RESULTS AND DISCUSSION

No single indicator fully or adequately describes the quality of estuarine waters. Instead, a suite of indicators is used to provide information relative to sanitary quality, ability to sustain aquatic life, ecosystem productivity, and aesthetics. Indicators of water quality used by the Harbor Survey Program include: fecal coliform bacteria; dissolved oxygen; nutrients; chlorophyll 'a'; and water clarity. Harbor-wide trends for several of these indicator parameters are shown in **Figure 6** and discussed in more detail in the following sections. Where possible, indicators are compared to NYSDEC standards. These standards reflect a range of acceptable water quality conditions (**Table 3**), as determined by the state-designated 'best usage' of the water body (**Figure 7**).

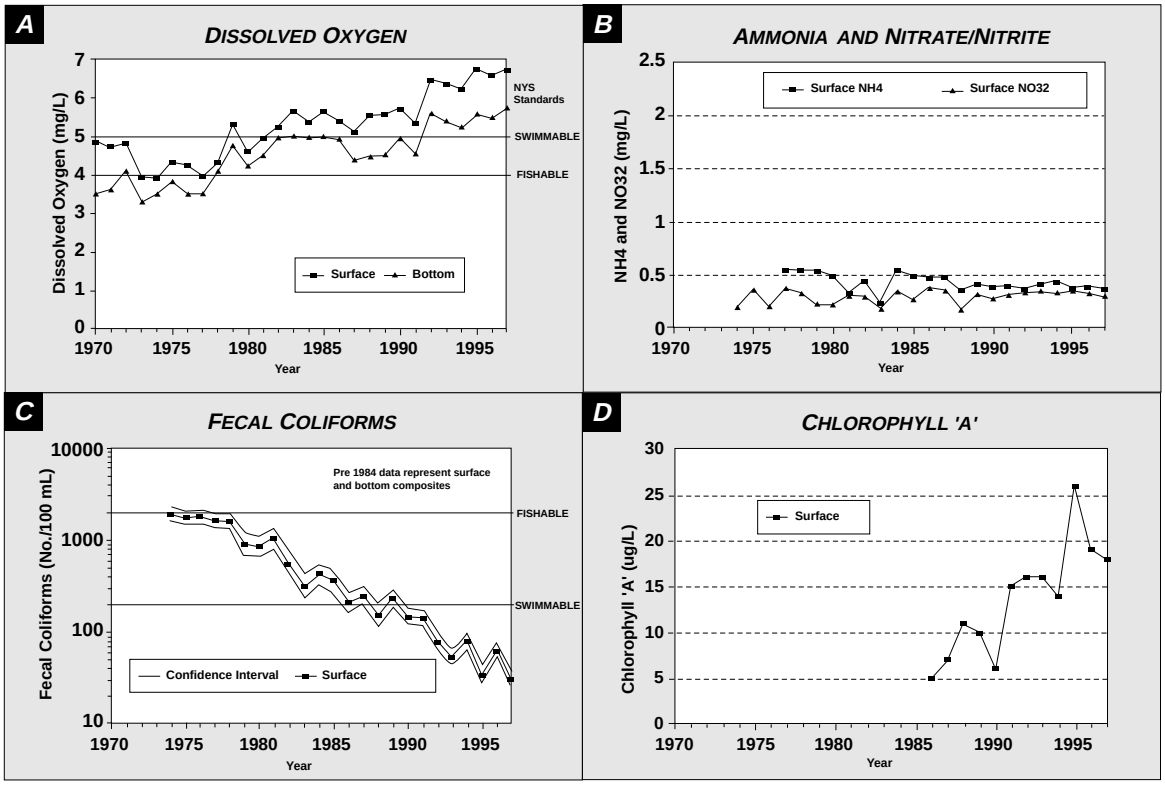
Coliform Bacteria

Coliform bacteria are measured in the Harbor as indicators of sewage-related pollution. Primary regional inputs of coliform to Harbor waters include: illegal sewage connections; intermittent, unplanned sewer system bypasses due to equipment malfunctions; permitted dry weather bypasses due to construction and upgrading; WPCPs; separate storm water outfalls; and most important, combined sewer overflows (CSOs), during and immediately after rain events. Smaller sources which can be locally important include non-point sources, (e.g., leaking septic tanks and direct storm water runoff), boat discharges, and tributary sources (HEP, 1996).

FIGURE 6

HARBORWIDE ANNUAL INDICATOR TRENDS

SUMMER AVERAGES



*** Harborwide averages represent 40 stations**

Figure 7 State-Designated Best Use Classifications for New York Harbor Waters

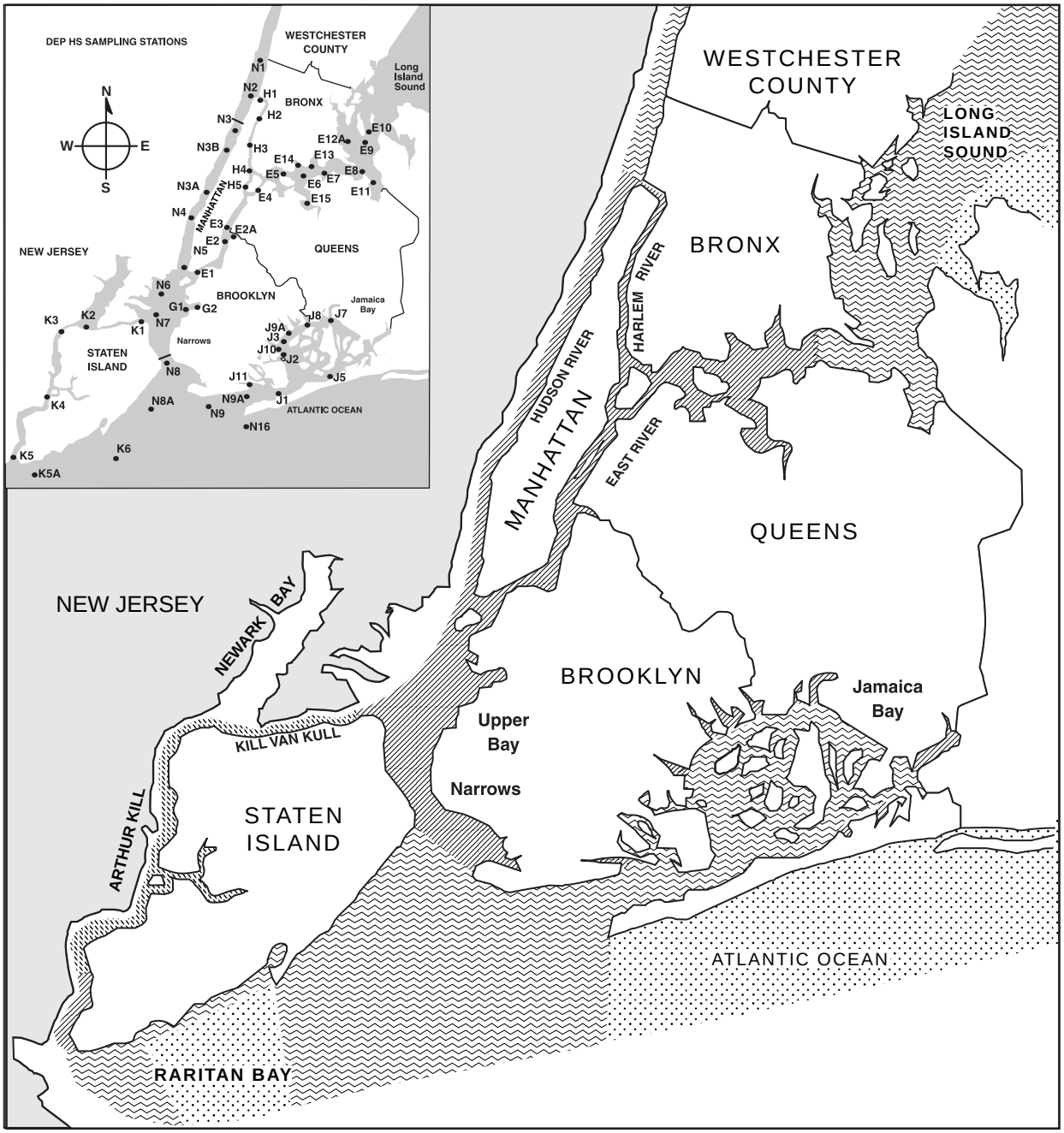
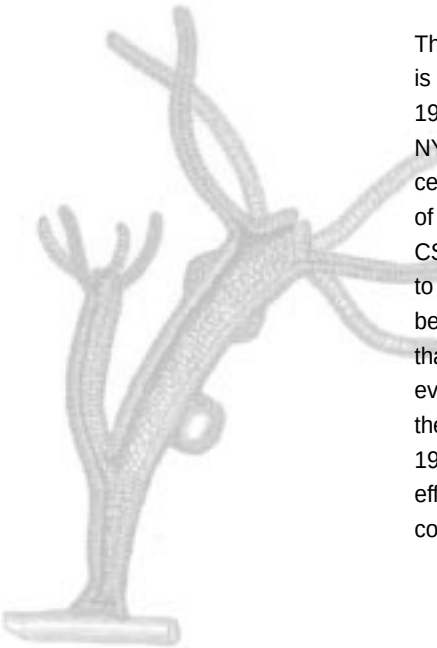


TABLE 3

Water Quality Standards
New York State Department of Environmental Conservation

Classes and standards for saline and fresh surface waters
(adapted from part 701.5 of "Title 6: Environmental Conservation" of the Official Compilation of Codes, Rules, and Regulations of the State of New York, 1974.)

Class	Best Usage of Waters	Total Coliform	Fecal Coliform	Dissolved Oxygen
SA	Shellfishing for market purposes and primary and secondary contact recreation.	Median MPN value ≤70MPN/100 ml in any series of samples.	No standard	5.0 mg/l
SB	Primary and secondary contact recreation and any other use except shellfishing for market purposes.	Monthly median ≤2,400 cells/100ml from 5 or more samples; no more than 20% of the samples >5,000 cells/100ml. Standard to be met during disinfection season.	Monthly geometric mean ≤200 cells/100 ml from 5 or more samples. Standard to be met during disinfection season.	5.0 mg/l
I	Secondary contact recreation and any other uses except primary contact recreation and shellfishing for market purposes.	Monthly geometric mean ≤10,000 cells/100ml from 5 or more samples. Standard to be met during disinfection season.	Monthly geometric mean ≤2,000 cells/100 ml from 5 or more samples. Standard to be met during disinfection season.	4.0 mg/l
SD	Fish survival	No standard	No standard	3.0 mg/l



The average fecal coliform content of CSOs is ~3.5 million cells/100ml (Appicella et al. 1990), while the average discharged from NYC WPCPs (in 1989) ranged from 6 to 43 cells/100 ml. Considering the predominance of combined sewers in NYC, this suggests CSOs to be the dominant source of coliforms to the Harbor. In fact, regional CSOs have been estimated to increase loadings by more than 4 orders of magnitude, during rain events, and account for more than 95% of the Harbor coliform load (Apicella et al., 1990). In contrast, disinfected WPCP effluents contribute less than 1% of the total coliform load to the Harbor.

Estimated Attainment of Water Quality Standards

Assessment of compliance with NYS DEC water quality standards for fecal coliform (FC) requires the testing of five or more samples per month. Since the Harbor Survey Program typically tests each site only 2-4 times per month, a true determination of compliance is not possible. Instead, a seasonal attainment of standards is inferred by comparing seasonal geometric mean data (from at least eight samples) to the appropriate monthly numeric standard (**Table 3**).

Since 1991, no more than 2 stations have been estimated to exceed FC standards in any given year.

TABLE 4

Number of Stations (out of 52) Potentially Exceeding NY State Coliform Standards[a]

Year	Total Coliform	Fecal Coliform
1989	8	3
1990	3	6
1991	na	1
1992	1	0
1993	0	0
1994	1	2
1995	1	2
1996[b]	1	1
1997[b]	na	0

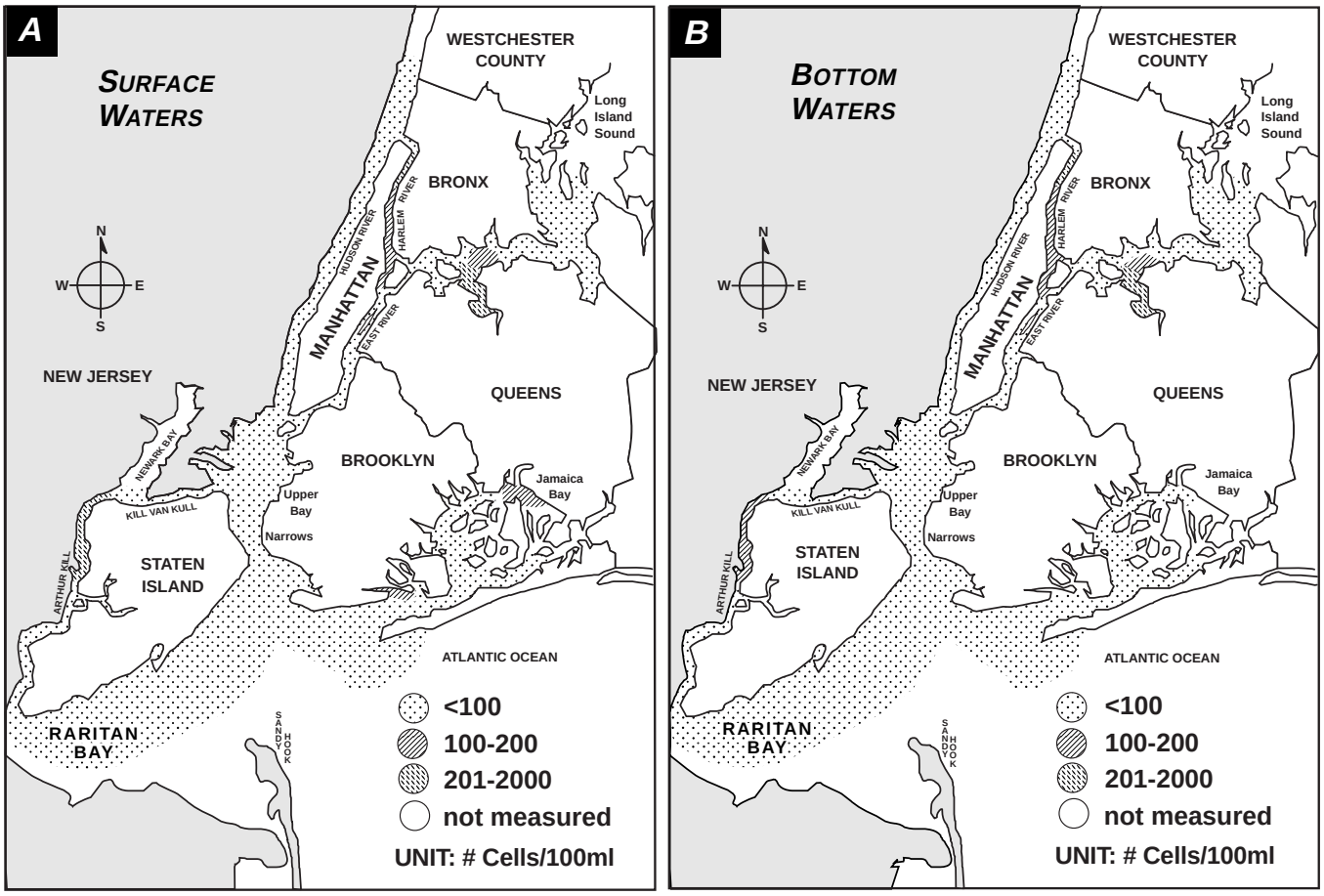
a Based on seasonal (summer) geometric mean data
b 53 stations monitored in since 1996
na Insufficient data available in 1991; TC not measured in 1997

Red Hook WPCP stacks as seen over wetland areas

Figure 8

Fecal Coliform in Surface & Bottom Waters

Summer Geometric Means, 1997



NYS Standards: ≤ 200/100ml=SB (Bathing); ≤2000 Cells/100ml=I (Fishing)

An examination of seasonal geometric means, shows estimated attainment of FC standards to have remained high in 1997 (**Table 4**), with no station found to exceed NYS FC standards. Data for 1996 also showed high compliance, with only a single station failing to comply with its bathing standard designation. In fact, since 1991 no more than 2 stations have been estimated to be out of compliance in any given year.

Average FC concentrations for summer 1997 were less than 100 cells/100ml for most of the Harbor (**Figure 8**;a and b). Only 3 scattered sites, i.e., the Northern Arthur Kill, Flushing Bay, and a portion of the Harlem River showed average conditions to exceed the bathing standard of ≤200 cells/100ml.

Average conditions, however, may mask short-term effects of wet weather and associated CSO and storm water discharges. Following precipitation, large portions of the Harbor exhibit increases in FC concentrations of as much as two orders of magnitude (**Figure 9**;a and b). Due to these sporadic increases in Harbor loadings, it is not surprising that the best sanitary quality (i.e., the lowest coliform concentrations) continues to be found at the Harbor limits in Western

Long Island Sound, the Hudson north of Manhattan, portions of Jamaica Bay, and the Raritan Bay-Lower NY Bay complex.

Trends

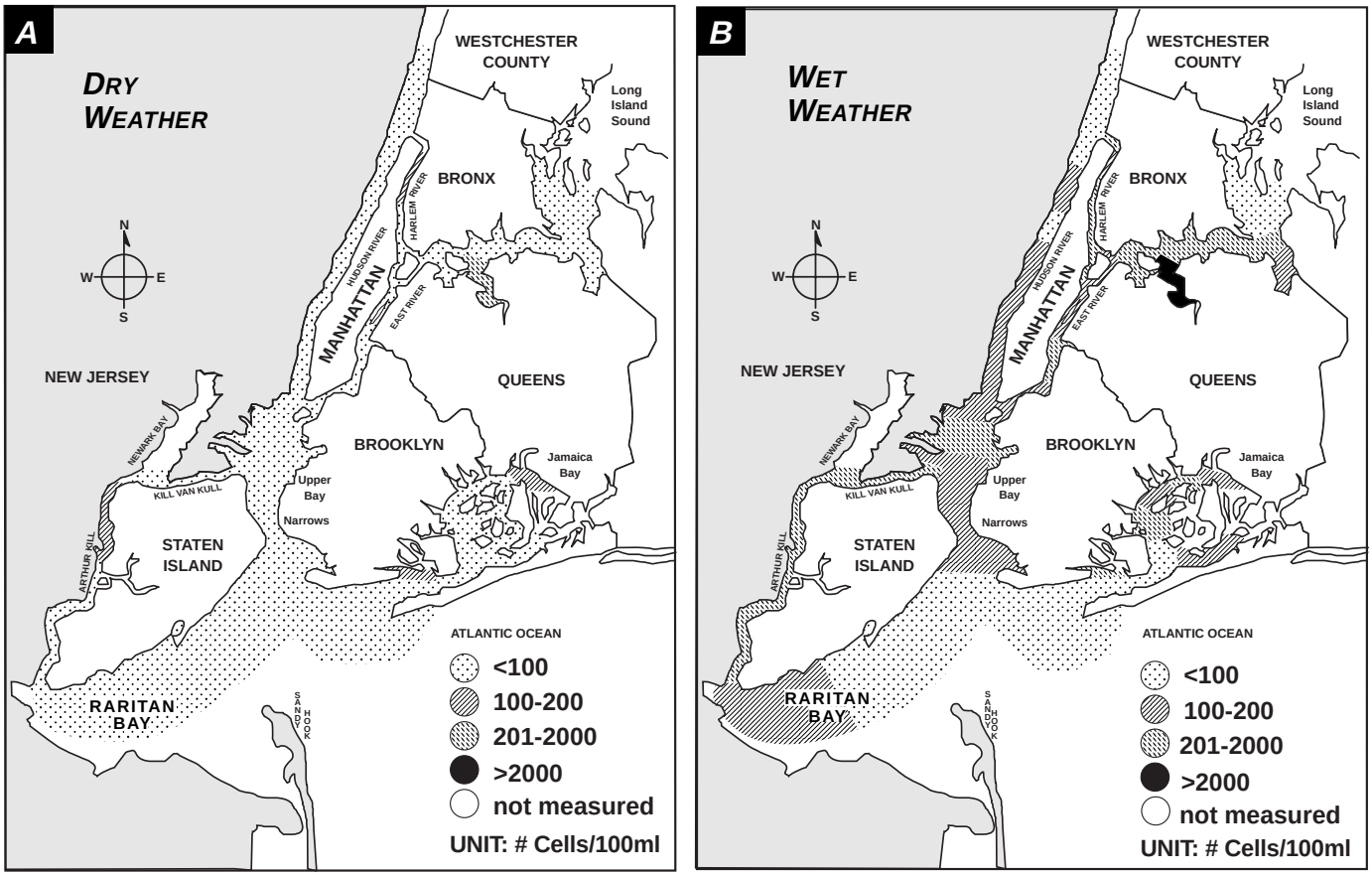
Coliform concentrations harbor-wide (**Figure 6**c) have exhibited significant (near two orders-of-magnitude) declines from the early 1970s to the present time (O'Shea and Brosnan, 1997; Brosnan and O'Shea,1996a). Examining FC trends separately for distinct areas of the Harbor (**Figure 10**;a-d) shows greatest improvement (nearly three orders of magnitude) to have occurred in the Inner Harbor Area (10a).

Coliform decreases in the Upper East River-Western Long Island Sound (10b) have been closer to 2 orders of magnitude. The Lower NY Bay-Raritan Bay and Jamaica Bay (10; c and d), which displayed lower FC concentrations in the 1970s, have subsequently experienced improvements closer to a single order of magnitude.

Coliform...have exhibited significant harbor-wide declines...

FIGURE 9 **EFFECT OF PRECIPITATION ON FECAL COLIFORM LEVELS**

Summer Geometric Means For Surface Waters, 1995-1997



NYS Standards: ≤ 200/100ml=SB (Bathing); ≤ 2000/100ml=I (Fishing)

FIGURE 10

FECAL COLIFORM TRENDS FOR DISTINCT HARBOR AREAS

Summer Geometric Means For Surface Waters, 1974-1997

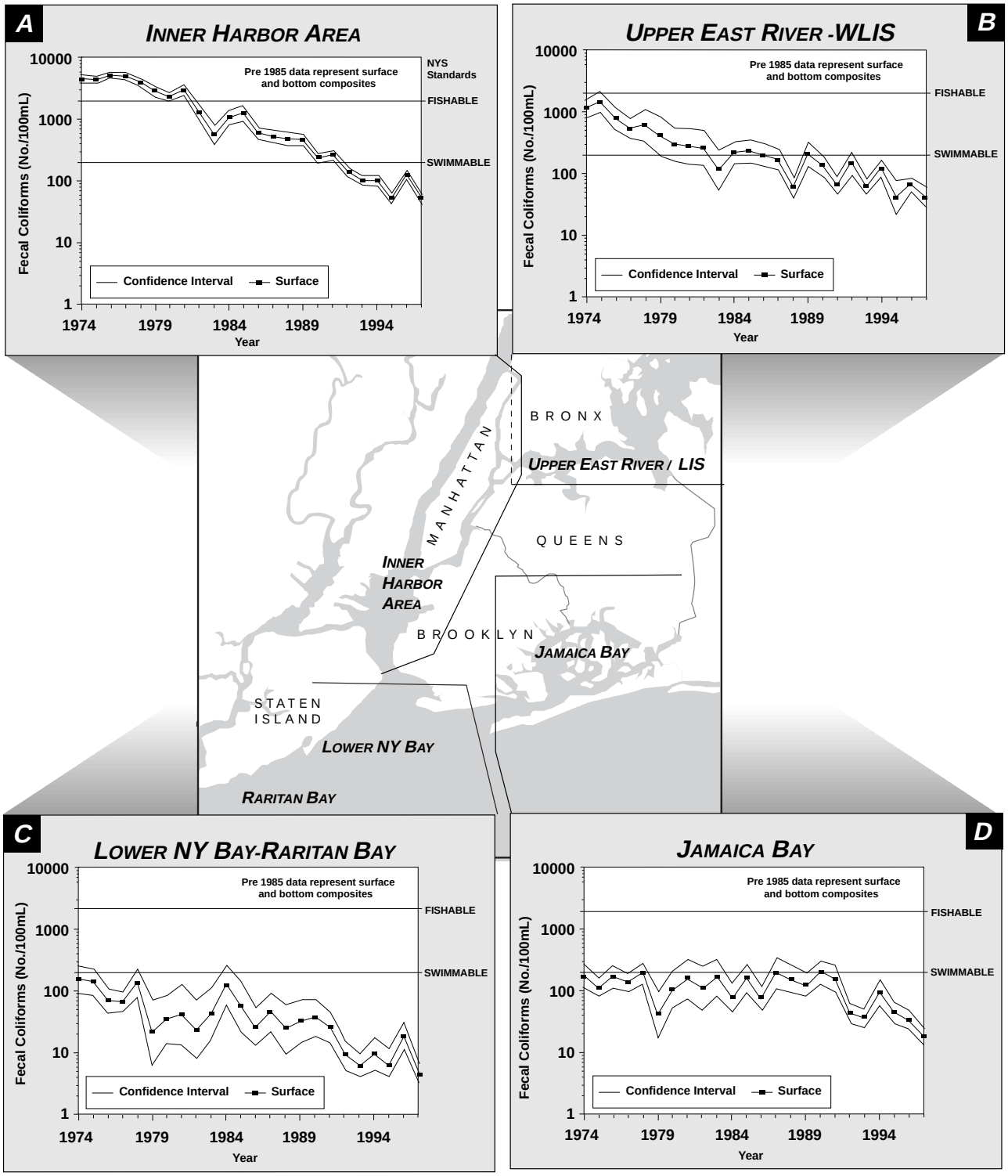
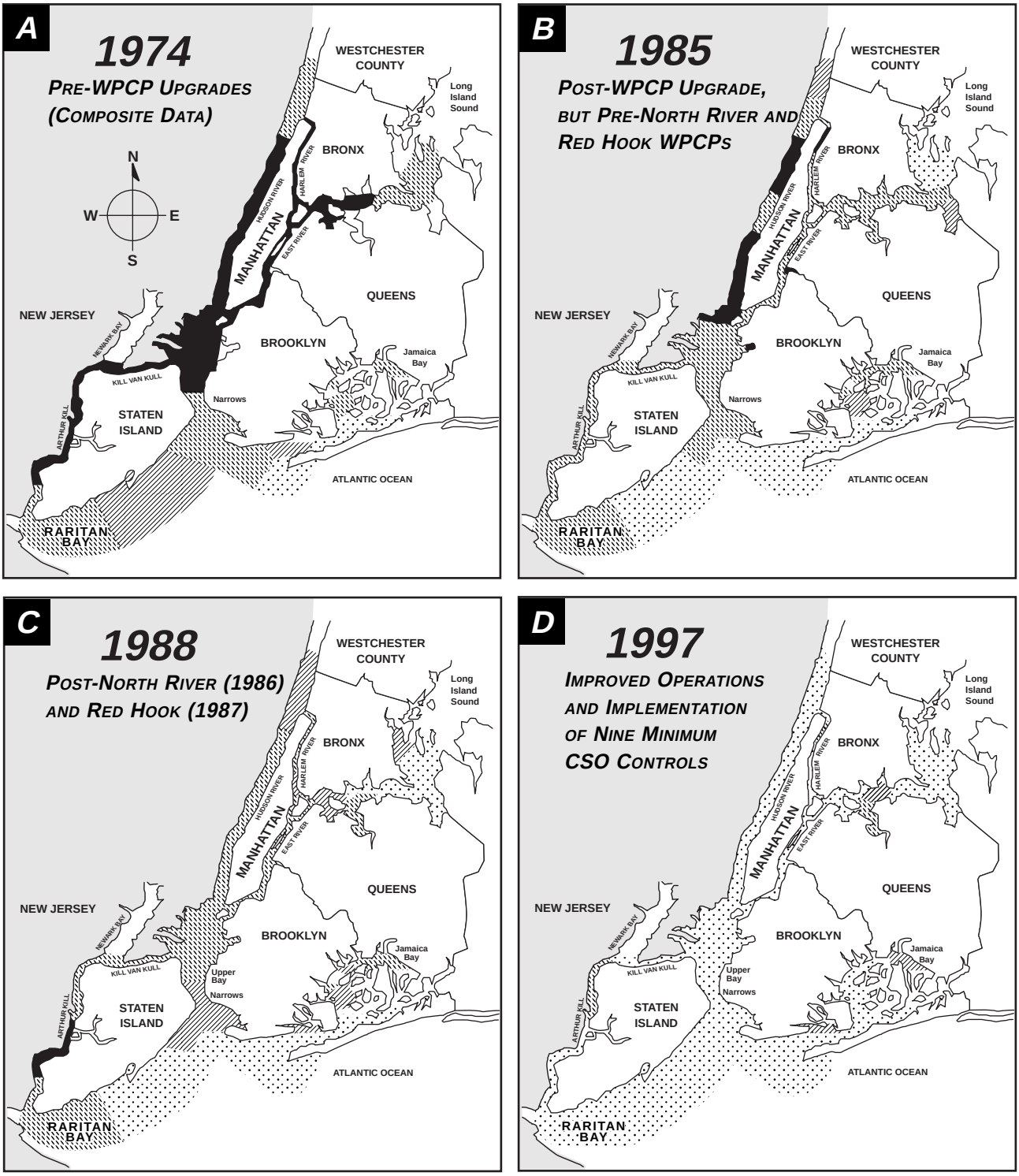


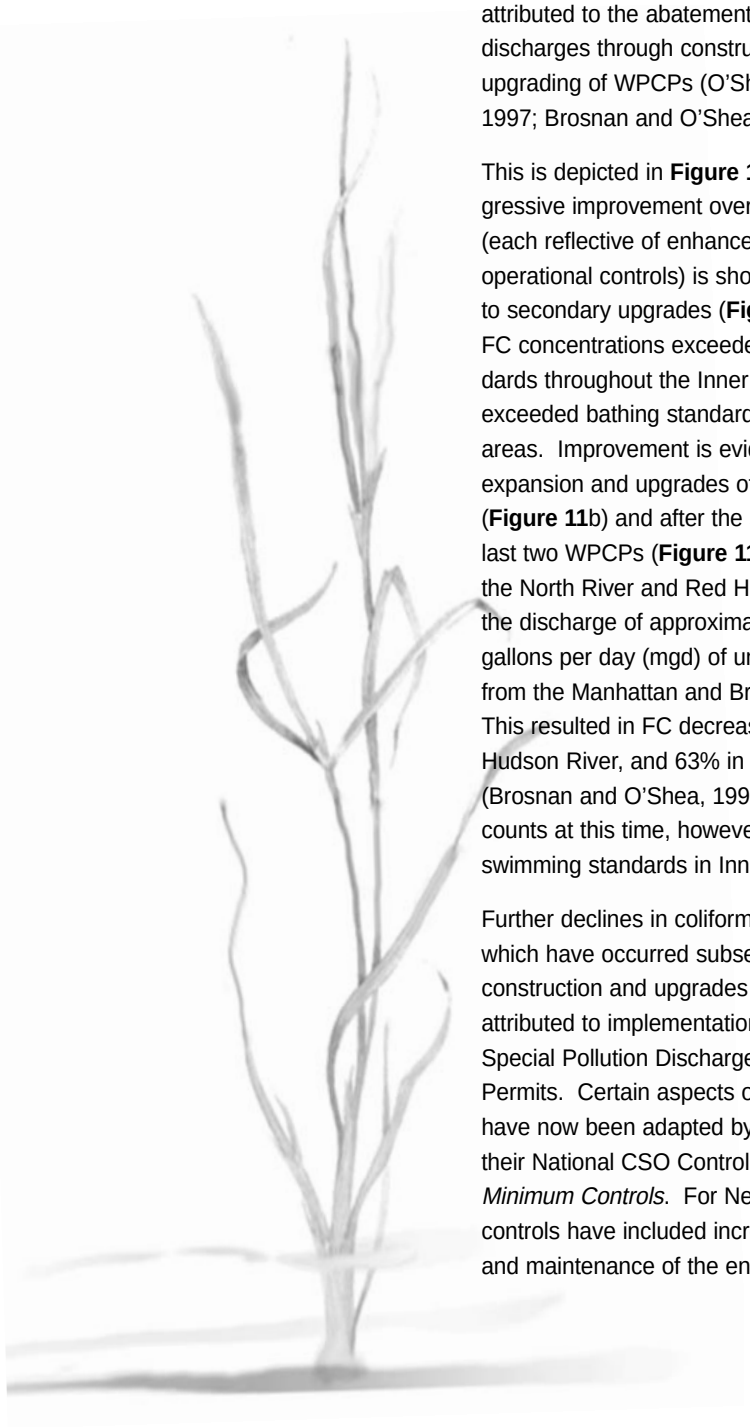
Figure 11 **Reductions in Fecal Coliform Over Four Time Periods**

Summer Geometric Means for Surface Waters



KEY: UNIT=Cells/100ml

< 100 | 100 -200 | 201 - 2000 | >2000 | Not Measured



Discussion

Declines in coliform and sanitary improvements in Harbor waters are primarily attributed to the abatement of raw sewage discharges through construction and upgrading of WPCPs (O'Shea and Brosnan, 1997; Brosnan and O'Shea, 1996b).

This is depicted in **Figure 11**; a-d, where progressive improvement over four time periods (each reflective of enhanced treatment and operational controls) is shown. In 1974, prior to secondary upgrades (**Figure 11**a), average FC concentrations exceeded fishing standards throughout the Inner Harbor area and exceeded bathing standards in most outlying areas. Improvement is evident following the expansion and upgrades of eight WPCPs (**Figure 11**b) and after the startup of the City's last two WPCPs (**Figure 11**c). Operation of the North River and Red Hook plants ended the discharge of approximately 210 million gallons per day (mgd) of untreated sewage from the Manhattan and Brooklyn shorelines. This resulted in FC decreases of 78% in the Hudson River, and 63% in the East River (Brosnan and O'Shea, 1996a). Average FC counts at this time, however, still did not meet swimming standards in Inner Harbor Areas.

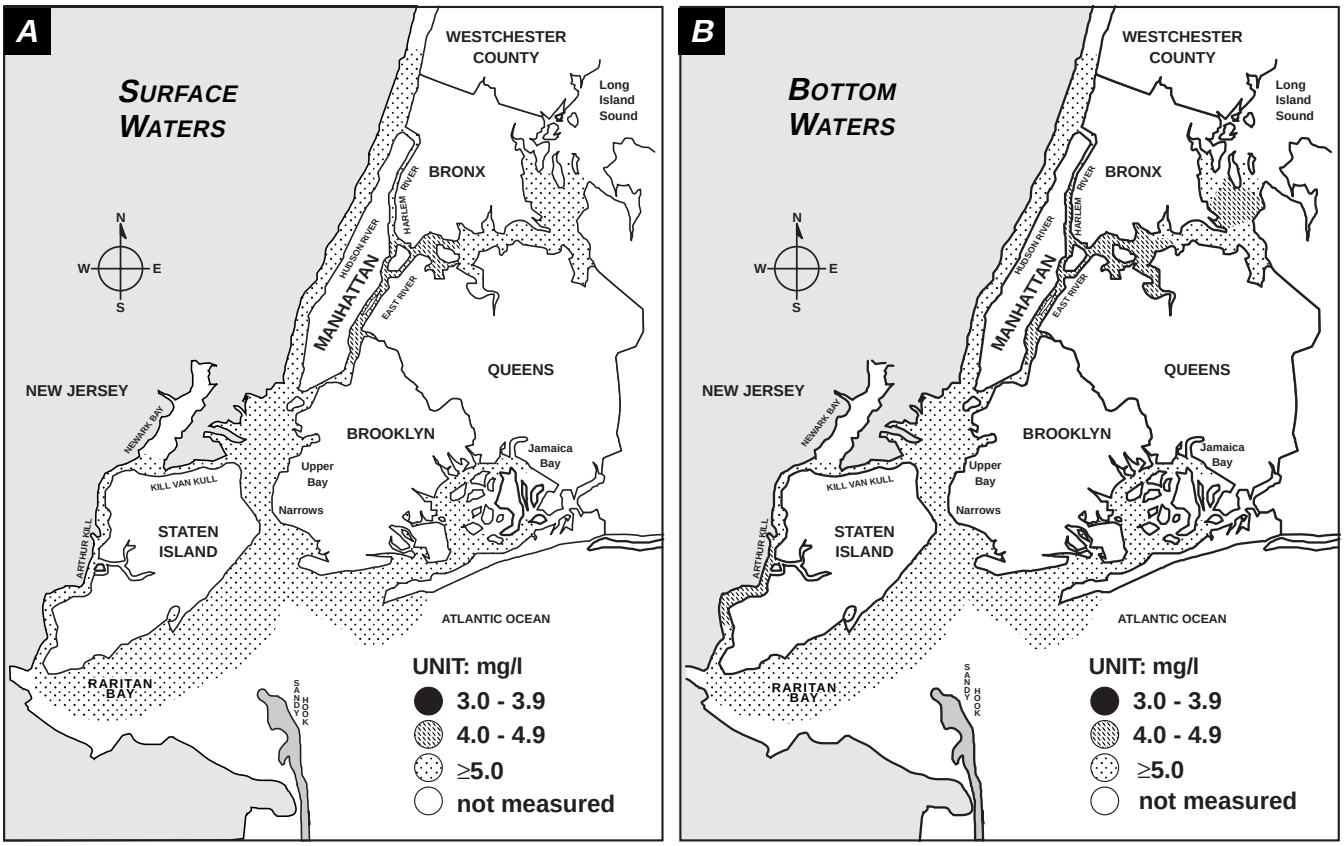
Further declines in coliform concentrations which have occurred subsequent to plant construction and upgrades (**Figure 11**d) are attributed to implementation of NYC's 1988 Special Pollution Discharge Elimination Permits. Certain aspects of these permits have now been adapted by USEPA as part of their National CSO Control Policy, *The Nine Minimum Controls*. For New York City these controls have included increased surveillance and maintenance of the entire sewage distribution system, including abatement of over 2.2 mgd of illegal discharges, reduced raw sewage bypassing by 5 mgd, and greater than 63% capture of wet weather (combined sewer) overflows at some treatment plants. In addition, previously un-intercepted sewage from Tottenville, Staten Island was sewered, beginning in 1993.

Average FC in 1997 met bathing standards for all waters, with the exception of Flushing Bay and portions of the Kills and Harlem River. (Note that each of these areas still met their designated best use classifications for secondary contact, i.e., fishing.) These improvements have been so substantial as to be apparent for both dry and wet weather conditions. Dry weather improvements are due primarily to decreased bypassing and abatement of illegal connections, whereas wet weather improvements are due to abatement of CSOs.

Dissolved Oxygen

Oxygen dissolved in the water column is required for respiration by all aerobic forms of life, including fish, and invertebrates such as crabs, clams, zooplankton, etc. The bacterial breakdown and natural decomposition of high organic loads from various sources can consume and deplete dissolved oxygen (DO). This, at times combined with water column stratification, can produce low DO levels, which when persistent may degrade habitat and cause a variety of sublethal effects upon aquatic organisms. Under extreme conditions or prolonged durations low DO can cause mortality. For example, studies conducted by USEPA and CTDEP have shown DO levels between 5.0 mg/l and 3.5 mg/l to be generally protective of

Figure 12 Average Dissolved Oxygen for Summer 1997



NYSDEC DO Standards: ≥ 3.0 mg/l = SD(Fish Survival); ≥ 4.0 mg/l = I(Fishing); ≥ 5.0 mg/l = SB(Bathing)

all but the most sensitive aquatic species. Concentrations below 2.0 mg/l may cause severe effects, even for periods of short duration (LISS, 1997). Consequently, DO is one of the most universal indicators of overall water quality in aquatic systems.

Harbor dissolved oxygen or DO concentrations tend to follow a seasonal cycle, being lowest in summer and highest in early winter and spring. During the summer of 1997, each of the 53 Harbor Survey stations was monitored a minimum of nine times. Average summer DO values for 1997 Harbor waters are shown graphically in **Figure 12**; a and b. These values were never below 4.0 mg/l, with only 13 survey stations having average values between 4.0-4.9 mg/l, and the remainder at or above 5.0 mg/l. These DO concentrations are typical of average summer conditions reported for the Harbor over the past three years.

Figure 13; a and b, shows the minimum DO values recorded for summer 1997. Dissolved oxygen measurements of <3.0 mg/l (defined as, hypoxia) were recorded a single time at each of four bottom stations in the Upper East River-Western Long Island waters. For summer 1996, readings below 3.0 mg/l were recorded 15 times, at least once at ten different stations (Boniecki and Lochan, 1998).

DO measurements of <3.0 mg/l were recorded a single time at each of four bottom stations in the Upper East River-WLIS.

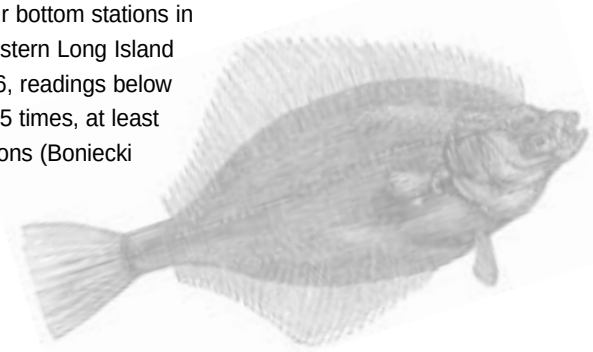
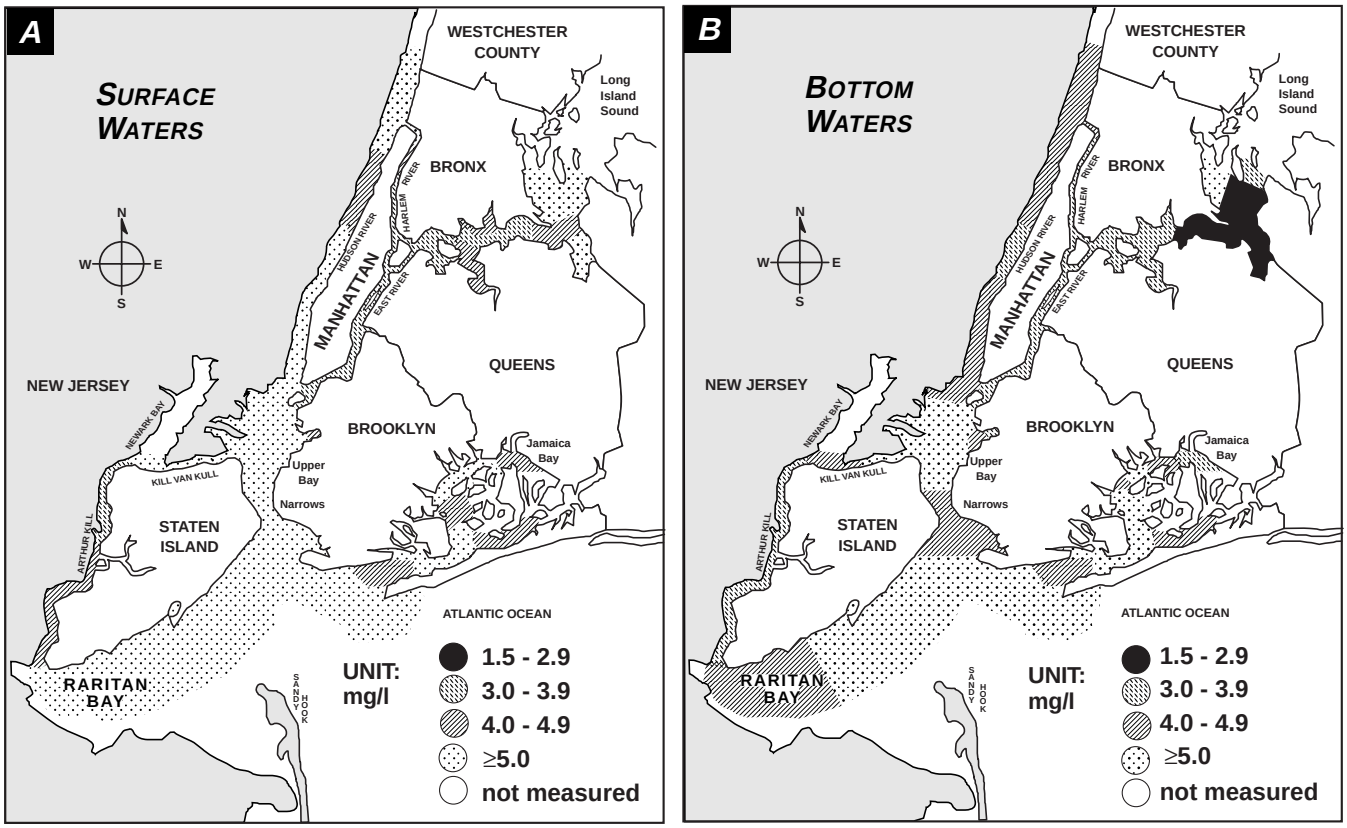


FIGURE 13 **MINIMUM DISSOLVED OXYGEN FOR SUMMER 1997**



NYSDEC DO Standards: ≥ 3.0 mg/l = SD(Fish Survival); ≥ 4.0 mg/l = I(Fishing); ≥ 5.0 mg/l = SB(Bathing)

Average dissolved oxygen achieved NYS standards...with exception of one site in WLIS.

Attainment of Water Quality Standards

Assessment of the adequacy of DO present in the Harbor is performed by comparing actual concentrations to NYS DEC Standards, which vary between 3-5 mg/l, depending on the designated best use of the waterway (**Figure 7** and **Table 3**). New York State standards require that measured dissolved oxygen is "never less than" the regulatory value. Consequently, in 1997, 30 stations were out of compliance with the applicable standard at least once due to either surface or bottom measurements. The most chronic 1997 violators of the "never less than" standard (i.e., > 50% of summer samples below standards) were two Western Long Island sites (E8 and E10), and two sites along the northeastern shore of Jamaica Bay (J7 and J8). The remainder of sites contravened standards less than 40% of the time, with 23 sites (representing a considerable portion of the Inner Harbor Area and Lower NY Bay-Raritan Bay) in full compliance for the summer.

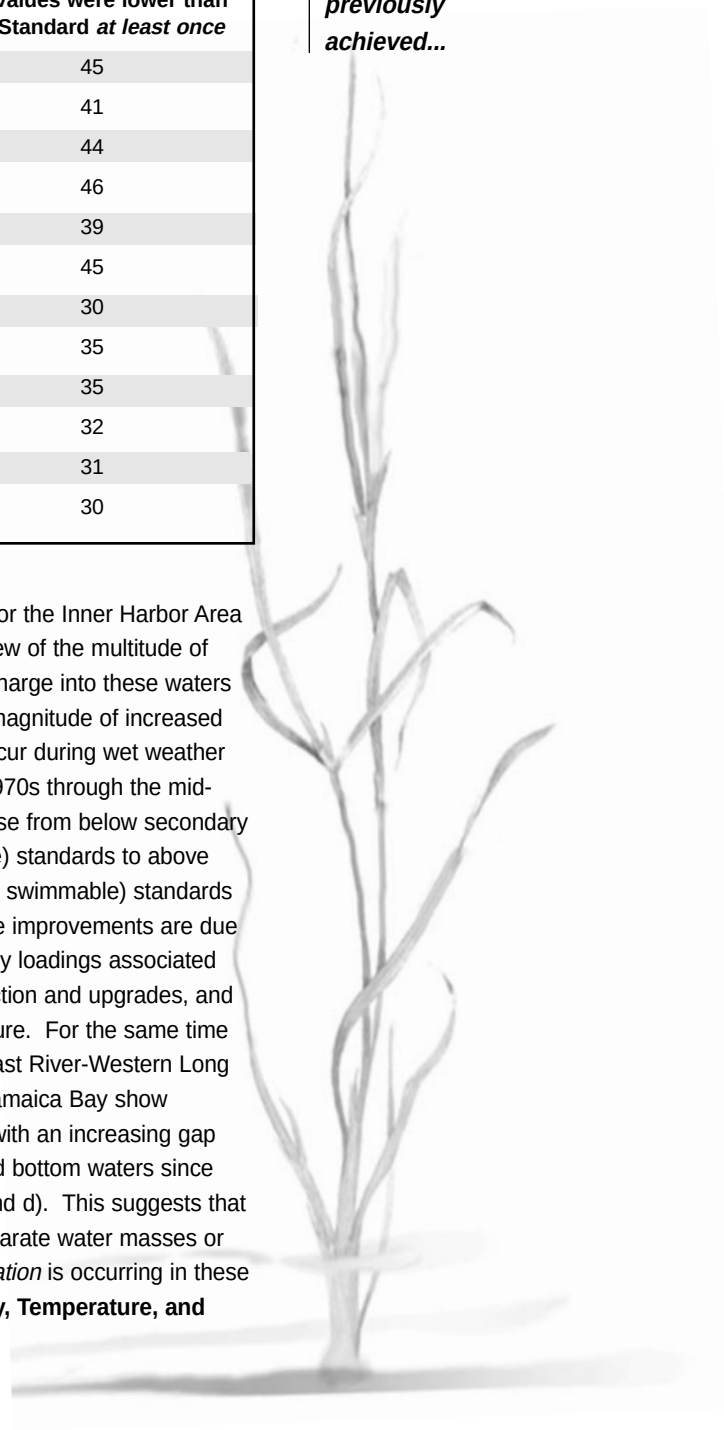
A somewhat less rigorous comparison is to examine average summer DO values to standards. While this is not a true assessment of compliance, it is more characteristic of summer conditions at sampling locations and allows for comparison of yearly variability and water quality improvement (or decline). For Summer 1997, average DO achieved NYS standards throughout the Harbor, with exception of one site in Western

TABLE 5

Comparison of Summer Dissolved Oxygen (DO) and New York State Standards

Year	Number of Stations where average DO values were lower than the Standard	Number of Stations where DO values were lower than the Standard *at least once*
1986	9	45
1987	24	41
1988	20	44
1989	22	46
1990	8	39
1991	16	45
1992	2	30
1993	4	35
1994	8	35
1995	3	32
1996	5	31
1997	1	30

...attainment of DO standards in the Harbor is clearly better than previously achieved...



Long Island Sound. Seasonal attainment of NYS DEC standards at 53 stations (52 before 1996), using both the "summer average" and the "never less than" approach for recent years, is presented in **Table 5**.

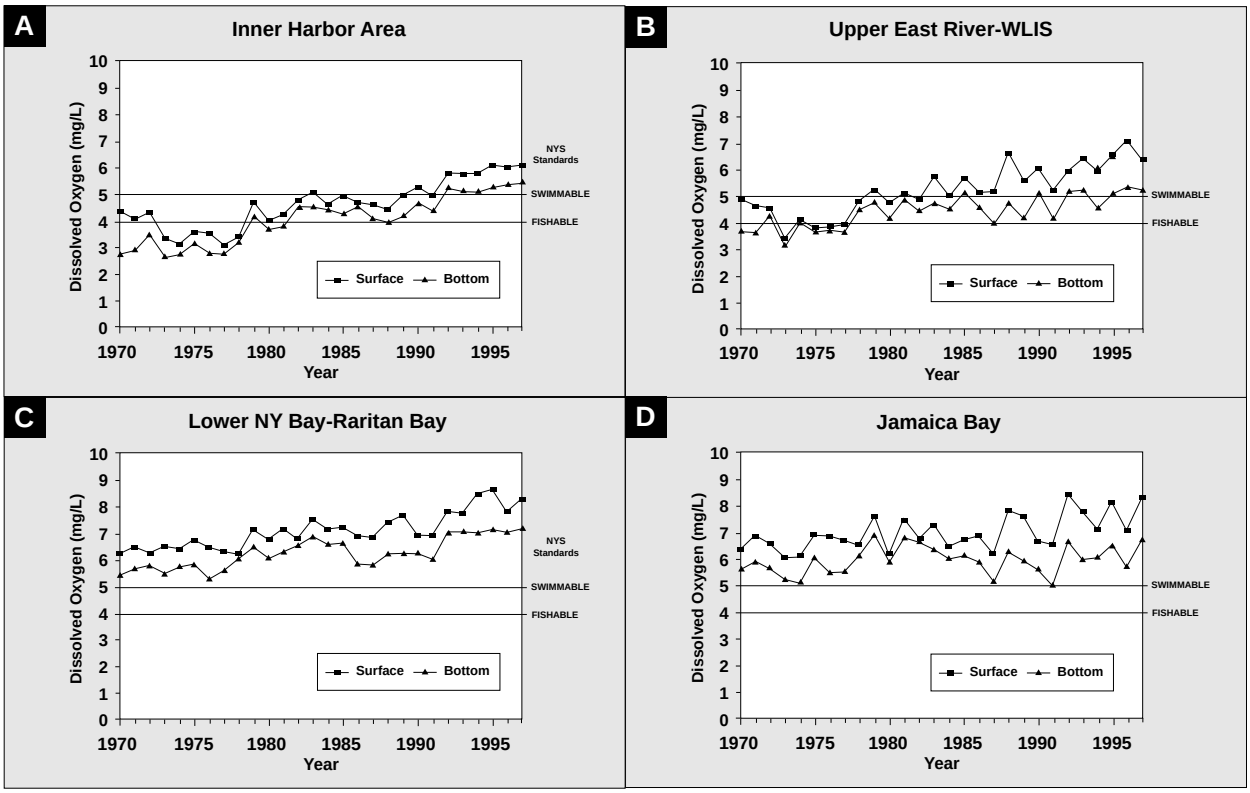
In general, from 1992 and on, attainment of DO standards in the Harbor is clearly better than previously achieved, with most sites demonstrating long term improvements. These improvements were evident throughout the Harbor, with exception of several sites in Jamaica Bay and Western Long Island Sound.

Trends

Dissolved oxygen concentrations have increased significantly (~2 mg/l) over the past 28 years (**Figure 6**a). Average DO trends for four distinct areas of the Harbor (**Figure 14**) show greatest improvement (between 1.7 and 2.7 mg/l) to have occurred in the Inner Harbor Area and the Lower NY Bay-Raritan Bay. Improvement for the Inner Harbor Area are noteworthy in view of the multitude of CSOs that may discharge into these waters (**Figure 2**) and the magnitude of increased loading known to occur during wet weather events. From the 1970s through the mid-1990s DO values rose from below secondary contact (i.e., fishable) standards to above primary contact (i.e., swimmable) standards (**Figure 14**a). These improvements are due to decreased sanitary loadings associated with WPCP construction and upgrades, and improved CSO capture. For the same time period, the Upper East River-Western Long Island Sound and Jamaica Bay show high DO variability, with an increasing gap between surface and bottom waters since the mid-80s (**14**;b and d). This suggests that formation of two separate water masses or pronounced *stratification* is occurring in these areas. (See **Salinity, Temperature, and Density**, p. 53)

FIGURE 14 **DISSOLVED OXYGEN TRENDS FOR FOUR HARBOR AREAS**

Summer Averages, 1970-1997



Discussion

Year-to-year variability in the frequency, duration and severity of low DO or hypoxia are linked to variations in vertical density stratification; wind mixing; tidal and gravitational circulation; and the quality of water coming into an area (Diaz et al., 1992). For example, DO minima in the Hudson appear to be related to summer river flow and flushing time (Clark, 1995). Recent declines in bottom DO in Western Long Island Sound have been linked to increases in the timing and intensity of stratification (HydroQual, Inc., 1995).

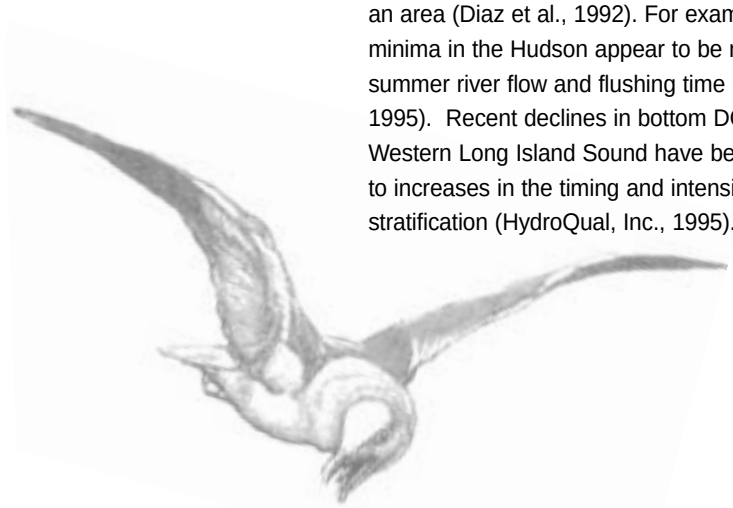
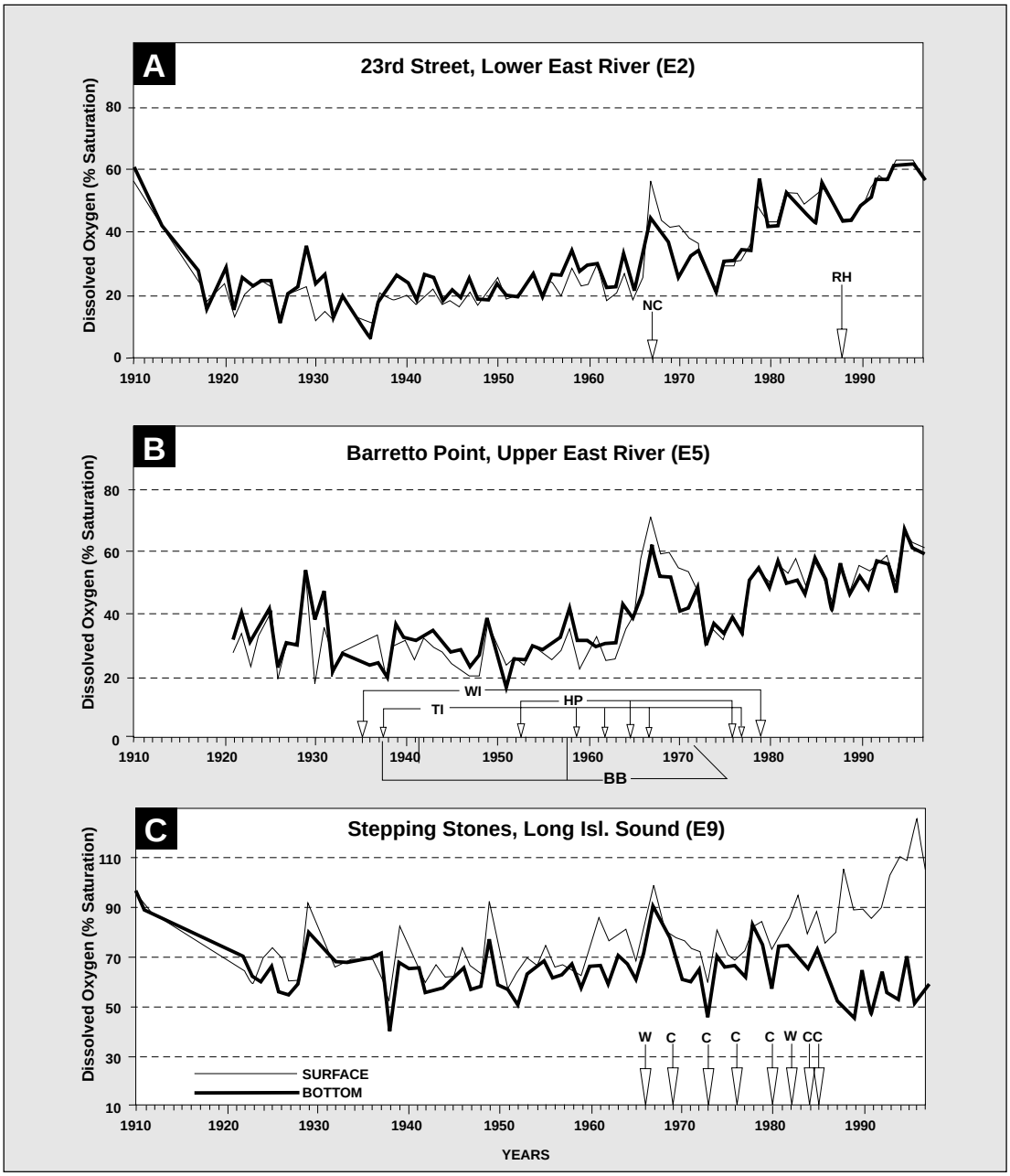


Figure 15 illustrates progressions of DO improvement at three points in the East River; a lower and upper East River site, and a Western Long Island Sound (WLIS) site. The effect of cumulative organic loadings (as one moves downstream) can be seen as lower DO levels at the two East River Sites (Figures 15a and b) compared to the WLIS site (15c). For the Lower East River Site (**Figure 15**a), average summer DO ranged between 7-37% saturation between 1918-1940. Levels then stabilized at or above 20% through the late 1950s; a period coinciding with construction and start-up of a number of WPCPs. Increased DO saturation

Figure 15

East River-Western Long Island Sound Dissolved Oxygen Trends

Summer Averages



Construction of, and significant upgrades to NYC WPCPs on the East River are depicted:
Wards Island (WI), Bowery Bay (BB), Tallman Island (TI), Hunts Point (HP), Newtown Creek (NC), and Red Hook (RH).
For bottom graph, Westchester (W) and Connecticut (C) WPCPs (west of the Housatonic River and >10 mgd) are depicted.

and greater year-to-year variability, evident during 1960-1980, parallel WPCP upgrades and start-up of the North River Plant. Dissolved oxygen substantially increased in the 1980s and especially in the 1990s; surpassing levels recorded at the beginning of the century.

For the same duration, an Upper East River Site (**Figure 15**b) showed higher variability, with DO saturation typically between 20-40%, until increasing in the late 1960s. More consistent improvements and highest DO levels are again evident in the 1980s and 1990s.

Sampling from Osprey to determine dissolved oxygen levels

Percent DO saturation in the WLIS (**Figure 15**c) shows greater variability and surface-to-bottom water differences than the East River Sites. Levels of DO were typically between 50-70% saturation until the 1960s, with single year peaks in surface water. Beginning in the 1960s, summer averages for surface waters show strong (more consistent) increases in DO saturation. From the late 1980s and through the 1990s, average DO is often super-saturated or greater than 100% (a condition indicative of algae blooms and eutrophic waters). In contrast, bottom water DO levels, seen to parallel surface conditions through most of the century, drop-off notably since the mid-1980s. Average values for recent years are lower than those recorded at the beginning of the century. This has occurred despite the virtual elimination of raw sewage discharges and concomitant decreases in BOD and TSS point source loads throughout the Harbor and region (Brosnan and Stubin, 1992).

Although the Western Sound has exhibited elevated nutrient concentrations for many years, sustained low summer DO or hypoxia is a relatively recent phenomenon. During the late 1980s and early 1990s the area of hypoxic waters documented in the Sound by the Long Island Sound Study (LISS) extended from 65 to 180 km^2 and lasted from 2 to 6 weeks (Stacey, 1990). Given the point source load reductions noted above, the concurrence of declining pollutant loads and worsening water quality is counter-intuitive.

While there is little consensus as to why the Sound's water quality has recently declined, a LISS-funded study revealed low DO to be closely related to changes in salinity and temperature between the Western Sound and the Verrazano Narrows (HydroQual, Inc., 1995). Together these factors increase stratification and restrict oxygen replenishment from the surface.

To improve Long Island Sound waters NYC DEP, together with Westchester County and the states of New York and Connecticut have developed a comprehensive management plan (LISS, 1993). The goal of current efforts is to substantially reduce nutrient loadings and thereby reduce eutrophication of Sound waters and demands upon DO (LISS, 1997)(see *Nutrient Removal,* p.18).

For a further discussion of DO trends in the Harbor and Western Long Island Sound, see Brosnan and O'shea, 1997; Brosnan and O'Shea, 1996b; Brosnan and Stubin, 1992.

Nutrients

Nutrients, natural life sustaining substances, are critical to maintaining an appropriate balance for the health and productivity of aquatic systems. For estuarine waters of the Harbor major nutrients of importance include nitrogen, phosphorus, carbon and silica (HydroQual, 1996). These elements form the basis of the food chain, controlling, either individually or in combination, phytoplankton growth in various parts and reaches of the Harbor.

Important nutrient sources to the Harbor include tributaries and oceanic transport, regeneration from coastal sediments, atmospheric deposition, CSO, storm water, and water pollution control plant effluents (Mueller et al., 1982; Lee et al., 1982; Malone, 1982; Lee and Jones, 1987; Jones and Lee, 1985; Gunnerson, 1982; Malone et al., 1985). The relative importance of these sources to the overall nutrient load that any area of the

A family enjoys a day of fishing

Harbor receives is typically a function of local hydraulics and proximity to sources. High nutrient concentrations have been associated with eutrophication, noxious water quality conditions, and ammonia toxicity. In addition, low dissolved oxygen (DO) that may result from nutrient and organic enrichment, may degrade habitat and reduce fish and shellfish productivity (HEP, 1996).

Eutrophication is a process whereby nutrients added to a water body at excessive rates cause a dramatic increase in primary productivity (i.e., plant growth), and associated organic carbon. Symptoms of eutrophic water bodies include elevated nutrient and phytoplankton concentrations, excessive macro algal biomass, and reduced transparency and DO. Nutrients measured include nitrogen (as ammonium, and nitrate plus nitrite), and phosphorus (as total phosphorus and orthophosphate). In marine water bodies, excess nitrogen is generally associated with eutrophication.

Attainment of Water Quality Standards

While there are no NYS DEC Standards for maximum allowable nutrient concentrations in marine waters, nutrient loadings to waters of Jamaica Bay and the East River are being carefully monitored and reduced to control eutrophication of these waters and limit algal growth (see *Nutrient Removal*, p.18).

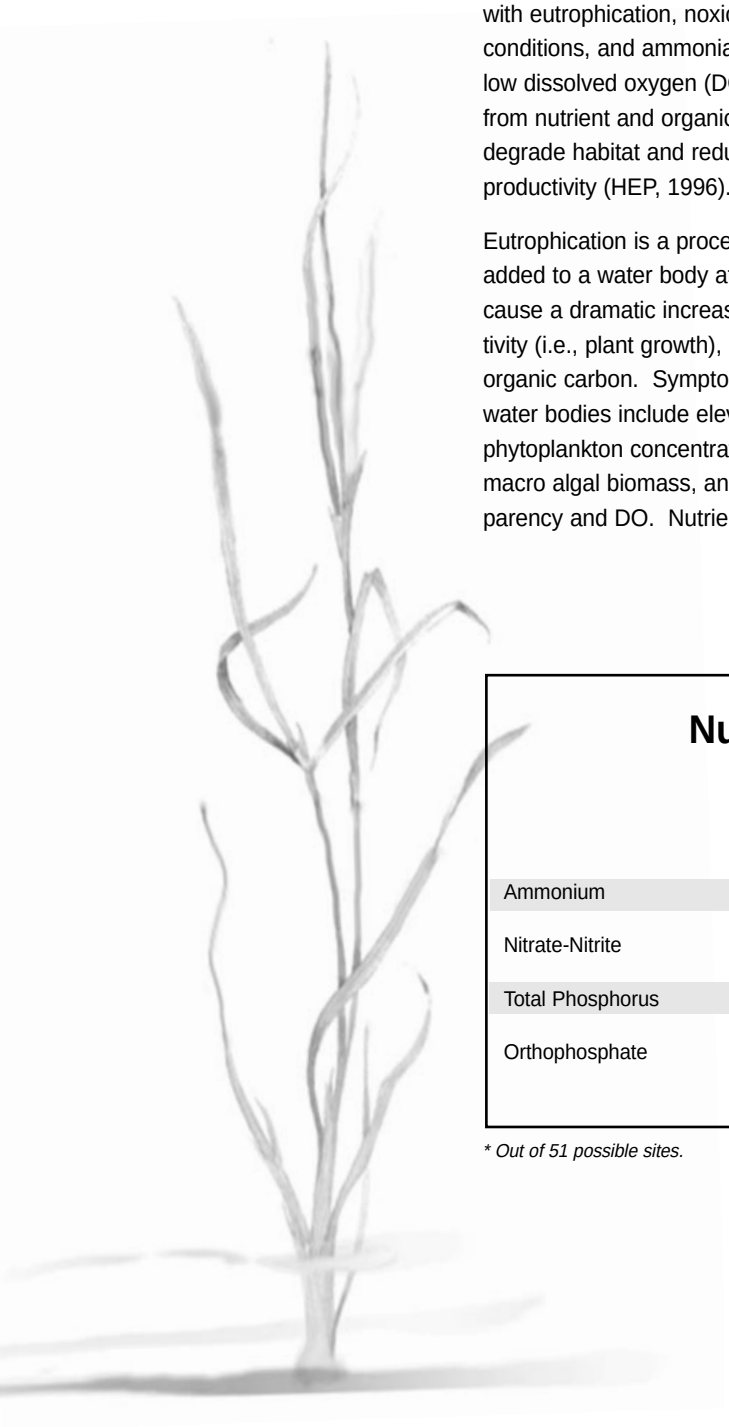


TABLE 6

Nutrient Trend Data, 1985-1997

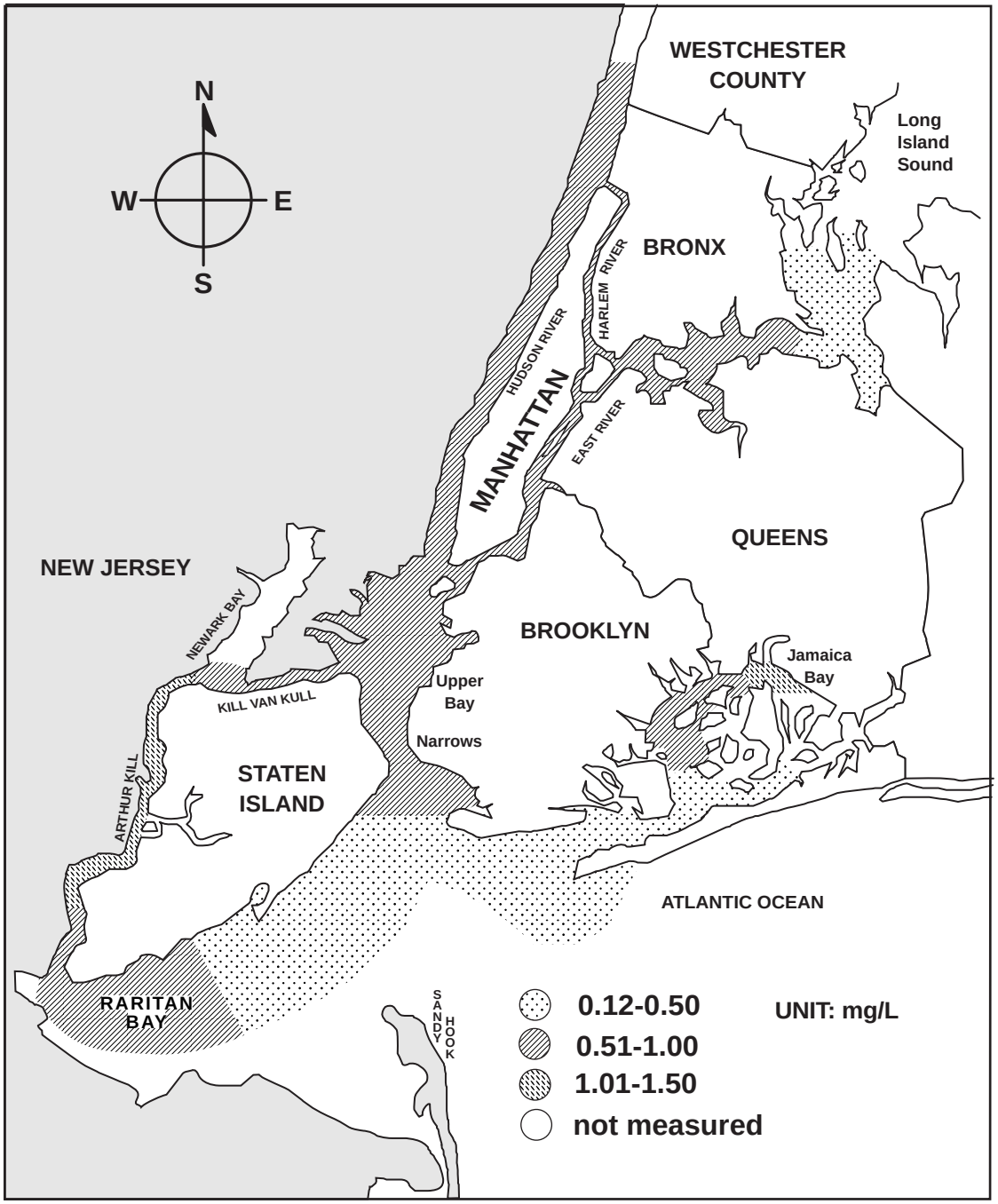
	Number of Stations* With:		
	Increasing Trend	**Decreasing Trend**	**No Trend**
Ammonium	1	13	37
Nitrate-Nitrite	2	5	44
Total Phosphorus	3	20	28
Orthophosphate	0	18	33

** Out of 51 possible sites.*

Figure 16

Total Dissolved Inorganic Nitrogen (NH_4 & NO_{3-2}) in Surface Waters

Summer Averages, 1997



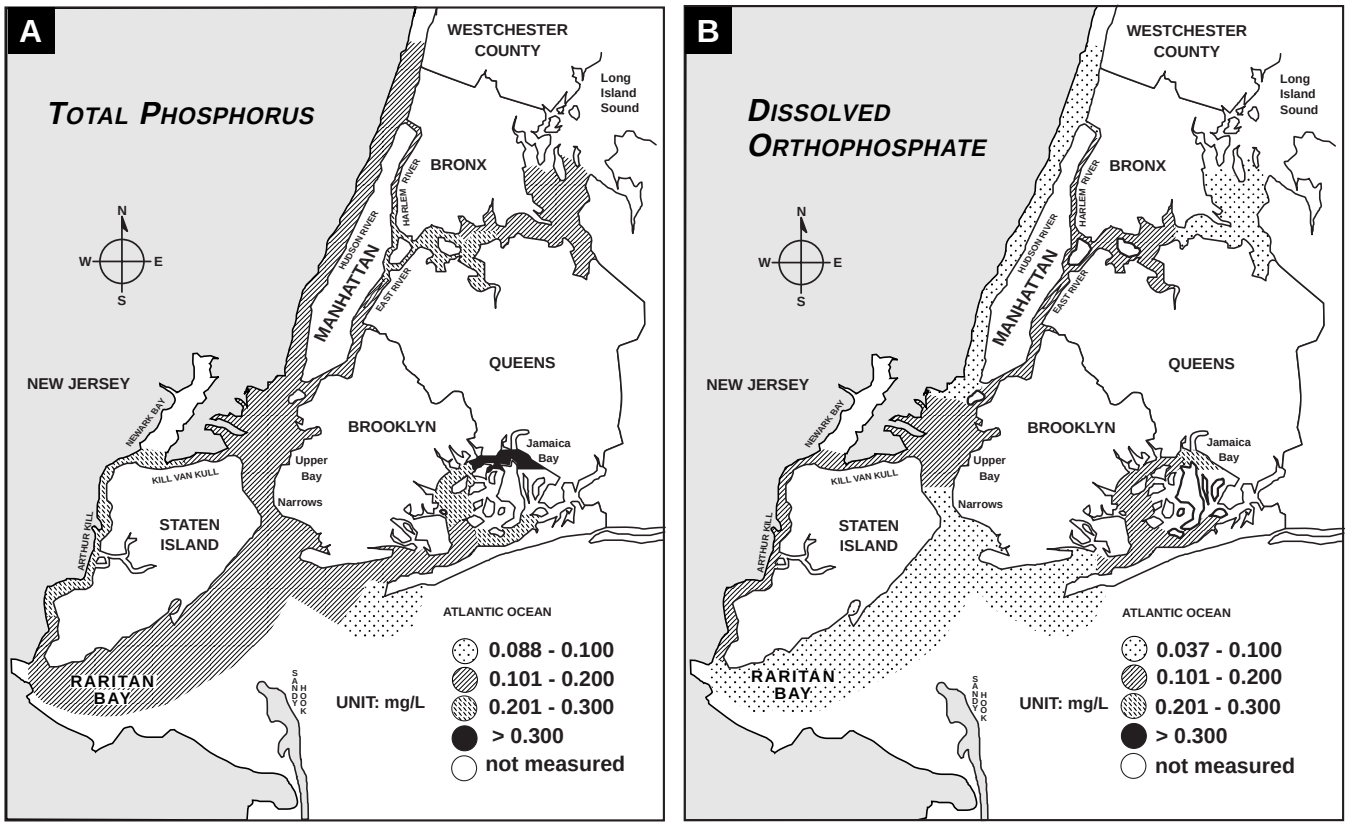
Highest summer averages (>1 mg/l) for total dissolved inorganic nitrogen (ammonium-plus nitrate- and nitrite-nitrogen) were observed (as in years past) in the northeastern portion of Jamaica Bay and the Arthur Kill (**Figure 16**). Overall, concentrations of measured nitrogenous components were very similar to values observed in 1995, though average values for 1997 never exceeded 1.5 mg/l. This is true despite a 1996-observed increase of ammonium concentrations in Jamaica Bay (Boniecki and Lochan, 1998). It should be noted that high nutrient variability (both within a season and year-to-year) is common in Harbor waters.

Total phosphorous values were high (>0.2 mg/l) in Jamaica Bay, the Kills, the lower Harlem River and the East River, north of Roosevelt Island to, and including, Flushing Bay (**Figure 17**a). Highest average values (>0.3 mg/l) were recorded in the northern portion of Jamaica Bay. Average concentrations for dissolved orthophosphate (Figure **17b**) were typically less than 0.20 mg/l for Jamaica Bay and most of the Inner Harbor Area, and less than 0.10 for the Hudson River, Western Long Island Sound, and Raritan Bay. Highest values (>0.20 mg/l) were observed in the northeastern portion of Jamaica Bay. Relative to values depicted in 1995, average 1997 values for total phosphorous and dissolved orthophosphate appear to have decreased for the Hudson

Bridge over Harlem River

Figure 17 **Total Phosphorus & Dissolved Orthophosphate in Surface Waters**

Summer Averages, 1997



River, the lower East River, the Arthur Kill, and Raritan Bay. Again reflective of the high temporal variability of Harbor nutrients, this decrease appeared more substantial in 1996 (Boniecki and Lochan, 1998).

Within-season variability was highest for total ammonium and nitrate-nitrite, with variability showing a tendency to increase, moving away from Inner Harbor Areas to outlying waters of the Western Sound and Lower NY Bay. Note that areas showing high variability also contain the lowest average nitrogen concentrations relative to the rest of the Harbor.

Trend Analysis

A trend analysis of the summer average 1985-97 data set was performed on 51 stations using SAS Pearson product-moment correlations and is summarized in **Table 6**, p.41.

Stations showing declining nutrient concentrations were widely scattered throughout the Harbor and largely outnumber sites for which increasing concentrations were observed. However, most sites displayed no significant trend for nutrients over the past 13 years.

This is not surprising, in that *secondary treatment,* at which WPCPs are federally mandated to operate, does not remove nitrogenous compounds. Advanced secondary processes and innovative biological nutrient removal technologies are now being implemented and evaluated by NYC DEP (see *Nutrient Removal*, p.18). Sites exhibiting an increasing nutrient trend are located in Jamaica Bay and Flushing Bay. Both of these bays seasonally display characteristics symptomatic of eutrophic conditions (see p.41).

...federally mandated, secondary treatment does not remove nitrogenous compounds

Discussion

The relatively low nitrogen-to-phosphorus ratio of Harbor waters (<7:1) suggests nitrogen to be more apt to limit phytoplankton growth. However, recent hydrodynamic modeling has disputed the feasibility of controlling algal growth (and secondarily, low DO), through high level nitrogen removal at WPCPs for most areas of the Harbor (HydroQual, 1996b). This strengthens a widespread assertion that primary productivity in the Harbor is not nutrient limited (Lee et al., 1982; Malone, 1982; Mayer, 1982). Instead, for many parts of the Harbor, summer productivity appears to be limited by turbidity from river-borne suspended sediments, flushing rate, zooplankton grazing, and weather (Lee et al., 1982; Malone, 1982; NYC DEP, 1986).

Fishing in Jamaica Bay

In contrast to the above, modeling of Long Island Sound has shown that the lowest DO values can be raised and that the duration of hypoxic events can be greatly diminished in WLIS through significant reductions of nitrogen. As noted above (p.40), NYC DEP, together with others, have embarked on an aggressive nutrient reduction program (LISS, 1997) to provide for these water quality improvements.

Chlorophyll 'a' and Phytoplankton

Chlorophyll 'a'

Chlorophyll 'a' is a plant pigment whose concentrations in the water is used as an estimate of phytoplankton biomass. The presence of algae may be reflective of eutrophic or other water quality conditions, (see *Plankton*, p.48) or in itself influence aspects of water quality, e.g., pH, color, taste, odor (American Public Health Association, 1985). Chlorophyll 'a' and plankton counts in some areas can vary dramatically over a period of days. This is due to the formation and dissipation of algal blooms which respond rapidly to environmental conditions.

Average 1997 chlorophyll 'a' concentrations (**Figure 18**;a and b) appear to have declined relative to 1995-1996 levels. This is true for winter/spring values (**Figure 18**a) in portions of the Upper East River-Western Long Island Sound and, with the exception of Jamaica Bay, near harbor-wide for summer concentrations (**Figure 18**b). In 1995, 30 stations had average summer concentrations in excess of 20 ug/l (generally indicative of eutrophic conditions). For summer 1997, only 18 stations (ten in Jamaica Bay; five in the Upper East River-Western Long Island Sound; and three in the Lower NY Bay-Raritan Bay) had average chlorophyll 'a' concentrations greater than 20ug/l. Highest summer time averages and the widest range of recorded values (from 3.7 to 285 ug/l) were observed in Jamaica Bay. Lowest summertime averages (<10 ug/l) were observed in the Inner Harbor Area.

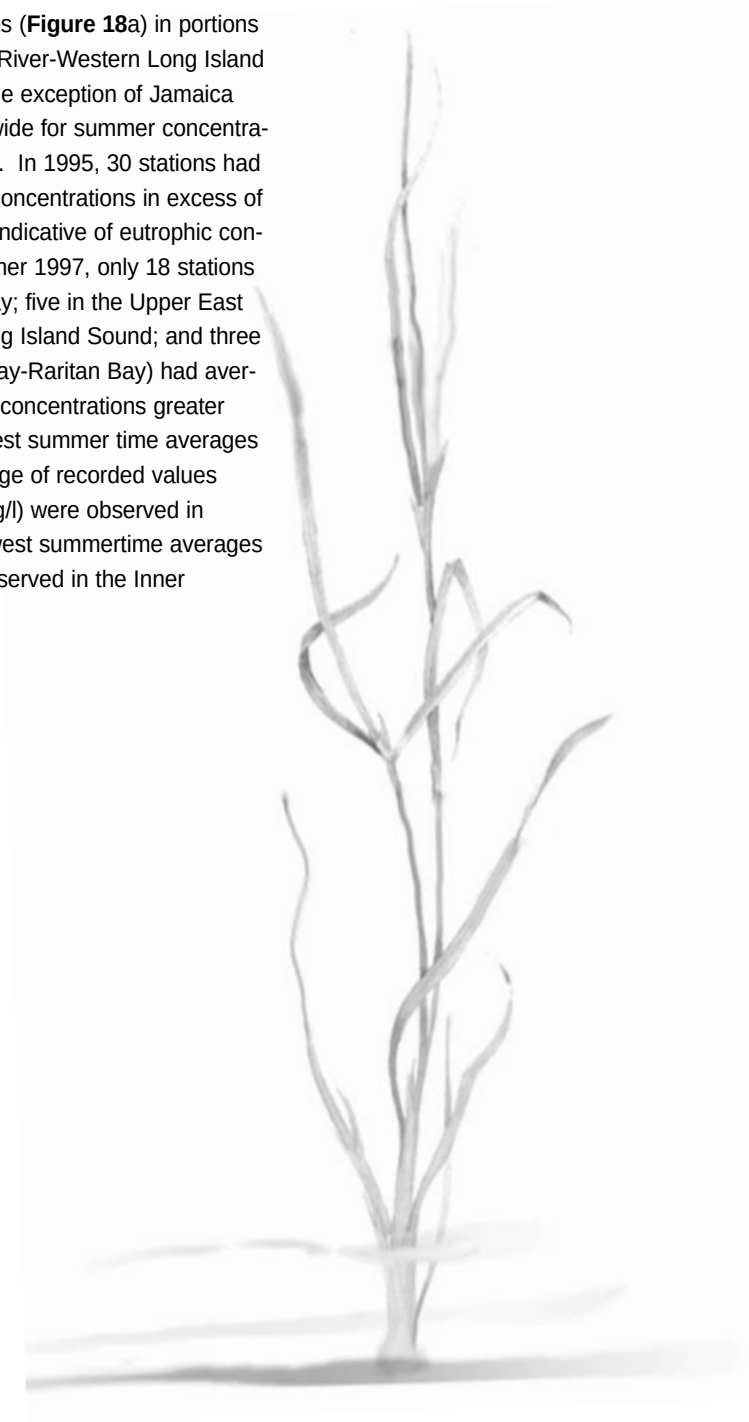
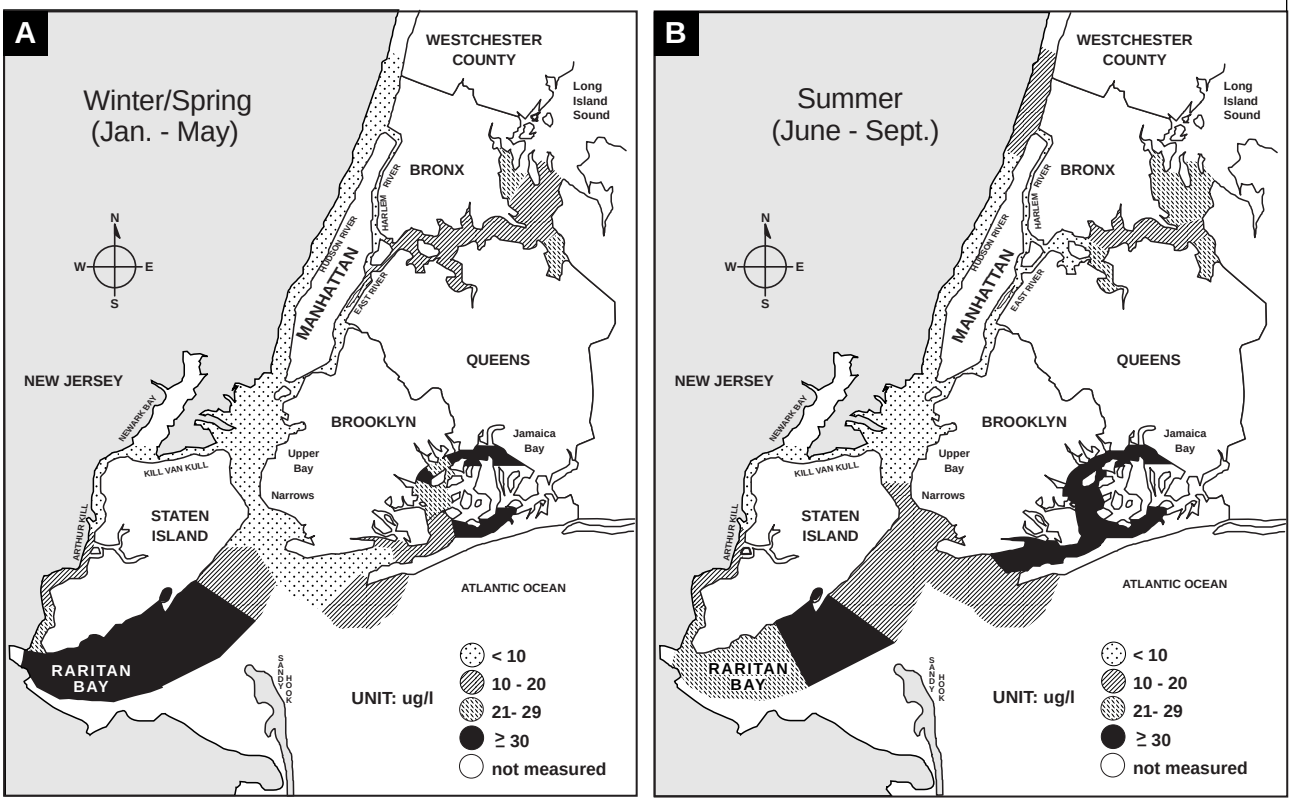


FIGURE 18

AVERAGE CHLOROPHYLL 'a' CONCENTRATIONS

Surface Waters, 1997

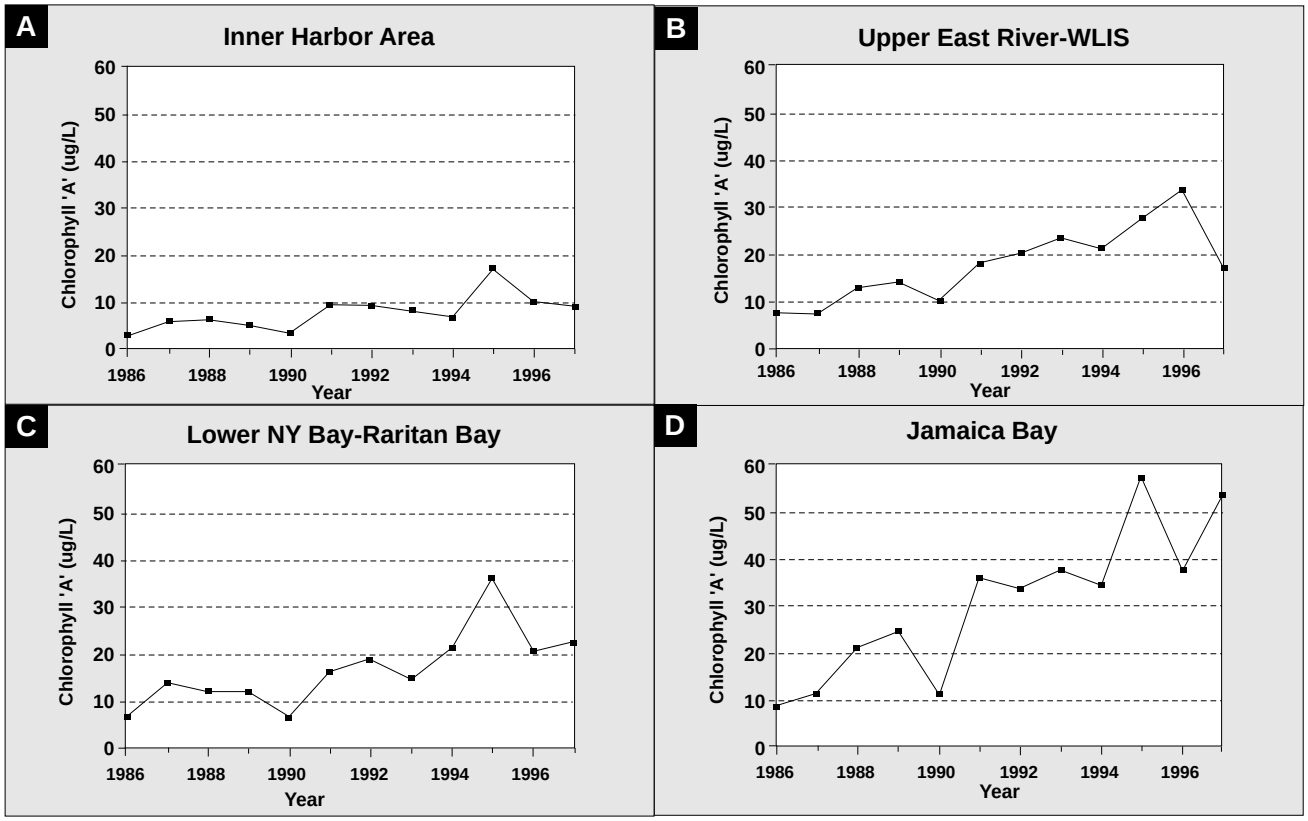


Trend Analysis

High variability inherent in chlorophyll 'a' measurements (both seasonably and on a year-to-year basis) combined with a limited number of pre-1989 chlorophyll 'a' samples makes temporal trends difficult to establish. Nevertheless, a regression analysis of 1989-97 summer averages revealed significant ($p<0.05$) increases at 20 sites, including those of Jamaica Bay and Lower NY Bay-Raritan Bay, a portion of the Upper East River-Western Long Island Sound, and other scattered sites. This is despite the immediate short-term decrease relative to 1995-1996 values noted above. While a depiction of Harbor-wide trends (**Figure 6**d) suggests increases in chlorophyll 'a' to be considerable, an examination of trends for four distinct Harbor areas demonstrates most change to have occurred in Jamaica Bay (**Figure 19**;a-d).

FIGURE 19 **HARBORWIDE CHLOROPHYLL 'a' TRENDS**

Summer Averages in Surface Waters



In general, high chlorophyll 'a' concentrations observed in the Harbor are typically associated with declining secchi depths (see p.52), a decrease in light transmittance (O'Shea and Brosnan, 1997), and an increase in top-to-bottom DO variability; conditions symptomatic of eutrophic conditions.

Plankton

Plankton, free-floating, often microscopic, aquatic plants (phytoplankton) and animals (zooplankton) form the basis of the food web. Since these organisms respond quickly to environmental changes, their species abundance and composition are potentially useful indicators of water quality (Gannon and Stemberger, 1978). The presence of certain species may indicate eutrophic (nutrient-rich) waters (Palmer, 1963), while the absence of others, may be indicative of chemical pollutants (Palmer, 1969). Additionally, the abundance of phytoplankton may further effect other basic aspects of water quality (see *Chlorophyll 'a'*, above).

While phytoplankton have been found to be a useful water quality indicator elsewhere, to date phytoplankton have been underutilized as environmental indicators for the Harbor. Limiting their use in this context has been their patchy distribution and transient nature in the Harbor, as well as, uncertainty

...high chlorophyll 'a' concentrations... are associated with declining Secchi depths...

concerning their origin and duration of exposure. Though subtle changes in phytoplankton assemblages may be indicative of ecosystem change, documentation of such change is lacking for the Harbor (HEP, 1996). Indeed, high variability of phytoplankton concentrations may be attributable to many factors, including seasonal changes in temperature and light, nutrient availability and grazing pressures.

Harbor phytoplankton concentrations tend to loosely follow a geographic distribution similar to chlorophyll 'a'. Harbor areas that typically contain high phytoplankton concentrations (or blooms) are outlying areas (Western Long Island Sound and Lower NY Bay/Raritan Bay) and embayments (Flushing Bay and Jamaica Bay). Blooms are cyclic in their intensity and foremost Harbor areas appear highest in early spring and late summer. (Monthly average summer cell counts in 1995 ranged from 5200 to 85,000 cells/ml (O'Shea and Brosnan, 1997)).

Species composition for selected high-chlorophyll sites suggest diatoms *Skeletonema costatum* and *Thalassiosira nordenskioldii* and the green algae *Nannochloris atomus* to be the most abundant species in 1997. This appeared true throughout the Harbor and for sites as diverse as Bergen Basin, Jamaica Bay and Hart Island, Western Long Island Sound. Both of these localities had a winter abundance of diatoms, with green algae becoming more predominant in early summer. Other areas, such as Flushing Bay and the Lower NY Bay appear to be almost exclusively dominated by diatoms. Zooplankton species appear notably scarce throughout the Harbor. Future Harbor Survey efforts will further explore the effective use of plankton assemblages as indicators of water quality.

Bloom Activity

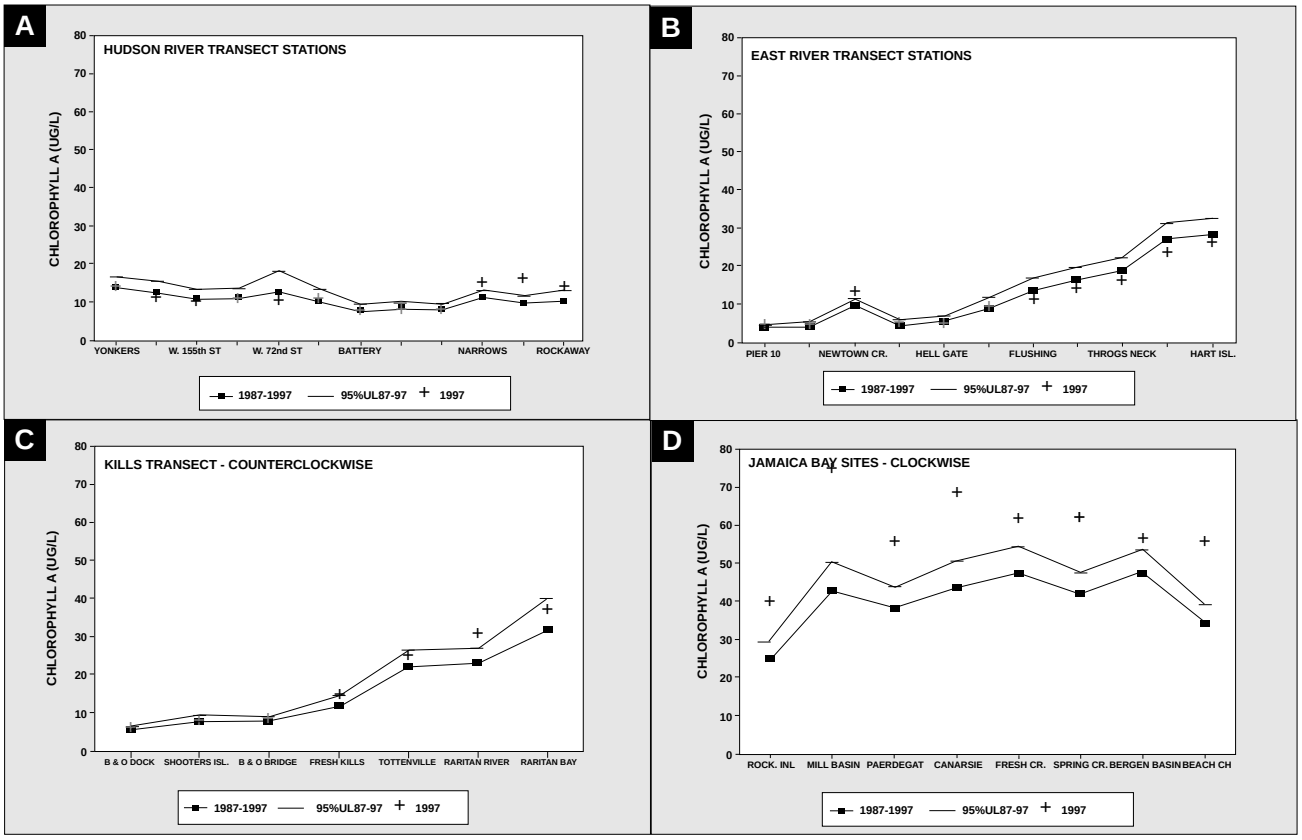
Using Chlorophyll 'a' data as a surrogate for phytoplankton productivity helps determine bloom activity associated with Harbor waters. Average 1997 Summer Chlorophyll 'a' values were compared to an eleven year average (1987-1997) for major Harbor transects (**Figure 20**;a-d). With the exception of Jamaica Bay, 1997 averages closely coincided with eleven-year averages for these transects. This suggests recent phytoplankton activity to be typical of productivity common to these waters. For the Hudson River (**Figure 20**a), phytoplankton activity decreases slightly as one approaches the Battery (upper NY Bay) and then rises again at the Narrows, perhaps due convergence of surrounding waters.

Along the lower East River transect (**20**b) lower chlorophyll 'a' concentrations (indicating less productivity) are apparent south of the Throgs Neck Bridge, with some bloom activity at Newtown Creek. Productivity is seen to increase moving into Western Long Island Sound.

...future Harbor Survey efforts will explore the use of plankton assemblages as indicators of water quality.

FIGURE 20 **CHLOROPHYLL 'a' IN SURFACE WATER TRANSECTS**

Summer Averages, 1987-1997 and 1997



Along the Kills transect (**20**c), moving counterclockwise around Staten Island, average productivity increases sharply through the southern Arthur Kill into Raritan Bay. Areas which exhibit high plankton activity typically exhibit more variable water quality, as algae blooms form and dissipate in response to local environmental conditions.

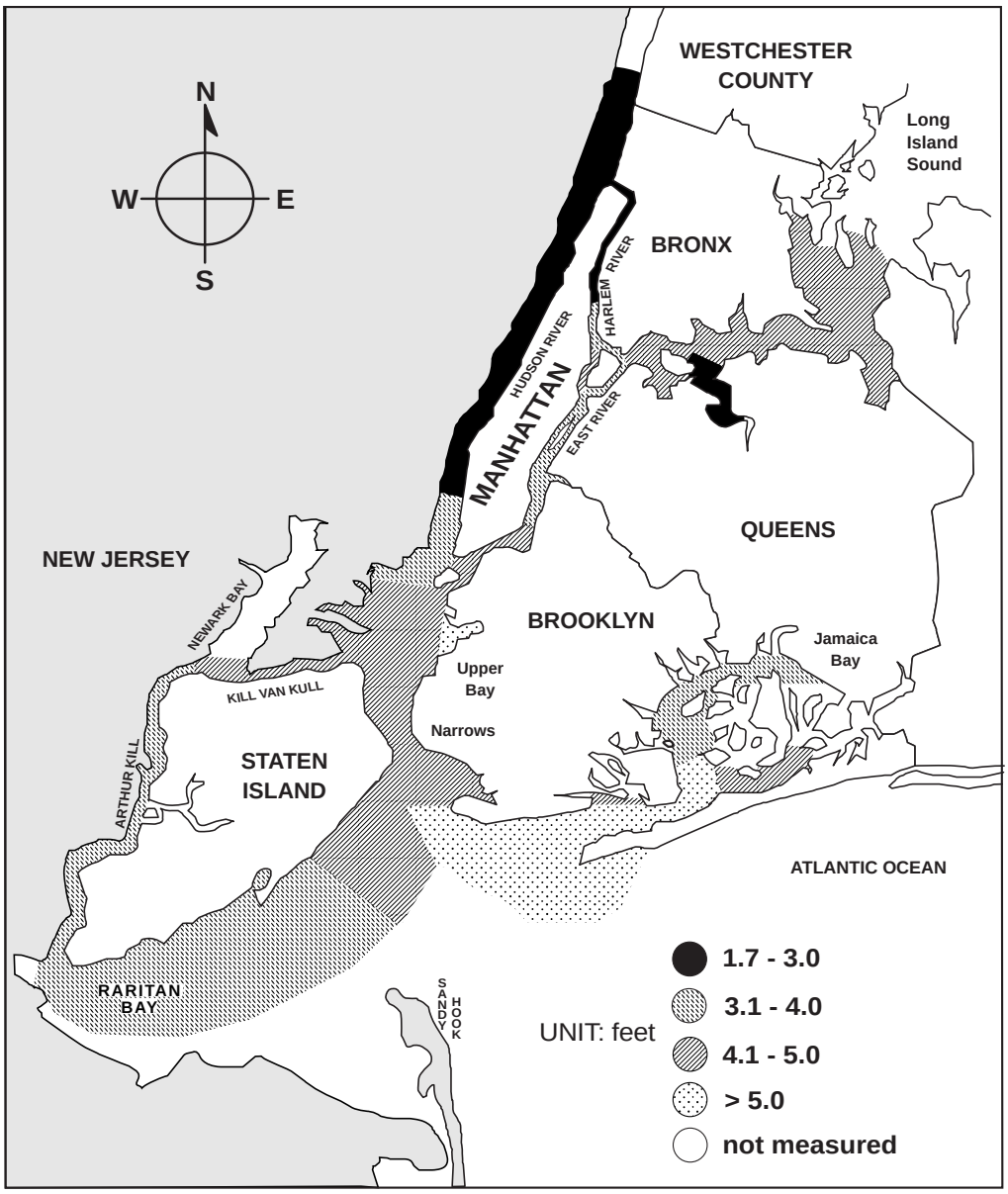
For Jamaica Bay (**20**d) average summer chlorophyll 'a' concentrations for 1997 are seen to be well above the running eleven-year average. This indicates a recent increase in bloom activity in Jamaica Bay. Jamaica Bay waters consistently exhibit the greatest average chlorophyll 'a' concentrations and highest levels of variability (see figures 18 and 19, above). Variability, (expressed as 95% upper confidence level) is a useful indicator of algal growth, because it reflects the degree of planktonic activity at a site. As alluded to before, sites with higher variability reflect a more dynamic bloom and die-off pattern, while low variability indicates a more constant level of productivity.

Secchi Transparency

A Secchi disk is used to estimate the transparency of surface waters. High Secchi transparency is indicative of clear water, with declines in Secchi depth typically produced

FIGURE 21 **SECCHI TRANSPARENCY OF SURFACE WATERS**

Summer Averages, 1997



by high concentrations of suspended solids or plankton blooms. Suspended solids can include: clay and silt from rivers or resuspended material from bottom sediments, and both inorganic and organic particles from point and nonpoint sources. The relative contribution of these factors varies from site to site. Low Secchi readings typically associated with degraded waters, are indicative of light limiting conditions, which in turn affect primary productivity and nutrient cycling.

Highest average summer transparencies (>5.0 ft) were located in portions of Lower NY Bay, Jamaica Bay Inlet, and Gowanus Canal, (**Figure 21**). Lowest secchi transparencies (<3 ft) were observed in the Hudson River and Upper Harlem River, and Flushing Bay.

Trend Analysis

A trend analysis of summer Secchi data from 1985-97 showed declines in transparency throughout the Harbor, with exception of the Kills. This decrease in Secchi transparency appears to follow increases in chlorophyll 'a'; concentrations. Over 70% of stations found to have increases in chlorophyll 'a', show decreases in Secchi transparency for virtually the same time period.

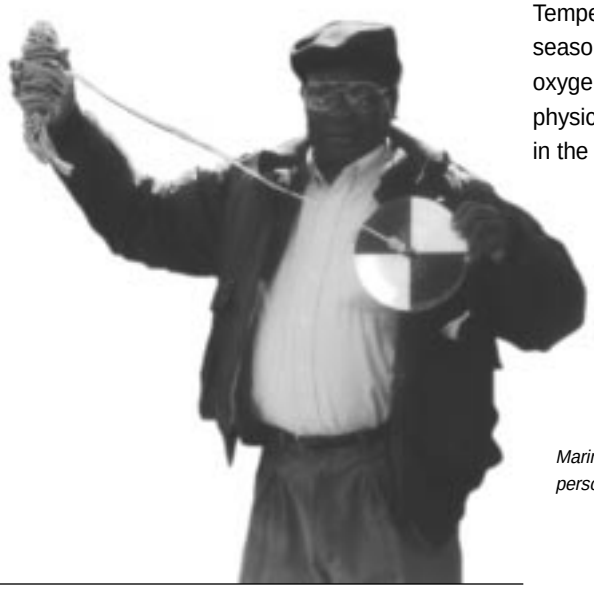
Discussion

In the Harbor, water clarity varies both seasonally and spatially. For example, in spring Secchi readings are likely a result of the suspended solid loads contributed by the spring freshet and snowmelt runoff. The onset of the spring phytoplankton bloom also decreases springtime water clarity. In the fall, algae blooms that are fed by the fall turnover can cause a similar decrease in transparency. Beyond seasonal changes, reduced clarity in the Harbor is also dependent on site differences. While some low transparency areas (Flushing Bay, Jamaica Bay and Raritan Bay) are likely due to high densities of phytoplankton, low Secchi readings in the Hudson are likely associated with higher concentrations of river borne suspended solids, and resuspension of bottom sediments from tidal scouring (O'Shea and Brosnan, 1997). Still other areas, such as the Upper Harlem River, may have poor transparencies due to storm-related runoff or combined sewer overflows.

...Secchi data show declines in transparency throughout the Harbor...

Salinity, Temperature, and Density

Salinity and temperature are important variables in estuarine systems, due to their influence on several key physical and biological processes. Salinity is a measure of the soluble salts present in the water, which fluctuates in response to tides and fresh water discharges. Along with temperature, salinity determines water density, and stratification. Salinity is also important in defining species habitat, as most organisms can only tolerate salinities within a selective range. Temperature also affects the spatial and seasonal distribution of species, and affects oxygen solubility, respiration, and other physical, biological, and chemical processes in the water column and sediment.



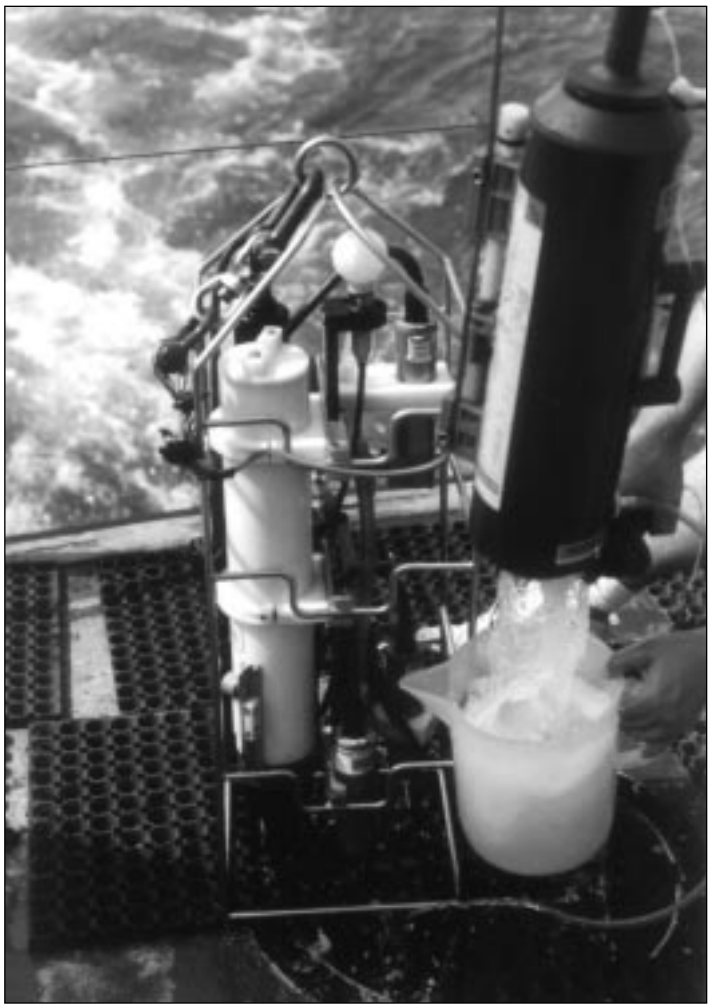
Marine Sciences Section personnel with Secchi disk

Average 1997 summer top and bottom salinity in the Harbor were lowest (<15 practical salinity units (psu)) in the Upper Hudson and Harlem Rivers and highest (>25 psu) in lower NY Bay/Raritan Bay, Jamaica Bay, and Long Island Sound. Surface-to-bottom salinity differences were greatest in the Hudson River and upper NY Bay, with average differences as high as 6.3 psu and 6.6 psu, respectively.

Average 1997 summer water temperatures (from 18 to 23°C) differed by less than 6 degrees throughout the Harbor and average surface-to-bottom differences were less than 2°C for any locality. Lowest summer temperatures were recorded in bottom waters of Western Long Island Sound and deep waters of Lower NY Bay. Highest temperatures were observed in surface waters of Jamaica Bay and the southern Arthur Kill.

Water density (expressed as Sigma-T) was derived from Sea-Bird CTD salinity and temperature readings and used to determine water column stratification (**Figure 22**). Lower salinities and higher temperatures produce less dense waters which overlay more saline, cooler waters. In turn, density stratification tends to inhibit the mixing of surface and bottom waters, contributing to lower dissolved oxygen in bottom waters. High stratification for extended durations can result in degraded bottom waters and reductions in habitat quality.

In the Harbor, stratification is more directly related to salinity than temperature (except for summer conditions in Western Long Island Sound), with greatest stratification occuring in the Hudson River and upper NY Bay (**Figure 22**). Surface-to-bottom water densities are most uniform in the tidal straits of the Harlem and East Rivers, and sections of the Kills, Jamaica Bay, and the Lower NY Bay.

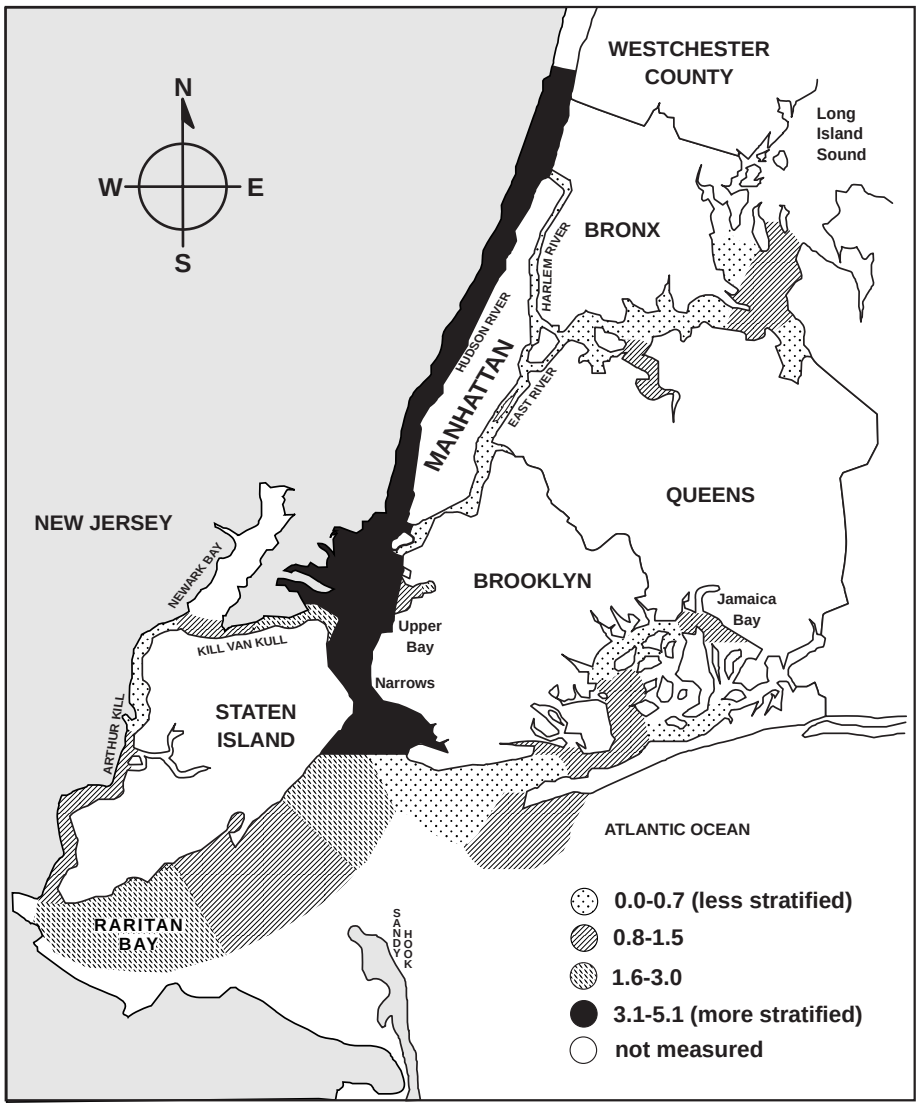


Sea-Bird CTD (conductivity, temperature, density) probe and Go-Flow water sampler

FIGURE 22

WATER COLUMN STRATIFICATION

Summer Averages, 1997



Sigma-T density calculated from raw salinity and temperature at each station.
(Difference between surface and bottom water densities, expressed as Sigma-T)

Trends

Salinity, temperature, and density vertical profiles can be quite variable between sites, and even at a single site over time. While significant long-term temperature and salinity trends have not been determined for most of the Harbor, hydrodynamic modeling has revealed an increase in vertical density stratification for waters of the Western Long Island Sound, beginning in the mid-80s (HydroQual, Inc., 1996a; 1995). This trend towards increased stratification coincides with a period of lower DO in Western Long Island Sound (see *Dissolved Oxygen*, p.39). Analyses indicated a strong correlation (R^2=0.72) between bottom DO and water temperature for the 1981-1995 period (HydroQual, Inc., 1996a).