zone. Exceedances of water quality standards in the bedrock zone is limited primarily to metals compounds (Table 7.11). Elevated concentrations of these analytes in this zone are believed to represent the influence of the mineral content of the bedrock matrix, and the incidental, localized effects of turbidity (and acid sample preservation) on sample analysis.

The results of geochemical analysis (Table 7.31), as well as comparison of existing and historical water quality data (Figures 7.490 - 7.502A), support the evidence of leachate mixing in the Recent sands. Geochemically, limited or no evidence of leachate migration to the bedrock is observed.

9.3.5 Integration With Numerical Flow and Solute Transport Analysis

With several exceptions, the qualitative results of numerical cross-sectional solute transport analysis agree with the findings of the groundwater quality/chemistry sampling programs (Table 7.33, Figures 7.595 - 7.597). These simulations predict little or no solute transport to the bedrock unit, except along the eastern margin of Landfill Section 6/7 where the elevation of the bedrock surface rises. Solute migration to Recent sands in Sections 1/9 and 3/4 and glacial sands in Section 2/8 is predicted by the model simulation, and observed in the field data. Dilute solute migration is also predicted to the Cretaceous sand unit in Section 1/9, and is observed in the field at several well locations. Model simulations suggest that extensive vertical interconnection of sand units are not required to observe a dilute solute influence at Section 1/9, and such interconnections would appear to largely overpredict the potential for vertical solute flux. Model predicted solute transport to the Cretaceous sand unit underlying Section 2/8 is not observed in field data, suggesting overestimation of vertical flux into this unit by the cross-sectional model. This situation is also apparent in the north-western area of Section 1/9. Three dimensional solute transport analyses indicate a leachate migration distribution similar in most areas to that observed in the field. Three dimensional analysis of a deep pumping well scenario indicates that such withdraws would result in induced recharge of saline water into the Recent and Cretaceous sands at Section 1/9.

9.3.6 Long Term Monitoring Program

Under the terms of the Consent Order, NYCDOS is required to develop a long term groundwater monitoring program meeting the requirements of 6 NYCRR 360-2.11(c). These regulations specify that the program must be capable of distinguishing landfill derived contamination from "existing" water quality at the site, and must identify trigger mechanisms to initiate contingency monitoring, as appropriate. The contingency monitoring program has already been triggered at Fresh Kills based on the currently observed water quality at the site, and development of corrective actions in ongoing in accordance with the specifications of Consent Order Appendix A-3 (closure and capping of Landfill Sections 2/8 and 3/4) and Appendix A-4 (leachate capture and treatment at Landfill Section 1/9 and 6/7).

Long term monitoring program development (Environmental Monitoring Plan and Site Analytical Plan) included definition of the site critical stratigraphic section, analytical data quality objectives project critical parameters, groundwater protection standards sample location and frequency, and sample collection and analytical protocols. These components of program design were developed through review of the existing water quality database, pending modifications to 6 NYCRR Part 360, and considerations regarding the physical spacing of the existing well array within each monitoring zone across the critical stratigraphic section, as well as the potential sensitivity of each monitoring zone to leachate impact.

The critical stratigraphic section was defined to include the shallow/refuse, intermediate depth (confined sand), and deep (bedrock) groundwater monitoring zones underlying the landfill. Critical parameters were defined (Table 8.2) as those analytes detected through the quarterly monitoring program. A distinction was made between routinely detected and sporadically detected organic compounds (Table 8.2A). Primary leachate indicators (including a suite of geochemical analytes) were also identified. The proposed sampling program consists of a rotating schedule for 6 NYCRR Part 360 expanded and baseline Parameter and isotope analysis (Tables 8.4 and 8.5). An increased frequency of analysis is identified for the sand units comprising the intermediate depth monitoring zone and the bedrock. Sampling and analytical protocols remain the same as those specified in existing Quality Assurance Program and Project Plans (QAPP, QAPjP).

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HYDROGEOLOGIC REPORT
GLOSSARY

advection - The process by which solutes are transported by the motion of flowing groundwater.

alluvial - Pertaining to or composed of alluvium or deposited by a stream or running water.

alluvium - A general term for clay, silt, sand, gravel, or similar unconsolidated material deposited during comparatively recent geologic time by a stream or other body of running water as a sorted or semisorted sediment in the bed of the stream or on its floodplain or delta.

anaerobic - Living or active in the absence of free oxygen.

angstrom unit - Abbreviated as Å, a unit of length equal to 10^{-8} cm

anion - A negatively charged ion.

anisotropy - Condition of having properties that very with orientation or direction; e.g. the condition under which one or more of the hydraulic properties of an aquifer vary according to the direction of flow.

annulus - The space between the well casing and the wall of the borehole or outer casing.

anoxic - Characterized by the lack of oxygen.

aquifer - A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to transmit economical quantities of water to wells and springs.

aquifer test - A test involving the withdrawal of measured quantities of water from or addition of water to a well at a controlled rate and the measurement of resulting changes in head in the aquifer during and after the period of discharge or addition to allow for estimation of aquifer hydraulic properties.

aquitard - A low permeability unit that can store groundwater and also transmit it slowly.

argillite - A rock derived from either siltstone, claystone or shale, and having undergone a somewhat higher degree of consolidation than is present in these rocks.

arkose - A sandstone containing 25% or more of feldspars, usually derived from the weathering of igneous rocks of granitoid texture.

artesian - Refers to groundwater under sufficient hydrostatic head to rise above the aquifer containing it.

Atterberg limits - Methods for describing the limit consistency of fine grained soils on the basis of moisture content.

avulsion - A catastrophic levee break resulting in the sudden switch of an entire river to a lower part of the floodplain.

bailer - A device used to withdraw a water sample from a small-diameter well or piezometer. A bailer typically is a piece of stainless steel or teflon tubing attached to a wire and having a check valve in the bottom.

bathymetric map - A topographic map of ocean or river channel relief.

bentonite - A colloidal clay, largely made up of the mineral sodium montmorillonite, a hydrated aluminum silicate mixed with cement to provide a seal in a well annulus.

biodegradation - Break down of organic matter to simpler chemical constituents through biological (microbial) activity.

biostratigraphy - The separation and differentiation of rock units based upon the assemblages of fossils they contain.

biozone - A biostratigraphic unit including all strata deposited during the existence of a particular kind of fossil.

borehole geophysics - The general field of geophysics developed around the lowering of various probes that measure rock properties into a well.

brecciated - Consisting of fragmental rock with components that are angular and therefore, as distinguished from conglomerates, are not waterworn.

calcareous - Containing calcium carbonate.

carbonaceous - Coaly. Pertaining to, or composed largely of carbon.

cation - A positively charged ion; most metals in solution are cations.

CEC - Cation exchange capacity; the amount of cations that can be adsorbed by clays and other charged particles.

clastic - Pertaining to a rock or sediment composed principally of broken fragments that are derived from pre-existing rocks or minerals and that have been transported some distance from their places of origin.

clay - Soil passing a No. 200 (74 um) sieve that can be made to exhibit plasticity (putty-like properties) within a range of water contents, and that exhibits considerable strength when air dry, e.g., Cretaceous clay, glaciolacustrine clay.

cobble - A rock fragment between 69 and 256 mm in diameter, thus larger than a pebble and smaller than a boulder.

colloid - Extremely small solid particles, 0.0001 to 1 micron in size, which will not settle out of a solution; intermediate between a true dissolved particle and a suspended solid which will settle out of a solution.

compaction - A decrease in the volume of sediments, as a result of compressive stress, usually resulting from continued deposition, but also from drying, dewatering and other causes.

competent bedrock - Unweathered bedrock.

compressibility - The change of specific volume and density under hydrostatic pressure.

confined aquifer - An aquifer that is overlain by a strata or rock or sediment with a significantly lower hydraulic conductivity than the aquifer, generally resulting in artesian conditions.

confining unit - A body of material of low hydraulic conductivity that is stratigraphically adjacent to one or more aquifers. It may lay above or below the aquifer.

conglomerate - A cemented clastic rock containing rounded fragments ranging in grain size from gravel to pebbles.

contour - A line connecting points of equal value on a map or diagram, most commonly points of equal concentration or elevation.

Cretaceous period - The third and latest of the periods of the Mesozoic era, occurring from 136 to 64 million years before present.

crevasse splay deposits - Delta-shaped deposits formed due to a break in a levee or other stream embankment.

cross-bedding - The arrangement of laminations of strata transverse or oblique to the main planes of stratification of the strata concerned.

cross-section - A profile portraying an interpretation of a vertical section of the earth explored by geophysical or geologic methods.

crystalline - An inexact, general term for igneous and metamorphic rock.

Darcy's Law - An equation that can be used to calculate the quantity of water flowing through a saturated soil material, requiring inputs of hydraulic conductivity, hydraulic gradient, and area.

datalogger - Electric monitoring device used to record and store digital data (e.g., changes in water levels in wells or piezometers).

deep well - A monitoring well installed in the weathered bedrock or bedrock hydrostratigraphic unit at Fresh Kills.

deglaciation - The uncovering of an area from beneath glacier ice as the result of the melting of a glacier.

density - The mass or quantity of a substance per unit volume. Units are in pounds per gallon (lb/gal), pounds per cubic foot (lb/ft^3), or kilograms per cubic meter (kg/m^3).

diabase - A volcanic rock of basaltic composition, exhibiting a large crystal structure due to slow cooling at depth.

diatom - A microscopic, single-celled plant growing in marine or fresh water. Diatoms secrete siliceous frastules that may accumulate in sediments in enormous numbers and can be used to age-date sediments.

DIC - Dissolved inorganic carbon; most commonly in the form of bicarbonate (HCO_3^-).

diffusion - The process by which both ionic and molecular species dissolved in water move from areas of higher concentration to areas of lower concentration.

dispersion - The phenomenon by which a solute in flowing groundwater is mixed with uncontaminated water and becomes reduced in concentration. Dispersion is cased by both differences in the velocity that the water travels at the pore level and differences in the rate at which water travels through different strata in the flow path.

DQO - Data Quality Objective

drawdown - A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer cased by pumping of groundwater from wells.

drilling fluid - A water- or air-based fluid used in the water well drilling operation to remove cuttings from the hole, to clean and cool the bit, to reduce friction between the drill string and the sides of the hole, and to seal the borehole.

effective porosity - The volume of the void spaces through which water or other fluids can travel in a rock or sediment divided by the total volume of the rock or sediment.

Eigen vector - In two dimensional geometry, the slope of the major axis of an ellipse.

Eigen value - In two dimensional geometry, the length of the major axis of an ellipse.

electrochemically-balanced - Having a net electrical charge of zero.

electrolyte - A chemical which dissociates into positive and negative ions when dissolved in water, increasing the electrical conductivity.

embayment - A continental border area that has sagged concurrently with deposition so that an unusually thick layer of sediment results. An embayment is similar to a basin of sedimentation or a geosyncline, and some embayments may be one flank of a larger subsiding feature.

endmember - The characteristic equilibrium chemistry of an evolved groundwater.

englacial - Within glacial ice

equipotential - A line in a two dimensional groundwater flow field such that total hydraulic head is the same along all points of the line.

erosion - The general process or group of processes by which soil and rock are moved from one place to another by running water (including rainfall), waves and currents, glacier ice, or wind.

eskers - Serpentine ridges of gravel and sand that mark channels in a decaying ice sheet, through which streams washed much of the finer drift, leaving the coarser gravel between the ice walls.

estuarine - Pertaining to a drainage channel adjacent to the sea in which the tide ebbs and flows.

eustatic - Pertaining to simultaneous, world-wide changes in sea level.

evapotranspiration - The portion of precipitation that is returned to the air through either direct evaporation or the transpiration of vegetation.

facies - A lateral subdivision of a stratigraphic unit based on different appearances in composition.

fault - A fracture or fracture zone within bedrock.

field blank - A water-quality sample where highly purified water is run through the field-sampling procedure and sent to the laboratory to detect if any contamination of the samples is occurring during the sampling process as a result of contaminants associated with the field sampling equipment.

finite-difference model - A particular kind of a digital computer model based upon a rectangular grid that sets the boundaries of the model and the nodes where the model will be solved.

floodplain - The surface of relatively smooth land adjacent to a river channel, constructed by the present river and covered with water when the river overflows its banks. It is built of alluvium carried by the river during floods and deposited in the sluggish water beyond the influence of the swiftest current.

flow lines - Lines indicating the direction followed by groundwater toward points of discharge. Flow lines are perpendicular to equipotential lines.

flow net - The set of intersecting equipotential lines and flowlines representing two-dimensional steady flow through porous media.

fluvial - Produced by river action, e.g. fluvial plain.

flux - Flow across a physical boundary, such as groundwater from one hydrostratigraphic unit to another.

foraminifera - Microscopic, marine unicellular animals that secrete tests composed of calcium carbonate, or build them of cemented sedimentary grains, consisting of one to many chambers. Usually used to age-date sediments.

fossiliferous - Containing organic remains.

fracture - A break in rock caused by intense folding or faulting.

gabbro - A coarse-grained (plutonic) basic igneous rock consisting of basic plagioclase.

geochemistry - Study of the groundwater chemistry in relation to chemical processes associated with groundwater in various geologic environments.

glacial till - Predominantly unsorted and unstratified drift, generally unconsolidated, deposited directly by or underneath a glacier without subsequent reworking by meltwater, and consisting of a heterogeneous mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

glaciofluvial - Pertaining to the meltwater streams flowing from wasting glacier ice and especially to the deposits and land forms created by such streams.

glaciolacustrine sediments - Silt and clay deposits formed in the quiet waters of lakes that receive meltwater from glaciers.

gneiss - A coarse-grained rock with alternating bands of granular minerals and schistose minerals formed during high-grade regional metamorphosis.

gravel - A term applied to grains larger than coarse sand and finer than pebbles, i.e., 2mm to 4mm

groundwater - The water contained in interconnected pores located below the water table surface.

grout - A fluid mixture of cement and water (neat cement) of a consistency that can be forced through a pipe and placed as required. Various additives, such as sand, bentonite, and hydrated lime, may be included in the mixture to meet certain requirements. Bentonite and water are sometimes used for grout. Usually used to seal casing in a borehole.

hardness - A measure of the amount of calcium, magnesium and iron dissolved in the water.

Hazen method - An empirical equation that can be used to approximate the hydraulic conductivity of a sediment on the basis of the effective grain size.

head - Energy contained in a water mass, produced by elevation, pressure or velocity.

head loss - That part of head energy which is lost because of friction as water flows.

heterogeneity - The varying with position of the properties within a medium (e.g., hydraulic conductivity within a soil material).

hollow-stem auger - A particular kind of a drilling device whereby a hole is rapidly advanced into sediments. Sampling and installation of the equipment can take place through the hollow center of the auger.

Holocene - The most recent period in the stratigraphic column, represented by post-glacial deposits.

Hvorslev Method - A procedure for performing a slug test in a piezometer that partially penetrates a water-table aquifer.

HX rock core - A 4-inch diameter rock core.

hydraulic conductivity - Fluid flow velocity through a porous media under a unit pressure head. It is governed by the properties of the soil matrix. The rate of flow of water in gallons per day through a cross section of one square foot under

a unit hydraulic gradient, at the prevailing temperature ($gpd/ft^{2)}$. In the SI System, the units are $m^3/day/m^3$ or m/day.

hydraulic gradient - The change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head.

hydrogeology - The study of the interrelationships of geologic materials and processes with water, especially groundwater.

hydrograph - A graph showing the stage, flow, volume or other property of ground or surface water with respect to time.

hydrostratigraphic unit - A formation, part of a formation, or group of formations in which there are similar hydrologic characteristics allowing for grouping into aquifers or confining layers.

igneous - Rocks formed by solidification from a molten or partially-molten materials.

impermeable - Having a texture that does not permit water to move through it perceptibly under the head differences ordinarily found in subsurface water.

infiltration - The flow of water downward from the land surface into and through the upper soil layers.

inorganic - An ion or compound created by non-biologic processes.

in-situ - In its natural position or place, specifically rocks, soils or fossils that are found in the original positions of formation, deposition or growth.

interfingering - Grading or passing from one material into another through a series of interlocking or overlapping wedge-shaped layers.

intermediate well - A monitoring well installed in a transmissive horizon within the unconsolidated overburden hydrostratigraphic unit at Fresh Kills; e.g., Recent, glacial or Cretaceous sand.

interstitial - Within pore space between sediment particles.

intrusion - A body of igneous rock that has forced itself into pre-existing rocks.

ion - An element or compound that has gained or lost an electron, so that it is no longer electrically neutral, but carries a charge.

isopach map - A contour map depicting the thickness of a soil or sediment.

isostatic - Subject to equal pressure from every side; being in hydrostatic equilibrium.

isotopes - Elements having an identical number of protons in their respective nucleus, but differing in the number of their neutrons.

isotropy - The condition in which hydraulic properties of the aquifer are equal in all directions.

joint - A fracture in rock, generally more or less vertical or transverse to bedding, along which no observable relative movement has occurred.

Jurassic - The middle of the three periods comprising the Mesozoic era, occurring from 195 million years to 135 million years before present.

K - Hydraulic conductivity.

kame - A steep-sided alluvial deposit formed against an ice front, usually where streams emerge from a glacier at a high elevation.

Kh - Horizontal hydraulic conductivity.

Kv - Vertical hydraulic conductivity.

lacustrine - Deposits formed in lakes.

laminated - Refers to sedimentary rock or sediments with layering or bedding less than 1 cm thick.

leachate - A solution formed by the dissolving out of soluble constituents from refuse by the infiltration and percolation of water.

leachate collection system - A system installed in conjunction with a liner to capture the leachate that may be generated from a landfill so that it may be collected and treated.

lense - A deposit, usually composed of sand, that has the general shape of a lense, thick in the middle and thinning toward the edges.

lenticular - A deposit that thins out from the center to a thin edge all around.

lithofacies - Facies particularly characterized by its rock type.

lithology - A term usually applied to sediments, referring to their general characteristics.

lithostratigraphy - Stratigraphy based only upon the physical and petrographic features of sediments or rocks.

littoral - Taking place on or near the shore.

lodgement - Till deposited beneath a moving glacier, characterized by compact fissile structure and stones oriented with their long axes parallel to the direction of flow.

log - A graphic representation of the lithologic or stratigraphic units traversed by a borehole. The similar presentation of the variation of some physical property, such as resistivity, with depth.

lost circulation - The result of drilling fluid escaping from the borehole into the formation by way of crevices or porous media.

melt-out till - Deposit formed by the release of material within a glacier (englacial) through the melting of the glacier ice.

metamorphic - Describes any rock derived from pre-existing rocks by mineralogical, chemical, and/or structural changes, essentially in the solid state, in response to marked changes in temperature, pressure, shearing stress, and chemical environment, generally at depth in the earth's crust.

methanogenesis - The formation of methane through biological activity.

microfossil - Fossil remains of microorganisms; sometimes used in age-dating of sediments.

moisture content - The weight of water contained in a soil divided by the total weight of the soil mass.

molecular diffusion - Dispersion of a chemical caused by the kinetic activity of the ionic or molecular constituents.

moraine - A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited chiefly by the direct action of glacier ice.

mudstone - A deposit that consists of an indeterminate mixture of clay, silt and sand; includes clay, silt, siltstone, claystone, shale and argillite.

natural gamma radiation log - A borehole log that measures the natural gamma radiation emitted by the formation rocks. It can be used to delineate subsurface rock types.

nested piezometer - A set of two or more piezometers set close to each other but set at different depths.

NX rock core - A 2-inch diameter rock core.

observation well - A nonpumping well used to observe the elevation of the water table or the potentiometric surface of a confined unit. An observation well is generally

of larger diameter than a piezometer and typically is screened or slotted throughout the thickness of the aquifer.

outwash - Stratified sand and gravel removed or washed out from a glacier by meltwater streams and deposited in front of or beyond the end moraine or the margin of an active glacier. The coarser material is deposited nearer to the ice.

outwash plain - A broad, gently sloping sheet of outwash.

overburden - The loose soil, silt, sand, gravel, or other unconsolidated material overlying bedrock, either transported or formed in place.

oxidation - A chemical reaction in which an element changes its valence state through a loss of electrons.

P-ECPT - Piezo-electric cone penetration test.

packer test - An aquifer test performed in an open borehole; the segment of the borehole to be tested is sealed off from the rest of the borehole by inflating seals, called packers, both above and below the segment.

palynology - The study of pollen and other spores and their dispersal; often used in the correlation of geologic strata.

peat - A dark-brown or black residuum produced by the partial decomposition and disintegration of mosses, sedges, trees and other plants that grow in marshes or similar wet places; e.g., Recent peat.

perched condition - Unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.

permeability - The property or capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure. Equals hydraulic conductivity for freshwater, but varies from hydraulic conductivity for fluids with a density different than that of freshwater.

pH - A measure of the acidity or alkalinity of a solution, numerically equal to 7 for neutral solutions, increasing with increasing alkalinity and decreasing with increasing acidity.

physiography - A synonym of geomorphology, or the description and interpretation of land forms.

piezometer - A nonpumping well, generally of small diameter, that is used to measure the elevation of the water table or the potentiometric surface or a confined unit. A piezometer generally has a short or no well screen to provide hydraulic head information at a point, rather than as an average across a screened interval.

porosity - The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

pumping test - Aquifer test.

purge - To remove specific quantities of water from a well.

Quaternary - The latest period in the stratigraphic column, 0-2 million years before present, represented by accumulations of glacial (Pleistocene) and post-glacial (Holocene) deposits.

radionuclides - Element produced by radioactive decay.

recharge - The processes by which water is absorbed and added to the zone of saturation; also, the quantity of water that is added to the zone of saturation.

recovery - The rate at which the water level in a well rises after the pump has been shut off. It is the inverse of drawdown.

reduction - A chemical reaction in which an element changes its valence state through a gain of electrons.

refuse - Discarded man-made objects and plant/food materials.

resistivity log - A borehole log made by lowering two current electrodes into the borehole and measuring the electrical resistance (inverse or conductance) between two additional electrodes. It measures the electrical resistivity of the formation and contained fluids near the probe.

retardation - A general term for the many processes that act to entrain or remove solutes dissolved in groundwater; it results in the solute front moving more slowly than the rate of advecting groundwater.

RQD - Rock Quality Designation; a classification index that describes the physical characteristics of rock material in a core. RQD equals the cumulative length of naturally-separated core pieces 4 inches or more in length, expressed as a percentage of the entire length of the core run.

runoff - That part of precipitation not infiltrated or evapotranspired that flows over the ground surface.

sand - A specific size classification of sediment particles that will pass a No. 4 (4.75 mm) sieve and be retained on a No. 200 (75 mm) sieve; usually subdivided into coarse, medium and fine. Examples are Recent, glacial and Cretaceous sand.

sand pack - Sand or gravel that is smooth, uniform, clean, well-rounded and siliceous. It is placed in the annulus of the well between the borehole wall and the well screen to prevent formation material from entering the screen.

sandstone - A sedimentary rock composed of abundant rounded or angular fragments of sand set in a fine-grained matrix (silt or clay) and more or less firmly united by a cementing material.

saprolite - A soft, earthy, decomposed rock, typically clay-rich, formed in place by chemical weathering of igneous and metamorphic rocks.

saturated zone - The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer.

scatterplot - An x-y graph of data.

schist - A medium- or coarse-grained metamorphic rock with subparallel orientation of the micaceous minerals that dominate its composition.

screen - Well screen.

sediment - An assemblage of individual mineral grains that were deposited by some geologic agent such as water, wind, ice or gravity.

sedimentary rocks - Rocks resulting from the consolidation of loose sediment that has accumulated in layers.

semivolatile - A class of organic compounds that cannot be purged from water by nitrogen gas (e.g., naphthalene).

serpentinite - A rock consisting almost entirely of serpentine minerals derived from the alteration of previously-existing olivine and pyroxene.

shale - A fine-grained sedimentary rock, formed by the consolidation of clay, silt, or mud. It is characterized by finely laminated structure and is sufficiently indurated so that it will not fall apart on wetting.

shallow well - A monitoring well installed across the water table; usually the refuse/full unit at Fresh Kills.

Shelby tube - A sampling device that is pushed into an unconsolidated sediment ahead of the drill bit to obtain an undisturbed soil sample. Typically the Shelby tube is pushed by hydraulic means.