New York City Department of Environmental Protection

2021 Watershed Water Quality Annual Report

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Environmental Protection

List of Acronyms

AEAP	Esopus Creek above Portal for Shandaken Tunnel
ARC	Ashokan Release Channel
BAP	Biological Assessment Profile
BEPA	Bureau of Environmental Planning and Analysis
BMP	Best Management Practice
BWS	Bureau of Water Supply
CATALUM	Catskill Alum Chamber Sampling Location
CATUEC	Catskill Upper Effluent Chamber
CCCLAB	Catskill Aqueduct Connection Chamber just prior to lower Catskill Aqueduct piped to a sample tap in the UV Plant Laboratory
CFR	Code of Federal Regulations
cfs	cubic feet per second
CROGH	New Croton Reservoir Gatehouse; elevation 213 feet above sea level
CUNY-RF	City University of New York Research Foundation
DBP	Disinfection Byproducts
DBPfp	Disinfection Byproduct formation potential
DEL17	Delaware Aqueduct Shaft Building 17 Sampling Location
DEL18DT	Delaware Aqueduct Shaft Building 18 Sampling Location
DEL19LAB	Shaft 19 Uptake Building piped to a sample tap in the UV Plant Laboratory
DELSFBLAB	South Forebay just prior to DEL19 Downtake piped to a sample tap in the UV Plant Laboratory
DEP	New York City Department of Environmental Protection
DOC	Dissolved Organic Carbon
DRO	Diesel Range Organics
DWG	Dividing Weir Gates
EARCM	Ashokan Reservoir effluent collected at Ashokan Reservoir pump house
EOH	East of Hudson
EWRM	Early Warning Remote Monitoring
FAD	Filtration Avoidance Determination
fDOM	Fluorescent Dissolved Organic Matter
GEFS	Global Ensemble Forecast System
GLEON	Global Lake Ecological Observatory Network
GWLF	Generalized Watershed Loading Function
HEFS	Hydrologic Ensemble Forecast System
HEV	Human Enteric Virus
IAR	Inactivation Ratio
LT2	Long Term 2 Enhanced Surface Water Treatment Rule

µg L^{-1}	microgram per liter
µmhos cm^{-1}	micromhos per centimeter
mg L^{-1}	milligram per liter
MIB	2-methylisoborneol
MPN	Most Probable Number
MST	Microbial Source Tracking
NASEM	National Academies of Sciences, Engineering, and Medicine
ND	Non-detect
nm	Nanometers
NR2	Neversink Reservoir Elevation Tap 2; elevation 1350 feet above sea level
NRT	Near real-time
NTU	Nephelometric Turbidity Units
NWS	National Weather Service
NYC	New York City
NYSDEC	New York State Department of Environmental Conservation
NYSDOH	New York State Department of Health
Obs	Observations
OGP	Operational Guidance Plan
OST	Operational Support Tool
PCN	Pepacton, Cannonsville, Neversink
PR2	East Delaware Intake Chamber Tap 2; 1186 feet above sea level
ROS	Regression on order statistics
RWBT	Rondout-West Branch Tunnel
Shaft 17	Delaware Aqueduct Shaft Building 17
Shaft 18	Delaware Aqueduct Shaft Building 18
SPDES	State Pollutant Discharge Elimination System
SRR2CM	Schoharie Reservoir Release, Shandaken tunnel outlet into Esopus Creek.
SSM	Single sample maximum
STRP	Sediment and Turbidity Reduction Project
SVOC	Semivolatile Organic Compound
SWAT	Soil Water Assessment Tool
SWTR	Surface Water Treatment Rule
TMDL	Total Maximum Daily Load
TNTC	too numerous to count
TP	Total Phosphorus
TSI	Trophic State Index

USEPA	United States Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	United States Geological Survey
UV	ultraviolet
VOC	Volatile Organic Compound
UV_{254}	Absorbance reading at 254 nm
WISKI	Water Information Systems KISTERS
WMP	Waterfowl Management Program
WOH	West of Hudson
WPP	Watershed Protection Programs
WQD	Water Quality Directorate
WQSR	Water Quality Science and Research
WR&R	New York City Watershed Rules and Regulations
WRF	Water Research Foundation
WRRF	Water Resource Recovery Facility
WUCA	Water Utility Climate Alliance
WWQMP	Watershed Water Quality Monitoring Plan
WWQO	Watershed Water Quality Operations
WWTP	Wastewater Treatment Plant

Acknowledgements

This report provides a summary of the scientific work conducted in 2021 to manage the water quality of the New York City water supply and to provide information for regulatory agencies and the public. New York City Department of Environmental Protection (DEP) Commissioner Vincent Sapienza, P.E., provided oversight of the department throughout 2021. Paul Rush, P.E., Deputy Commissioner, and Lori Emery, MPA, Director of Water Quality and Innovation provided direction for the many activities of the Bureau of Water Supply and the Water Quality and Innovation Directorate (WQI).

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Everyone involved in this report takes pride in their work and they are to be commended for their dedication. Notably, the production of this report required the scientific expertise and cooperation of many more staff members than those named above. All deserve special recognition and thanks for their willing participation in the many facets of the work to operate the largest unfiltered water supply in the nation. Although we could not name them all, thanks go to all those who contributed directly and indirectly to this report.

The 2021 Watershed Water Quality Annual Report is dedicated to three members of the Water Quality leadership team who retired during the year. We thank them for their service and dedication to the mission of the Bureau of Water Supply. These individuals were significant contributors to science and research within the watershed and to the production of this annual report over three decades.

Andrew Bader, Chief of Watershed Water Quality Operations

Andy started with DEP as a limnologist at the Grahamsville Laboratory. Before becoming Chief of Watershed Water Quality Operations (WWQO) in 2017, Andy served as the Section Chief of Watershed Field Operations from 2003-2007, and as the Deputy Chief of WWQO for West of Hudson from 2007-2017. In that role, Andy provided oversite for WWQO's East of Hudson, Kingston, and Grahamsville teams, along with Systems Support.

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Lorraine started with DEP in 1990 as the Deputy Chief of Watershed Field Operations. In 2005, she became the Deputy Chief of Drinking Water Quality Control, and then Chief of the Watershed Water Quality Science and Research (WQSR) Division in 2007. In that role, Lorraine provided oversight for water quality science, research, and reporting for the watershed and for the Waterborne Disease Risk Assessment Program.

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Jim started with DEP in 1988 as the Catskill District Limnologist before becoming the Director of the Hydrology Program. Jim finished his DEP career as Deputy Chief of Program Evaluation and Planning in the division of Watershed Water Quality Science and Research. In that role, Jim was a leader in water quality science and research and took primary responsibility for production of the Watershed Water Quality Annual Report.

Executive Summary

Chapter 1 Introduction

This report provides summary information about the watersheds, streams, and reservoirs that are the sources of New York City's drinking water. It is an annual report that provides a detailed description of the City's water resources, their condition during 2021, and compliance with regulatory standards. It is complementary to the New York City 2021 Drinking Water Supply and Quality Report (2021-drinking-water-supply-quality-report.pdf), which is distributed to consumers annually to provide information about the quality of the City's tap water. Thus, the two reports together document water quality from its source to the tap. In 2021, reductions of some components of the Watershed Water Quality Monitoring Plan (DEP 2018) continued due to the COVID-19 pandemic while maintaining the critical components of the plan. The reductions are summarized in Appendix A.

The New York City Water Supply System provides drinking water to almost half the state's population, which includes over 8.5 million people in New York City and 1 million people in upstate counties. The City's water is supplied from a network of 19 reservoirs and three controlled lakes that contain a total storage capacity of approximately 2 billion cubic meters (570 billion gallons). A summary of the number of sites, samples, and analyses that were processed in 2021 by the three upstate laboratories is provided. Grab sampling, robotic monitoring, and an early warning system are all employed. These data are used to guide system operations to provide high quality drinking water to the City.

Chapter 2 Water Quantity

In New York's Climate Division 2, which includes the WOH reservoirs, the 2021 precipitation total was 9.83 inches (250 mm) above the 20th-century mean. In New York's Climate Division 5, which includes the EOH reservoirs, precipitation was 5.87 inches (149 mm) above the 20th-century mean. Most of the excess rainfall occurred during the second half of the year including notable rainfall associated with Tropical Storm Henri (August 22-23) followed by Tropical Storm Ida eight days later. The statewide average temperature for New York State in 2021 was 47.8 degrees Fahrenheit (8.8 degrees Celsius), which was 3.3 degrees Fahrenheit (1.9 degrees Celsius) above the 20th-century mean and the third warmest in the last 127 (1895-2021) years for New York. Usable storage capacity of the water supply was usually at or above normal during the first half of the year and greatly exceeded historic capacity during the second half.

Chapter 3 Water Quality

In 2021, apart from Schoharie and the west basin of Ashokan, turbidity levels in the Catskill/Delaware System reservoirs were close to their median historic levels. Multiple rain events, including two tropical storms, elevated turbidity in Schoharie and Ashokan West reservoirs episodically. Turbidity levels were below historic median concentrations in the East Basin of Ashokan due to dividing weir and release operations. Consequently, low turbidity in inputs from Rondout and Ashokan East reservoirs resulted in low turbidity levels in Kensico. Turbidity in all monitored Croton System reservoirs was close to historic annual median levels.

For streams, Schoharie Creek (at the inflow site S5I) and Esopus Creek (at the inflow site E16I) in the Catskill System exceeded their historical 75th percentiles for turbidity during much of the year due to a December 2020 rain-on-snow event that affected water quality into 2021 and numerous rain events particularly in the second half of the year that caused flow and turbidity spikes. Turbidity was generally low in Delaware System streams, except during a wet period in July and a smaller runoff event in August. Streams in the Croton System were generally well within range of the 10-year median turbidity values, although a few higher values were related to storm events.

In 2021, fecal and total coliforms were very high compared to historic median 75th percentile levels in most of the NYC water supply reservoirs and controlled lakes. These higher values were associated with wet periods and storm events in July and September through November. Relatively low coliform inputs from Ashokan East likely accounts for the typically low fecal coliform levels in Kensico. All terminal reservoir basins remained “non-restricted” for coliform-restricted assessments in 2021. For non-terminal reservoir coliform-restricted evaluations, seven of the 17 reservoirs evaluated had no exceedances of the total coliform standard. Routine stream samples for West of Hudson (WOH) main inflows often exceeded their historical monthly ranges for fecal coliforms in 2021. These exceedances were frequently associated with the high number of rain events in 2021, as well as the rain-on-snow event in December 2020. Fecal coliform results were usually lower or within historical monthly ranges in the East of Hudson (EOH) streams even during the wetter periods and storm events, except for an exceedance at WESTBR7 in late October after a rain event.

In 2021, there were no changes in phosphorus-restricted status as compared to the previous five-year assessment period. Source water reservoirs and potential source water (i.e., terminal) reservoirs that remained restricted were New Croton, Cross River, and Croton Falls. West Branch Reservoir was non-restricted, reflecting the influence of Delaware System water on its water quality status. When comparing total phosphorus (TP) sample results to benchmark values, Cannonsville Reservoir had the highest number of exceedances (42%) in the Delaware System and Ashokan West had the highest number of exceedances (32%) in the Catskill System. Croton System reservoirs New Croton, Cross River, and Croton Falls had high numbers of exceedances of the benchmark value for TP (91%, 90%, and 66%, respectively). Total phosphorus in streams was elevated during storm events when turbidity was also elevated.

Trophic state indices (TSI) are used to describe algal productivity of lakes and reservoirs. In 2021, TSI was close to historic median levels in both Ashokan basins and low in Schoharie Reservoir, where high turbidity limited both light and algal productivity. TSI levels in the Delaware System reservoirs, as well as West Branch and Kensico, were mostly at or below historic median levels and generally correlated with annual median TP concentrations. Neversink was the exception, where slightly higher chlorophyll was observed in June through August and October. TSI trends varied in the Croton System. TSI was higher than historic levels at EOH FAD basins, Boyd Corners and Croton Falls, but was lower at Cross River. Although total and dissolved phosphorus were elevated in Boyd Corners much of the year, TSI was only elevated in July and August.

Evaluation of additional reservoir and stream analytes in 2021 included chloride and other analytes that are compared to benchmark values set in the NYC Watershed Rules and Regulations. Chloride increases have been generally correlated with road density. In the Delaware System, only Cannonsville exceeded both the single sample mean chloride concentration (44% of all samples collected) and the annual mean standard. Pepacton slightly exceeded the annual mean standard of 8.0 mg L^{-1}. In the Croton System, Croton Falls had the highest number of exceedances of the single sample maximum (100%) and annual mean benchmark value. Cross River also exceeded both standards with 78% of samples above the single sample maximum and annual mean of 39.7 mg L^{-1}. All samples collected in New Croton exceeded the single sample maximum and the annual mean was 64.4 mg L^{-1}. West Branch Reservoir exceeded the annual mean benchmark chloride value and 60% of the samples exceeded the single sample maximum. This was a slight increase when compared with the previous year. Kensico Reservoir exceeded the single sample maximum value for 46% of samples and slightly exceeded the annual mean value. The Catskill/Delaware System annual mean benchmark of 10 mg L^{-1} was met or exceeded in 10 of the 24 streams monitored. The Croton System annual mean chloride benchmark of 35 mg L^{-1} was exceeded in 12 of 13 monitored Croton streams. All chloride samples were well below the health secondary standard of 250 mg L^{-1}.

The New York State Department of Environmental Conservation (DEC) and the New York City Department of Environmental Protection (DEP) finalized a Memorandum of Understanding (MOU) in 1997 governing several aspects of enforcement protocols in the New York City water supply watersheds. For the past 25 years, DEP has submitted annual reports to fulfill the requirements for describing the results of the Addendum E analysis along with any other documentation of water quality concerns. New this year, and moving forward, this report will include the information needed to satisfy the requirement of the Addendum E report so that a separate stand-alone annual report is no longer required. In 2021, 525 samples were collected at 75 sites, analyzed, and later compared to water quality guidance values. There were 11 sites at which the mean value contravened the guidance values, and four sites exceeded the spike threshold.

DEP has been monitoring all 19 New York City reservoirs for the presence of zebra mussel (*Dreissena polymorpha*) larvae (veligers), as well as settlement of juvenile zebra mussels. In 2021, sampling locations remained the same as in 2020, with the addition of multi-plate colonization substrates being deployed in Amawalk, Muscoot, and New Croton reservoirs. West of Hudson reservoirs were not monitored in 2020 or 2021. A survey conducted in Amawalk Reservoir in November 2021 revealed the presence of settled adults on naturally occurring substrate near the inflow of the Muscoot River and on the dam face near the spillway. Furthermore, attached adults were found in the release channel below the spillway and within the natural stream channel below the release channel. Data indicated that downstream movement of zebra mussels from Lake Mahopac was dependent on the elevation of the lake and its spill status, i.e., the only time veligers were detected in samples downstream of Lake Mahopac was during or following periods of elevated streamflow

DEP has been performing water quality assessments of watershed streams based on resident benthic macroinvertebrate assemblages since 1994. In 2021, DEP collected samples from 20 stations in 14 streams throughout New York City's watershed. Of the six Croton System sites assessed in 2021, only one was considered moderately impaired. The remaining five sites scored as slightly impaired. Of the seven Catskill System sites assessed in 2021, four were considered slightly impaired with the remaining three considered non-impaired. Of the seven Delaware System sites assessed, four were considered slightly impaired and three sites were assessed as non-impaired.

Routine annual surveillance monitoring for metals, a wide range of semivolatile and volatile organic compounds, and the herbicide glyphosate was performed at several keypoint locations with some reductions in sampling as noted in Appendix A. Most metal sample results were well below state and federal benchmarks. Antimony, arsenic, beryllium, cadmium, chromium, lead, mercury, selenium silver, and thallium were non-detect in all samples. Zinc, mercury, and chromium samples were all below their detection limits. Nickel was detected on one occasion each at CRO1T and CRO1B with concentrations ranging from 1.0 to 1.1 $\mu g\ L^{-1}$. All results were well below the NYSDEC regulation of 100 $\mu g\ L^{-1}$. Additionally, all detected barium, copper, and iron results were well below their respective benchmarks. There were a few detections of barium, copper, and zinc that were well below their respective standards. Standards for manganese and aluminum were occasionally exceeded in 2021. Most of these exceedances occurred well upstream of the NYC distribution system.

There were nine water quality special investigations conducted throughout the system in 2021. Five of these occurred in the Kensico basin and are reported in Chapter 4, and four are reported in Chapter 3. The four covered in this chapter include the completed analysis of a septic-to-sewer conversion study; sampling for taste and odor compounds, with particular focus on New Croton Reservoir; a pilot study of water transfer from the Delaware to the Croton System to improve water quality; and a screening for per- and polyfluoroalkyl substance (PFAS) compounds as part of a larger emerging contaminant project.

Chapter 4 Kensico Reservoir

Kensico Reservoir is the terminal reservoir for the unfiltered Catskill/Delaware water supply. Monitoring of the outflow from Kensico takes place at DEL18DT. The City's high-frequency monitoring ensures that every effort is taken at this location to meet strict requirements for turbidity and fecal coliform concentrations set forth in the federal Surface Water Treatment Rule (SWTR). During 2021, all DEL18DT turbidity results were less than the SWTR 5 NTU limit and only five of 365 DEL18DT fecal coliform results exceeded the SWTR 20 fecal coliforms $100mL^{-1}$ limit, which meant DEP continued to meet the SWTR turbidity and fecal coliform limits. The Waterfowl Management Program continues to be instrumental in keeping coliform bacteria concentrations well below the limits set by the SWTR. Routine turbidity curtain inspections suspended in 2020, due to the COVID-19 pandemic, were not resumed in 2021 to allow Field Operations to focus upon resuming routine monitoring programs. Overall, water quality from Kensico continued to be excellent during 2021.

In addition to DEP's routine monitoring, there were five special investigations/projects conducted in the Kensico watershed in addition to limited video monitoring for bryozoans at the Delaware Shaft 18 sluice gates.

There were three monitored storm event special investigations monitored within the Kensico watershed this year: 1) Tropical Storm Henri beginning August 22; 2) Tropical Storm Ida beginning September1; and 3) a storm event beginning October 26. Each of these storm events produced over 4 inches of precipitation. Throughout the time of these three storm events, turbidity did not exceed the 5 NTU SWTR turbidity limit at DEL18DT. Additionally, the 20 fecal coliform $100mL^{-1}$ limit was exceeded for only four samples during Tropical Storm Ida and once during the October 26 storm event. The six-month average of the percent exceeding 20 fecal coliform $100mL^{-1}$ was approximately 2 percent after Tropical Storm Ida and 3 percent from the October 26 storm event through the end of 2021, well below the SWTR 10 percent limit.

The remaining special investigations/projects were Kensico shoreline stabilization, a potential septic discharge within the Whippoorwill Creek watershed. The second phase of the Kensico shoreline stabilization project to mitigate turbidity issues during periods of northeast winds began in 2020 and continued through 2021 along the shoreline south of the Delaware Shaft 18 facility. Routine sampling and continuous monitoring buoys were utilized to monitor for contraventions of the SWTR turbidity limit at DEL18DT. There were no contraventions during

2021 and the project is expected to be completed summer 2022. A potential septic discharge in the Whippoorwill watershed was investigated because of elevated fecal coliform and microbial source tracking (MST) results. Four property owners gave permission for dye testing and results indicated system failures; three of the systems were repaired. At least eight other properties are suspected of septic system failure, but those property owners denied permission for dye testing.

During 2021, Water Quality and Water Treatment Operations continued to collaborate with Water Quality and Innovation (WQI) to modify flow through the sluicegates at the outflow from Kensico Reservoir to control bryozoan growth. Video surveys conducted in September confirmed the success of the collaboration, demonstrating minimal growth due to reduced flow, and no occlusion downstream was reported.

Chapter 5 Pathogen Monitoring and Research

DEP collected 423 samples for protozoan analysis and 52 samples for *Cryptosporidium* infectivity testing in 2021. Most 2021 samples were collected at Kensico and New Croton reservoir outflows (34%), streams (27%), and the outflows of the CDUV plant and Hillview Reservoir (25%). Additional samples were collected at upstate reservoir effluents, and wastewater treatment plants (WWTPs).

For the two-year period from January 1, 2020, to December 31, 2021, DEP Catskill/Delaware source water results continued to be below the (now expired) Long Term 2 Enhanced Surface Water Treatment Rule (LT2) *Cryptosporidium* threshold for additional treatment (0.010 oocysts L^{-1}). The calculation for 2020-2021 was a mean of 0.0014 oocysts L^{-1} at the Delaware outflow – which is similar to the LT2 means of the past few years.

Based on historical data, protozoan concentrations leaving the upstate reservoirs and Kensico Reservoir were generally lower than levels at the stream sites that feed these reservoirs, noting that fewer stream samples were collected in 2021 compared to the past. WWTP sampling resumed September 7, 2021, and none of the 13 samples collected were positive for *Giardia* cysts or *Cryptosporidium* oocysts. As per the Hillview Consent Decree and Judgement, DEP continued weekly protozoan monitoring at the Hillview Reservoir outflow (Site 3) through 2021, with 52 routine samples collected. Of the 52, there were 15 samples positive for *Giardia* (two less detections than 2020) and four samples positive for *Cryptosporidium* (two more than 2020). All 52 Hillview samples tested for infectious *Cryptosporidium* by cell-culture immunofluorescent assay were negative.

Chapter 6 Water Quality Modeling

The staff of the Modeling and Analysis division is involved in the development, testing, validation, and application of climate, watershed/terrestrial, reservoir, and water system operation models. To support this modeling work, the staff compiles, analyzes, and organizes data from a variety of sources. Following testing and validation, models are used to identify the processes that are important to production, fate, and transport of pollutants of concern within the watersheds, reservoirs, and water supply system. The models are applied to evaluate the impacts of climate change, to evaluate components of DEP's watershed protection program, and to provide guidance regarding the operation of the water supply system.

In 2021, DEP completed its first set of nutrient export simulations for West of Hudson reservoirs using Soil and Water Assessment Tool (SWAT-HS). Model performance was good for total nitrogen, nitrate, total phosphorous, and dissolved phosphorus. Nutrient response increased with degree of agriculture use in the watershed, except for Neversink Reservoir. Progress continued in 2021 on the development of a fate and transport model for UV_{254} in reservoirs. DEP developed stream models of UV_{254} in Cannonsville (r2 =0.95) and Neversink (r2=0.75) inflows as a surrogate for disinfection byproduct formation potential. Soil temperature, concentration of total phosphorus in stream flow, and stream flow rate were the best predictors of UV_{254}.

DEP also extended the time-period of validation for simulations of turbidity and water temperature for Schoharie and Ashokan reservoirs. DEP updated previously developed empirical equations for estimating various model inputs and developed some new equations. In addition, bathymetry was updated according to a survey conducted in 2014. The performance of the water temperature and turbidity models were acceptable for operations.

DEP continued the application of OST to guide operations. The 109 OST runs that used W2 water quality simulations were completed from December 24, 2020, through April 14, 2021, to support operational decisions surrounding turbidity issues generated by the Christmas 2020 storm. These runs examined potential impacts of diversion from Pepacton, Cannonsville, and Neversink (PCN) reservoirs on Rondout and Kensico turbidity. Several other operations were examined using the Operational Support Tool (OST), such as Delaware Aqueduct Shaft 4 operations and Ashokan Dividing Weir gate settings.

In 2021, DEP also made several enhancements to OST water quality models, and how DEP visualizes model inputs used in initialization. A Power BI application was created to examine different sources of water quality data used to initialize OST W2 simulations. DEP also expanded the flexibility of assigning water temperature and turbidity values to PCN reservoirs that do not currently have water quality models in OST. To shorten the runtime needed to assess alternative operations, a mode of OST was set up allowing us to run OST using only the W2 model in Kensico.

The National Weather Service (NWS) enhanced their Global Ensemble Forecast System (GEFS) meteorological forecasts and associate HEFS forecast of inflow to the reservoirs. DEP incorporated the new Hydrologic Ensemble Forecast System (HEFS) forecast into OST. Moreover, DEP helped NWS develop their own inflow forecast post-processor (ENSpost) that enhances accuracy of HEFS inflow ensembles and then added this forecast as another option in OST.

In 2021, DEP constructed a new version of VoPro model, updated OST rules to support the operation of pump stations and developed a phone application to report information from OST runs critical to operations during the Rondout-West Branch Tunnel (RWBT) outage. The Croton VoPro tool functions using the same forecasts, equations, etc. as our OST model and is much like a version of VoPro on which DEP has previously reported. This new VoPro is different from our original VoPro by focusing on operation of reservoirs in the Croton system. VoPro provides instantaneous feedback and assessment of short-term operations.

Progress continued in 2021 on the climate change indicators work, with an increase of airport weather stations examined and an automated generation of climate change indicator maps. The expanded list of weather stations will allow us to compare trends over space and add confidence in observed trends.

In 2021, DEP constructed an automated process for downloading NWS GEFS ensemble meteorological forecasts and running the forecasts through GWLF hydrological model. Once the forecasts have been tested, DEP will add them as another option in OST and VoPro.

The modeling group published three papers in peer-reviewed journals in 2021 and gave four presentations at professional conferences. Moreover, the CUNY sub-contract with the University of Massachusetts resulted in a master's thesis by one of Dr. David Reckhow's students.

Chapter 7 Further Research

BWS remains at the forefront of the industry through a complimentary array of programs: research undertaken within the bureau, participation in The Water Research Foundation (WRF) research, interactions with national and international groups and universities such as the Water Utility Climate Alliance (WUCA), the Global Lake Ecological Observation Network (GLEON), Cardiff University in Wales, and Virginia Tech. In 2021, internal research initiatives included data modernization, a taste and odor working group, salinity task force, and a monthly training for R statistical software to conduct statistical analysis and perform data visualizations. In 2021, research efforts on taste and odor expanded by including an international partnership with Cardiff University and a workshop hosted by WRF.

Emerging and ongoing research is disseminated throughout the bureau in several ways. BWS developed a Research Agenda to align its research with operational and regulatory priorities. In 2020, BWS created the Research Advisory Council (RAC) to establish and manage a research process and act as a forum to communicate and support research initiatives and has continued to expand on those efforts in 2021. In addition, BWS holds an annual internal conference, inviting staff to present on critical research underway within the bureau. In 2021, the conference theme was Integration: Past, Present and Future, and 173 BWS staff participated in the two-day conference. In addition to the annual conference, BWS also highlights ongoing research or related activities with monthly "Thirsty Thursday" webinars. In 2021, 526 staff participated in eight webinars.

1. Introduction

1.1 Water Quality Monitoring in the Watershed

This report provides an overview of the watersheds, streams, and reservoirs that are the sources of New York City's drinking water. It is an annual report that provides the public, regulators, and other stakeholders with a detailed description of the City's water resources, their condition during 2021, and compliance with regulatory standards. It also provides an overview of operations and the use of field, laboratory, robotic, and continuous water quality monitoring data and models for the management of the water supply. This summary is complementary to the New York City 2021 Drinking Water Supply and Quality Report (available at: https://www1.nyc.gov/assets/dep/downloads/pdf/water/drinking-water/drinking-water-supply-quality-report/2021-drinking-water-supply-quality-report.pdf), which is distributed to consumers annually to provide information about the quality of the City's tap water. These two reports together document water quality from its source to the tap.

The New York City Water Supply System (Figure 1.1) provides drinking water to almost half the state's population, which includes over 8.5 million people in New York City and 1 million people in upstate counties, plus millions of commuters and tourists. New York City's Catskill/Delaware System is one of the largest unfiltered surface water supplies in the world. The City's water is supplied from a network of 19 reservoirs and three controlled lakes that contain a total storage capacity of approximately 2 billion cubic meters (570 billion gallons). The total watershed area for the system is approximately 5,100 square kilometers (1,972 square miles), extending over 200 kilometers (125 miles) north and west of New York City. This resource is essential for the health and well-being of millions and must be monitored, managed,

Figure 1.1 New York City Water Supply System.

and protected for the future. The mission of the Bureau of Water Supply (BWS) is to deliver a reliable and sufficient quantity of high-quality drinking water to protect public health and the quality of life for the City of New York. To gather and process the information needed to meet these goals, there is an ongoing program of water quality monitoring and modeling. Monitoring of the watershed is accomplished by the Directorate of Water Quality & Innovation's (WQI) Division of Watershed Water Quality Operations based primarily at three upstate New York locations: Grahamsville, Kingston, and Hawthorne. Much of the information generated by field, laboratory, automated monitoring, and data analysis activities are presented here to provide an overview of watershed water quality in 2021, and to show how high-quality source water is reliably maintained through constant vigilance and operational changes. In addition to the work of WQI, DEP supplements its capabilities through contracts and interactions with other organizations (see Chapter 7 Innovation and Research).

1.1.1 Grab Sample Monitoring

Water quality of the reservoirs, streams, and aqueduct keypoints is monitored throughout the watershed to meet several objectives including regulatory compliance, water supply operations, and to demonstrate the effectiveness of watershed protection measures. The Watershed Water Quality Monitoring Plan (WWQMP; DEP 2018) is DEP's comprehensive plan that describes why, what, when, and where water quality samples are taken throughout the watershed. The sampling effort is continuously evaluated and tailored to meet specific DEP objectives. In 2021, DEP collected 13,756 samples from 308 watershed locations and performed nearly 16,515 analyses to support various water quality objectives.

In 2021 BWS continued to reduce some components of the WWQMP (DEP 2018) due to the COVID-19 pandemic. These reductions were proposed by DEP and approved by the NYSDOH. As restrictions of the COVID-19 pandemic were lifted, a phased reintegration plan was developed in accordance with monitoring priorities. Appendix A outlines the dates and actions taken to resume priority sampling objectives of the WWQMP. The sampling reductions documented here will be reflected throughout the report where data frequency may be different from previous years and will not be further highlighted as COVID-19 reduced sampling.

1.1.2 Robotic Monitoring (RoboMon) Network

DEP's Robotic Monitoring (RoboMon) network provides high frequency, near real-time (NRT) data that are essential for guiding water supply operations and supporting water quality modeling. The data are of particular importance when water quality conditions are changing rapidly, and operational responses may be required. In addition to water quality surveillance, these data are used to run the Operations Support Tool (OST), and reservoir and watershed models. The data generated by the RoboMon network have proven to be invaluable for the protection of the water supply (particularly during storm events), during water quality special investigations, and during the construction phase of water supply infrastructure projects that can potentially affect water quality. In 2021, over 2.9 million measurements were recorded from 30 sites (23 buoys and 7 stream sites). These automated water quality monitoring systems have become critical in managing the day-to-day operation of the water supply as we strive to reliably deliver the highest quality drinking water. The sites and associated parameters are included in Appendix B.

Except for the intake site near Delaware Shaft 18 at Kensico (Site 2BRK), DEPs robotic monitoring buoys are removed from the reservoirs before ice over. Because of the critical nature of monitoring turbidity at Ashokan Reservoir, DEP deploys two under-ice buoys on Ashokan. The units are positioned near the East and West Basin gatehouses which help guide operational decisions throughout the winter months. These buoys are typically installed in December and removed in April when the routine profiling buoys can be redeployed.

Changes in the robotic monitoring program during 2021 included adding a fixed depth buoy to monitor turbidity in the vicinity of the Rondout Effluent Chamber during installation of the new siphons that will control reservoir level during the Rondout-West Branch tunnel shutdown. Also, an additional under ice monitoring buoy was deployed on Rondout for winter 2021.

1.1.3 Early Warning Remote Monitoring

The Early Warning Remote Monitoring (EWRM) team continued to operate a network of real-time, continuous, water quality monitoring stations at critical aqueduct monitoring locations. Instrumentation and sensors vary by site and are outlined in Appendix C. The data generated by this program are critical for the operation of the water supply, for fluoride residual monitoring, State Pollutant Discharge Elimination System (SPDES) monitoring, and for regulatory compliance including calculation of the inactivation ratio (IAR) for pathogens and viruses. Data from reservoir effluent chambers and gatehouses are also critical for making decisions about diversions, releases, and treatment operations. In addition to the instrumentation and parameters listed in Appendix C, the ToxProtect 64 fish biomonitoring systems were operated at DEL18DT and CROGH sites in 2021 to provide rapid detection of contaminants that may not be detected by standard instrumentation (Figure 1.2).

Figure 1.2 Fish biomonitoring station.

1.2 Tools for Optimizing Water Quality

1.2.1 Bureau of Water Supply Operational Reporting and Dashboards

WQI Data and Technology Operations (DTO) staff commenced a collaborative project with DEP's Bureau of Information Technology (BIT), BWS Source Water Operations (SWO), Water Treatment Operations (WTO), and Water Innovation & Research (WIR) staff to develop a modern cloud-based data warehouse that will support consolidation of a variety of data-driven dashboards and reports using Microsoft's enterprise business intelligence package called Power BI. The goal of the project is to explore development of a shared data repository that will allow managers and staff to access water quality and operations data from computers and smart phones. In 2021, BWS staff began planning, design, and development of a prototype utilizing the high-frequency WQI Early Warning and Remote Monitoring (EWRM) data. BWS and BIT staff were successful in a proof-of-concept which enabled near real-time access by streaming these sensor-derived data to Power BI on web and mobile devices with the Power BI app installed

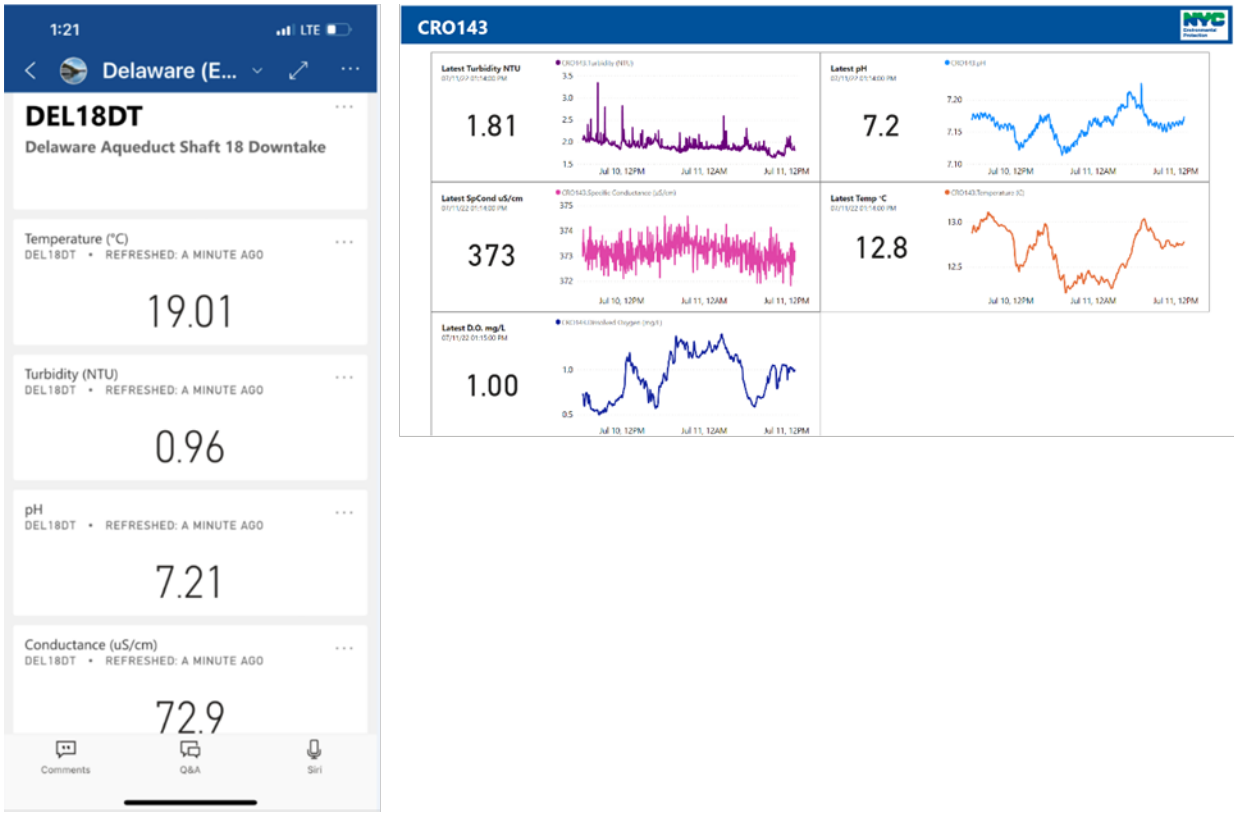


Figure 1.3 Near real-time data access prototype. The screen capture on the left shows mobile device appearance for access to near real-time EWRM and trend review using a browser on the right.

With a successful prototype, the project scope was expanded during 2021 to integrate additional critical datasets within the cloud data warehouse and to continue the expansion of dashboards and reporting capabilities within a collaborative environment (Figure 1.3). Datasets planned for integration include additional sensor data derived from stream and reservoir monitoring systems (Robomon), laboratory grab sample results, reservoir operations datasets, and delivery and treatment advisories, as well as treatment plant operational datasets. The continued expansion of these additional datasets is intended to enhance DEP's ability to make swift operational changes during storms and other water quality events. Additional benefits that are important to consider include the ability to easily adopt artificial intelligence (AI) and machine learning (ML) models and services that may assist or augment current BWS modeling efforts.

1.2.2 Heat Map Visualizations

WQI staff have been using R programming tools to expand the visualization or leverage the large amounts of data collected from robotic monitoring buoys. Typically, data from the various profiling buoys are viewable via a web browser application (Figure 1.4). However, the end user is only able to see one profile at a time, which could limit their interpretation of the data.

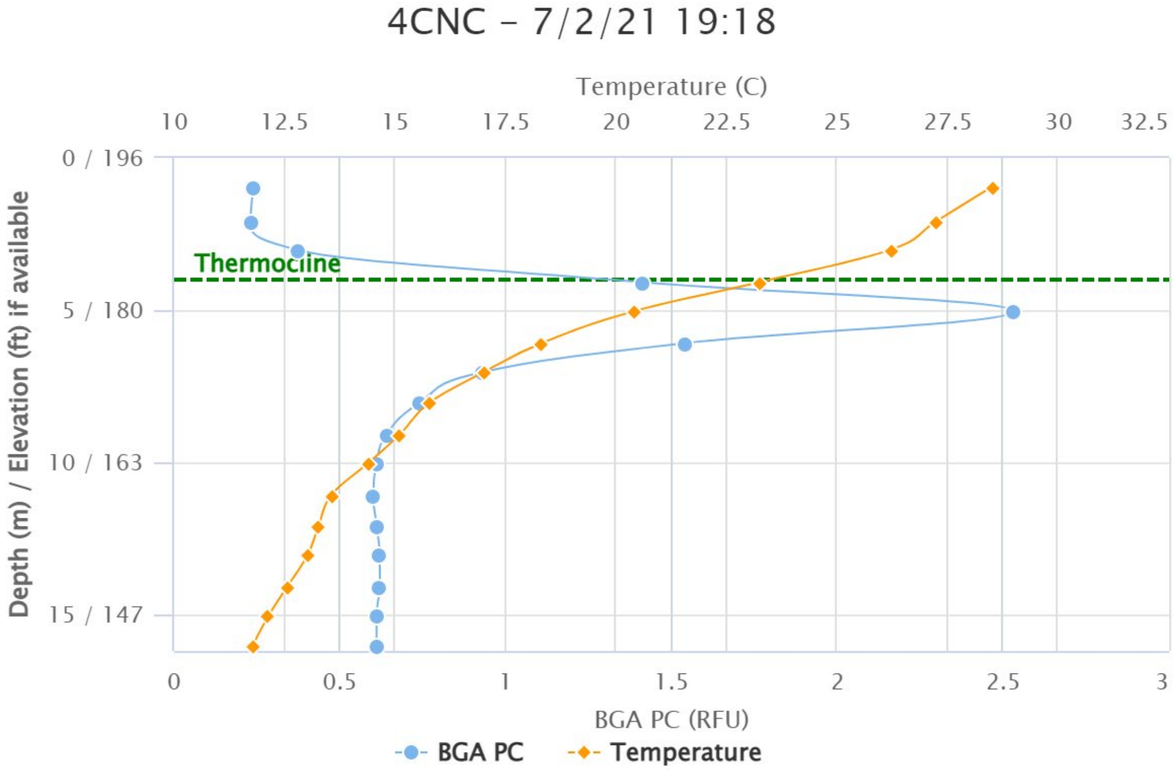


Figure 1.4 Profiling buoy data visualization

While the individual profile charts are useful to end users, it is beneficial to view the profile data over the course of time or the entire deployment season. These combined profile charts, or heat maps, provide additional perspectives on the water quality data captured throughout the year. Thanks to these heat maps, end users can more easily see water quality trends developing to inform operation of the system. These heat maps have also become useful after water quality events to help assist in determining the extent and/or cause of events, as can be seen in the heat map below where the effects of the remnants of tropical storms Henri and Ida disrupted blue green algae activity in New Croton Reservoir (Figure 1.5). Heat maps can be configured for any of the water quality parameter sensors installed on a profiling buoy, easily generated via R programming scripts, and readily distributed to assist with operations.

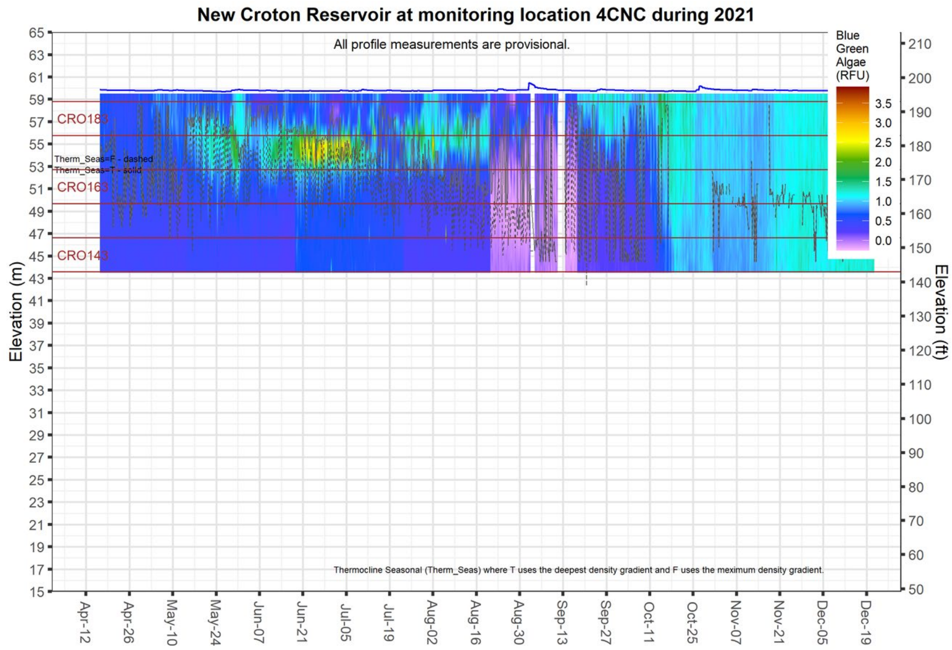


Figure 1.5 Heat map of blue-green algae (BGA) data.

1.2.3 Water Quality Index

In 2021, WQI, WTO, and SWO staff continued to utilize the Water Quality Index to assist in routine operations to provide the best quality water to Kensico Reservoir, which then flows into the distribution system (Figure 1.6).

Water Quality Index for 05/18/22

Input Data

	Turbidity (NTU)		F. Coli (/100mL)			UV-254 (abs/cm)		Phyto (ASU/mL)	
	Value	Date	Value	Reported	Date	Value	Date	Value	Date
Neversink	1.4	05/16/22	0.5	<1	05/16/22	0.068	05/16/22	71	05/13/22
Pepacton	0.89	05/18/22	0.5	<1	05/17/22	0.043	05/16/22	190	05/11/22
Cannonsville	3.3	05/16/22	0.5	<1	05/16/22	0.058	05/16/22	31	05/09/22
Rondout	0.90	05/18/22	0.5	<1	05/17/22	0.052	05/16/22	210	05/11/22
Schoharie	12.0	05/17/22	2	E2	05/17/22	0.066	05/16/22	2.5	05/16/22
Ashokan West	4.1	05/16/22	0.5	<1	05/16/22	0.038	05/16/22	250	05/16/22
Ashokan East	1.5	05/16/22	0.5	<1	05/16/22	0.034	05/16/22	530	05/16/22
West Branch	1.0	05/17/22	4	E4	05/17/22	0.055	05/16/22	200	05/16/22
Kensico	0.90	05/17/22	2	E2	05/17/22	0.038	05/16/22	76	05/16/22

Enter analyte importance (as percentage):

Rank %	25%		25%			40%		10%	>>	100%
Limit	1.5		20			0.040		500		

*Calculated Relative Analyte Weight (Analyte/Limit * Rank): (Note - if an analytical result is less than the limit the rank is multiplied by 20% to lower the relative weight.)*

Index

Index	Site	Turbidity	F. Coli	UV-254	Phyto
73	Neversink	4.7	0.1	68.0	0.3
47	Pepacton	3.0	0.1	43.0	0.8
113	Cannonsville	55.0	0.1	58.0	0.1
56	Rondout	3.0	0.1	52.0	0.8
267	Schoharie	200.0	0.5	66.0	0.0
77	Ashokan West	68.3	0.1	7.6	1.0
43	Ashokan East	25.0	0.1	6.8	10.6
60	West Branch	3.3	1.0	55.0	0.8
11	Kensico	3.0	0.5	7.6	0.3

The lower the value of the index the higher the quality

Results Display Notes
Coliform data with ***E*** in the final result, use the number without the E as part of the calculation
Any data with **<** in the final result, show values multiplied by 0.5
Coliform data with **>** in the final result, show values divided by 0.5
Coliform data reported as CONF, were disregarded and the next most recent value was utilized.

Site Data Includes
Neversink (NRR2CM, NR2), Pepacton (PRR2CM, PR2), Cannonsville (WDTOCM, CR2), Rondout (RDRRCM, RR3), Schoharie (SRR2CM), Ashokan East (EM, DW East), Ashokan West (WM, DW West), West Branch (CWB1.5), Kensico (DEL18DT)

Figure 1.6 Water Quality Index for Catskill/Delaware reservoirs.

The calculation built into the index uses the most recent laboratory grab sample data available for turbidity, fecal coliform, UV_{254}, and phytoplankton to calculate an index score for each of the nine reservoirs in the Catskill and Delaware systems. The reservoirs are then ranked in a report according to their index scores. Under normal conditions, the four parameters are equally weighted by the calculation to determine the final index score. However, at managerial discretion, the weighting can be adjusted as water quality concerns change throughout the year. For example, following a storm event, the weighting could be modified to favor turbidity in the calculation. An official Water Quality Index report is issued weekly to those involved in making operational decisions about reservoir diversions.

1.3 Operational Strategies

In 2021, a combination of water quality and infrastructure improvements were driving operational changes at different time periods during the year. In the Catskill System, the elevation and location (East Basin/West Basin) of withdrawal at Ashokan Reservoir can be adjusted as needed throughout the year to divert the best quality water from the reservoir. These changes are also made to meet operational needs (e.g., lowering the West Basin to create a void to accept more runoff during large storm events). At the beginning of the year, the Catskill Aqueduct was shut down for the Catskill Repair and Rehabilitation Project (CAT-RR) until February 8, 2021, when flow was restored with an East Basin draw. At the same time of restart, the Ashokan Reservoir West Basin elevation and turbidity continued to rise throughout February. The dividing weir was opened at this time to prevent excessive West to East Basin spill, which can lead to short-circuiting of turbid water at the East Basin intakes. While less impactful, opening the weir ultimately resulted in increased turbidity in the East Basin. As a result, diversion flow from Ashokan Reservoir was decreased throughout March and April. Water from Ashokan Reservoir was diverted mostly from the East Basin for the remainder of the year, except for a period between mid-June and mid-July. The dividing weir was utilized nearly the entire year to enable the transfer of water from the West to East basin to balance the system. A second Catskill Aqueduct shutdown occurred at the end of the year from October 1, 2021, through mid-December (Figure 1.7).

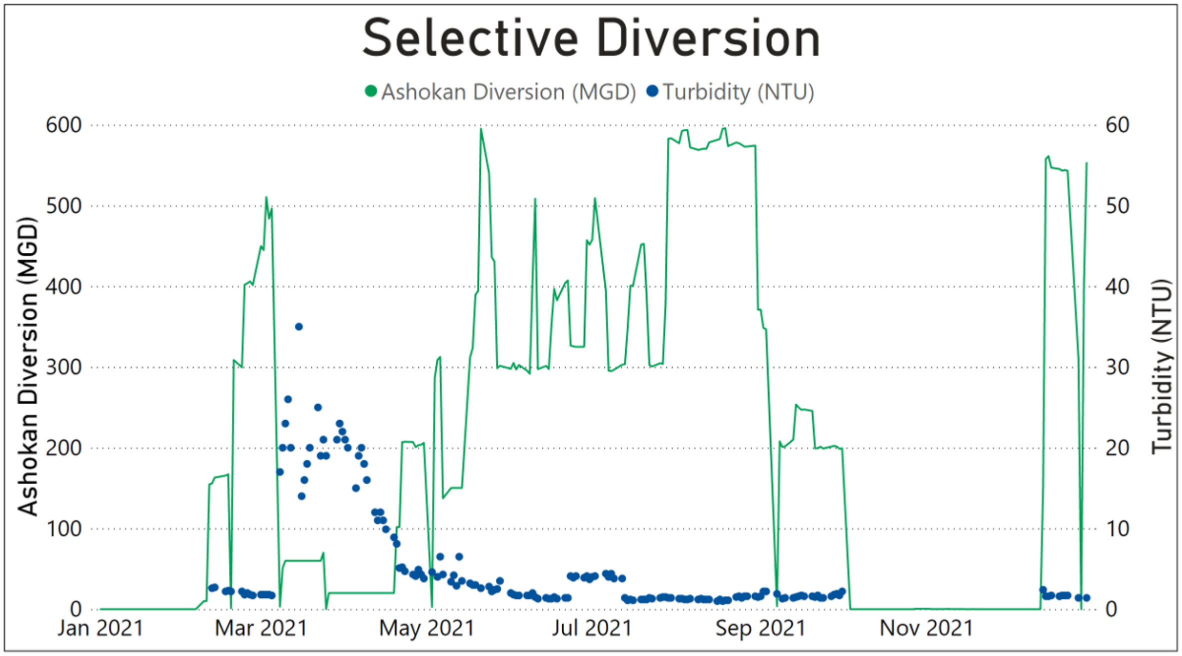


Figure 1.7 Ashokan diversion in relation to turbidity in 2021.

The Delaware System experienced an increase in the disinfection byproduct formation potential (DBPfp) surrogates UV_{254} and DOC due to significant autumn storms that inundated the watershed. In late 2020, the watershed experienced a rain-on-snow event that led to an influx of natural organic matter (NOM). As a result, increased concentrations of UV_{254} and DOC were observed at all four reservoir effluents in the Delaware System throughout spring 2021 and into early summer. During late summer, the watershed was inundated by the remnants of two tropical storms, Henri and Ida, which were separated by only 10 days. The addition of these two storms, along with already elevated levels of DOC and UV_{254}, contributed to the most sustained level of DBPfp surrogates across all Delaware System reservoirs since the aftermaths of tropical storms Irene and Lee in 2011 (Figure 1.8).

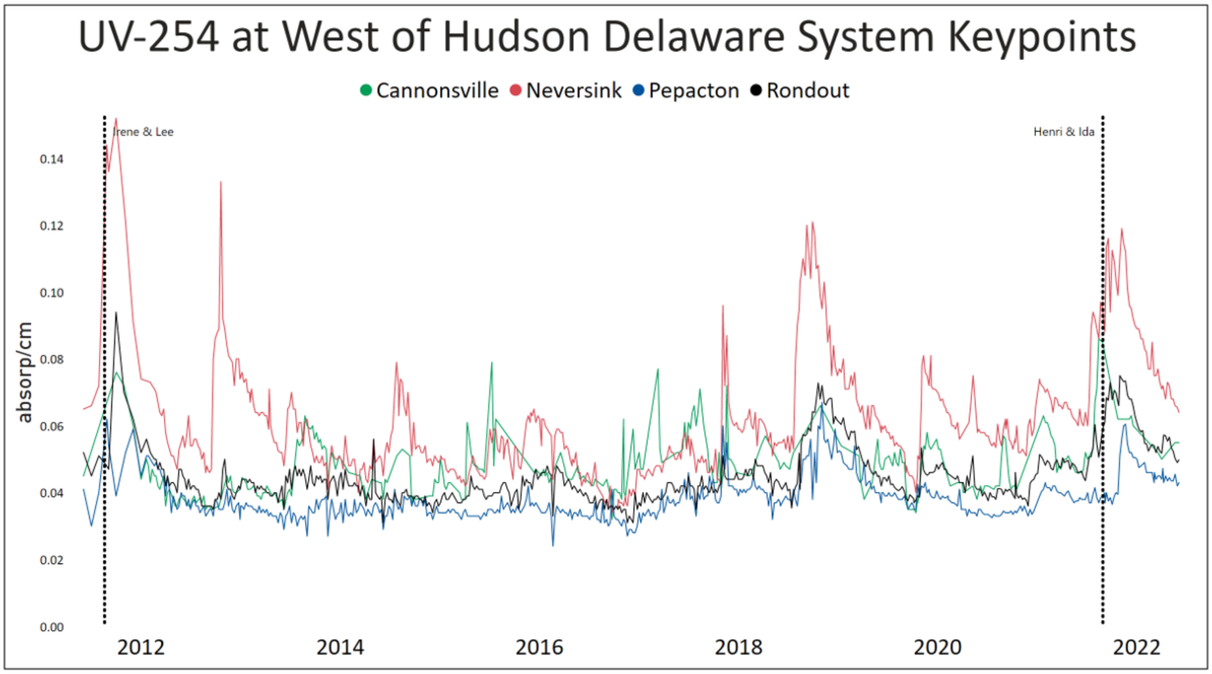


Figure 1.8 UV_{254} at Delaware System Keypoints.

In preparation for an autumn 2022 shutdown of the Rondout to West Branch Tunnel (which was deferred to 2023), work on the Kensico shoreline stabilization project continued in 2021. Because of the proximity of this work to Delaware Shaft 18, and as a precautionary measure, Kensico was operated in float mode for most of the year to minimize the potential for turbidity excursions. This required vigilant monitoring of continuous, robotic, and laboratory water quality data to mitigate the impacts of storm related increases in turbidity, fecal coliforms, and natural organic matter (NOM). For example, DEP limited the amount of water leaving the Kensico basin during tropical storms Henri and Ida. While this was successful in mitigating turbidity impacts from within the Kensico watershed, it resulted in periods of increased coliform counts and higher than normal levels of NOM leaving Kensico for an extended period. Fecal coliform levels peaked at 82 CFU/100 mL on September 2, 2021, with four hits over 20 CFU/100 mL over the next four days. This required additional operational changes, and increased water quality monitoring to ensure compliance with the New York State Sanitary Code. In addition to constraints related to ongoing shoreline work, DEP was unable to divert low-NOM water from Ashokan to Kensico from early October through mid-December due to the shutdown of the Catskill Aqueduct for the CAT-RR project. This eliminated DEP's ability to reduce the DBPfp entering Kensico which ultimately contributed to the fourth quarter 2021 violation of the Stage 2 Disinfection By-Product Rule. When the CAT-RR shutdown ended in mid-December, DEP began to maximize the use of Ashokan water to lower the levels of NOM in Kensico Reservoir.

In summary, the combination of water quality and operational constraint factors contributed to exceedance of the Locational Running Annual Average (LRAA) for haloacetic acids (HAA5) at three distribution system locations in the fourth quarter of 2021, resulting in a violation of the Stage 2 Disinfection By-Products (DBP) rule. The main contributing factors were an increase in natural organic material (NOM) in the water supply due to significant rain events and higher than normal chlorine targets needed to address increased NOM and coliform levels in the distribution system. As operational conditions and infrastructure projects allowed, DEP began addressing the HAA5 levels by lowering chlorine targets and by ensuring that the water delivered to Kensico Reservoir had the lowest possible concentrations of NOM. Specifically, DEP limited diversions from Neversink Reservoir into Rondout Reservoir, and maximized the delivery of Ashokan water to Kensico.

1.3.1 Croton Water Filtration Plant

Water Treatment Operations staff at the Croton Water Filtration Plant (CWFP) provided continual distribution of filtered water throughout 2021. Extensive testing was performed throughout the year to optimize coagulation, increase plant production, and to gain experience utilizing granulated activated carbon (GAC) as the filtration media. To improve water quality and reduce geosmin/2-methylisoborneol (MIB), pilot testing was performed using polyaluminum chloride (PACl) as the primary coagulant and to increase contact time by dosing sodium hypochlorite as a pre-treatment, upstream of the filters.

2. Water Quantity

2.1 Introduction

The New York City Water Supply System is dependent on precipitation (rain and snow) and subsequent runoff to supply the reservoirs. As the water drains from the watershed, it is carried via streams and rivers to the reservoirs. The water is then moved via a series of aqueducts and tunnels to terminal reservoirs before it reaches the distribution system. The hydrologic inputs and outputs affect turbidity, nutrient loads, and water residence times, which are primary factors that influence reservoir water quality.

2.2 2021 Watershed Precipitation

The average precipitation for each watershed was determined from daily readings collected from a network of precipitation gauges located in or near each watershed. The total monthly precipitation is the sum of the daily average precipitation values calculated for each reservoir watershed. The 2021 monthly precipitation total for each watershed is plotted along with the historical monthly average (1991-2020) (Figure 2.1).

For the first half of the year, except for May and in some cases February, the total monthly precipitation (Figure 2.1) shows that precipitation was generally less than the previous 30-year historical average (1991-2020). During the second half, all watersheds, except Cannonsville, had above average precipitation from July through October while drier than average conditions generally prevailed during the last two months of the year. Pepacton was the lone exception where precipitation in November and December was equivalent to historic levels. Several notable rain events affecting large portions of the water supply occurred in 2021. During a four-day period in early July, most watersheds exceeded 2 total inches while half exceeded 3 inches with a high of 4.85 inches recorded at Neversink. During a five-day period beginning on August 18 most watersheds exceeded 3 inches ranging from 3.25 inches at Pepacton to 6.85 inches at Ashokan. The highest one-day totals during this period occurred on August 22-23 (Tropical Storm Henri) at Ashokan (3.54 inches) and at Kensico (4.36 inches). Just over a week later the remnants of Hurricane Ida moved through New York State with Ashokan, Rondout, and Neversink exceeding 3 inches and Croton and Kensico watersheds receiving 5and 5.8 inches, respectively. Additional water supply wide rain events occurred on September 23 when rain amounts ranged from 1.4 to 3.3 inches and from October 24-26 when three-day totals ranged from 2.7 to 5.5 inches. The National Climatic Data Center's (NCDC) climatological rankings (https://www.ncdc.noaa.gov/cag/) were queried to determine the 2021 rankings for New York. Overall total precipitation for New York State in 2021was 46.20 inches (1,173 mm), which was 5.91 inches (150 mm) above the 20th-century mean (1901-2000) and the sixteenth wettest year in the last 127 years (1895-2021). In New York's Climate Division 2, which includes the WOH reservoirs, the 2021 precipitation total was 9.83 inches (250 mm) above the 20th-century mean. In New York's Climate Division 5, which includes the EOH reservoirs, precipitation was 5.87

inches (149 mm) above the 20th-century mean**.** Also, the statewide average temperature for New York State in 2021 was 47.8 degrees Fahrenheit (8.8 degrees Celsius), which was 3.3 degrees Fahrenheit (1.9 degrees Celsius) above the 20th-century mean and the third warmest in the last 127 (1895-2021) years for New York.

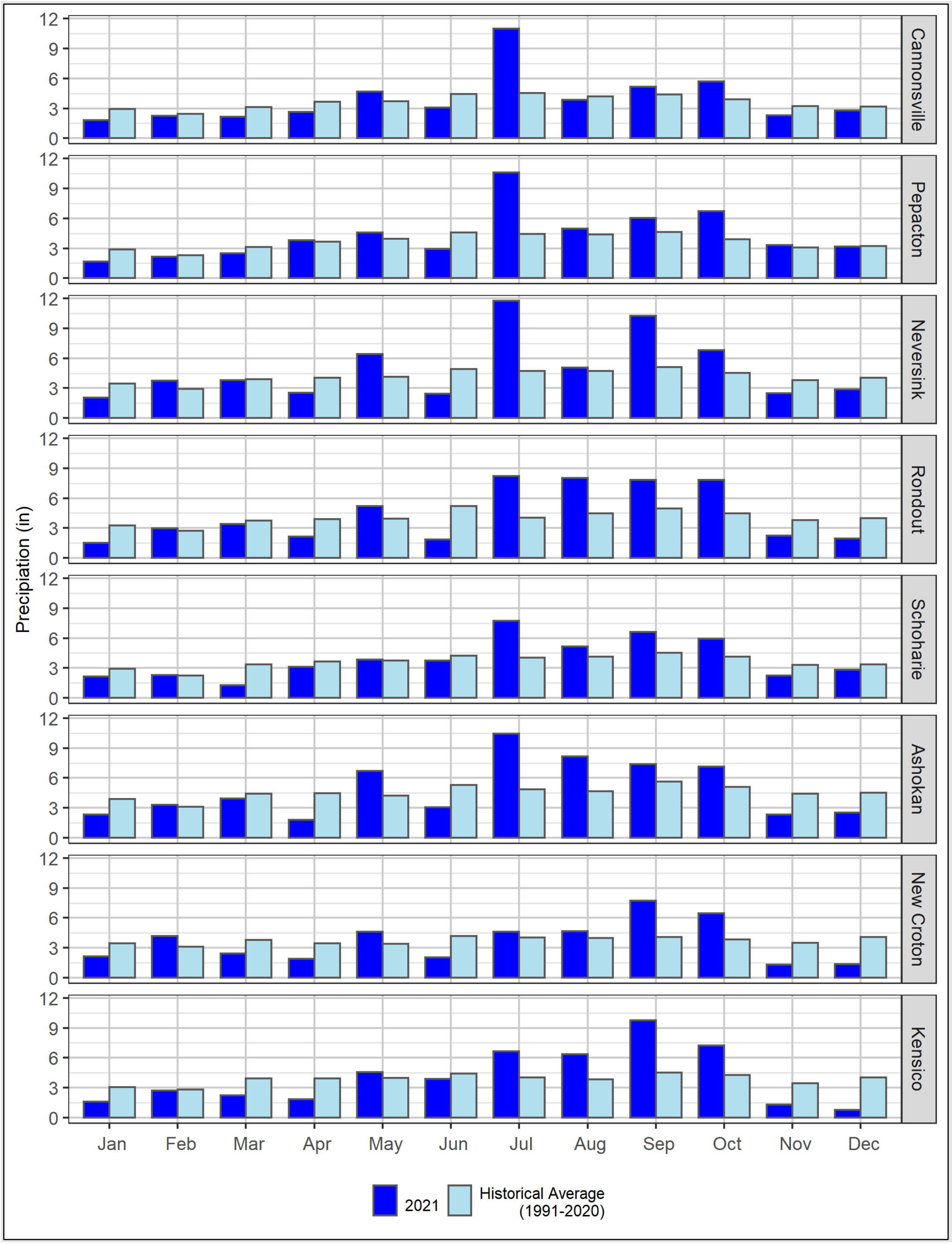


Figure 2.1 Monthly precipitation totals for New York City watersheds, 2021 and historical values (1991-2020).

2.3 2021 Watershed Streamflow

Streamflow in a watershed can be affected by meteorological factors such as type of precipitation (rain, snow, and sleet), intensity, amount, duration, spatial distribution over the drainage basin, direction of storm movement, antecedent conditions, and resulting soil moisture and temperature. Physical characteristics of the watershed also affect streamflow. These include land use, vegetation, soil type, drainage area, basin shape, elevation, slope, topography, watershed orientation, drainage network pattern, and occurrence and area of ponds, lakes, reservoirs, sinks, and other features of the basin. Annual streamflow normalized by watershed area is a useful statistic to compare between watersheds and allows for comparisons of the hydrologic conditions in watersheds of varying sizes. It is calculated by dividing the annual flow volume by the drainage basin area, yielding a depth that would cover the drainage area.

Selected United States Geological Survey (USGS) stations (Figure 2.3) were used to characterize streamflow in the different NYC water supply watersheds (Figure 2.2). The period with a complete record to calculate annual statistics for the WOH USGS stations ranges from 58 years at the Esopus Creek Allaben station to 115 years at the Schoharie Creek Prattsville station. The EOH USGS stations have a 26-year period of record, except for the Wappinger Creek site (93-year period of record). Wappinger Creek is not located in the EOH System but is included here because it is in nearby Dutchess County and its longer period of record is more comparable to those found in the WOH System. Figure 2.2 shows the 2021 monthly streamflow for each of the stations and a boxplot of the historical (1990-2021 for WOH and 1995-2021 for EOH) streamflow for the site and month. The 2021 streamflow values largely reflect the precipitation patterns. Except for March, the monthly streamflow values were mostly at or below the 25th percentiles for the first half of the year. In March, WOH streamflow sites were above the historical median, with most exceeding the 75th percentile while EOH stream flows were between the 25th and 75th percentile. During the second half of the year streamflow at WOH sites often exceeded the 75th percentile from July to October with near median flows in November and median to below 25th percentile flows in December. At EOH sites, stream flows were near their historic medians in July and August, but often exceeded historic 75th percentile flows from September to November ending the year with relatively low flows in December.

Overall, New York State had relatively low computed runoff (streamflow per unit area) for the 2021 water year (October 1, 2020-September 30, 2021), ranking as the 85th highest annual runoff (30.33 percentile) out of the last 121 years) as determined by the USGS (http://waterwatch.usgs.gov/index.php?r=ny&m=statesum). Daily flow/runoff data from October 1-December 31, 2021, are provisional and subject to revision until final approval from the USGS.

Figure 2.3 shows the 2021 mean daily streamflow, along with the minimum, maximum, and median daily streamflow for the previous 30 years, for the same USGS stations used to characterize annual areal-normalized streamflow. While the patterns generally reflect the monthly precipitation patterns, the higher time resolution of these plots are useful in that they identify shorter term wet and dry periods as well as individual storms. At WOH sites, peak flows were observed throughout the year but were mostly confined to the summer/autumn period at the EOH sites. The peak flows often followed dry periods which can be especially detrimental to water quality since contaminants can accumulate and then be quickly transported to streams during the first large rain event.

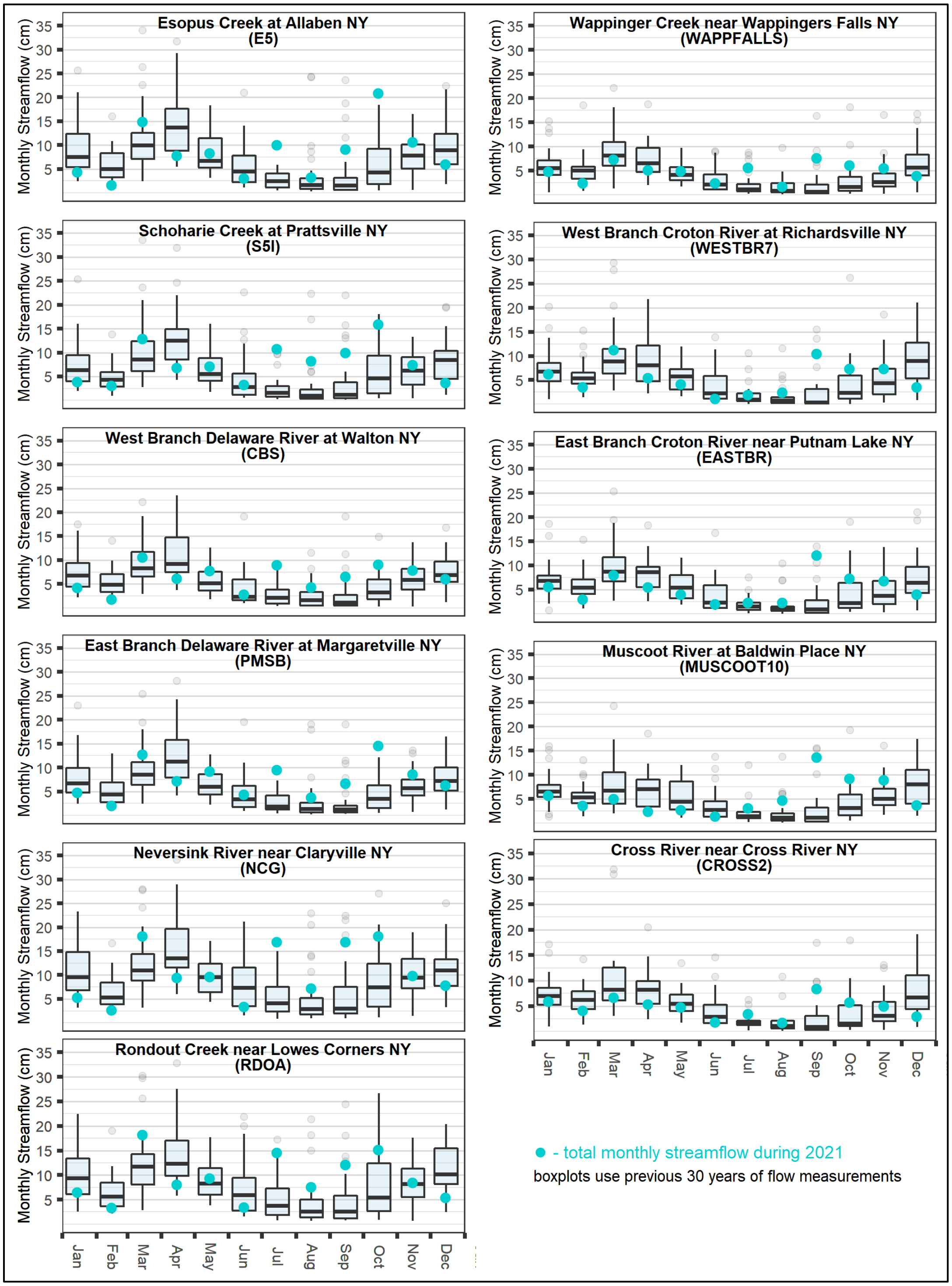


Figure 2.2 Historical areal-normalized streamflow vs. 2021 monthly areal-normalized streamflow with the historical data (1990-2020 for WOH and 1995-2020 for EOH) displayed as boxplots and the values for 2021 displayed as a solid blue dot. The gray circles indicate outliers (see Appendix D for a key to the boxplot).

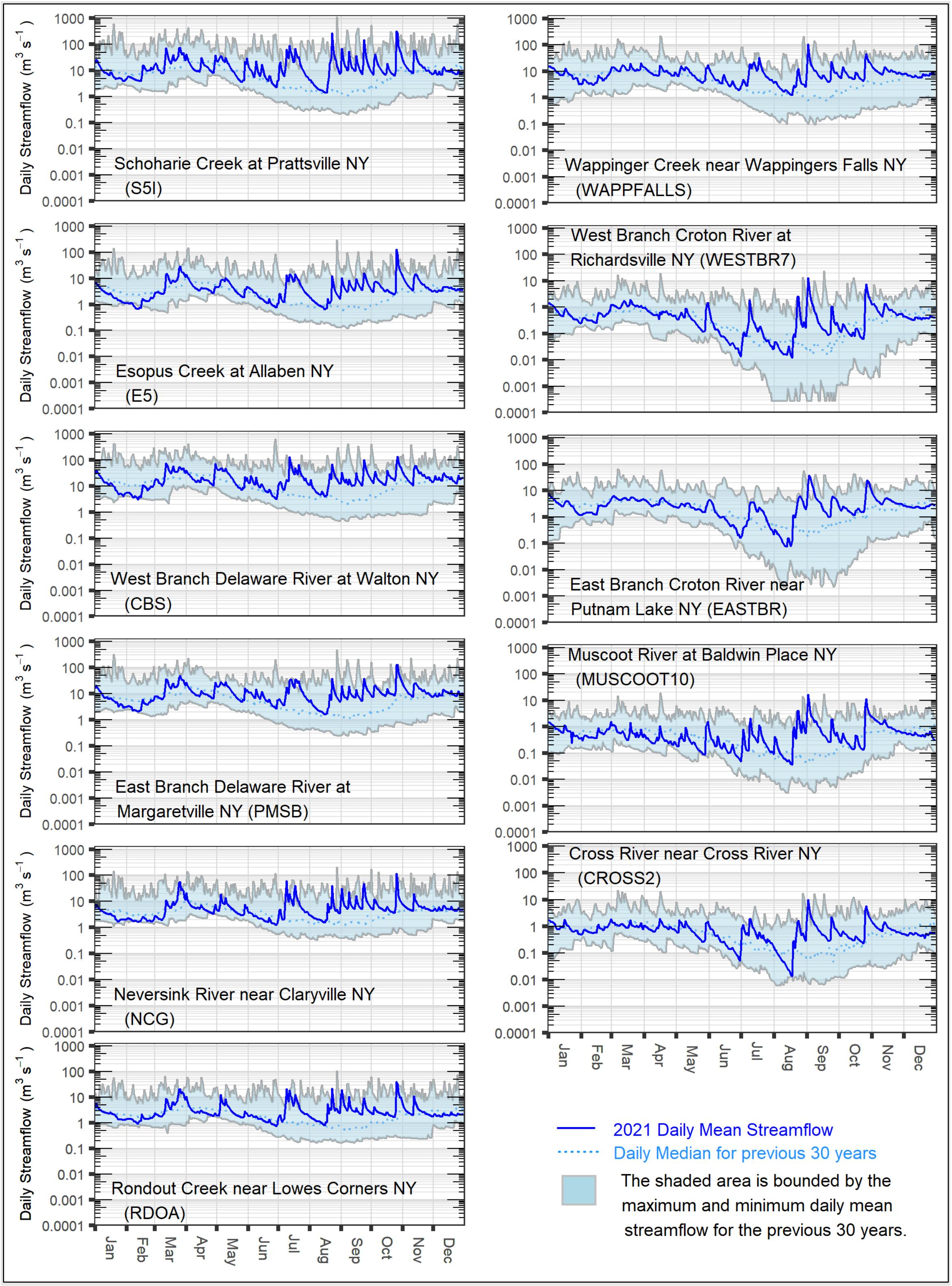


Figure 2.3 Daily mean streamflow for 2021 at selected USGS stations.

2.4 Reservoir Usable Storage Capacity in 2021

Ongoing daily monitoring of reservoir storage allows DEP to compare the system-wide storage in 2021 (including Kensico Reservoir) against average historical values for 1991-2020 for any given day of the year (Figure 2.4). Storage capacity was well above normal at the start of the year due to a rain-on-snow event in late December 2020. From February to the end of May capacity fluctuated between 86% and 98% and was often above normal capacity. Although normal capacity levels were observed in June, a series of rain events, including the remnants of Hurricane Ida on September 1, allowed capacity to greatly exceed normal levels throughout the second half of the year.

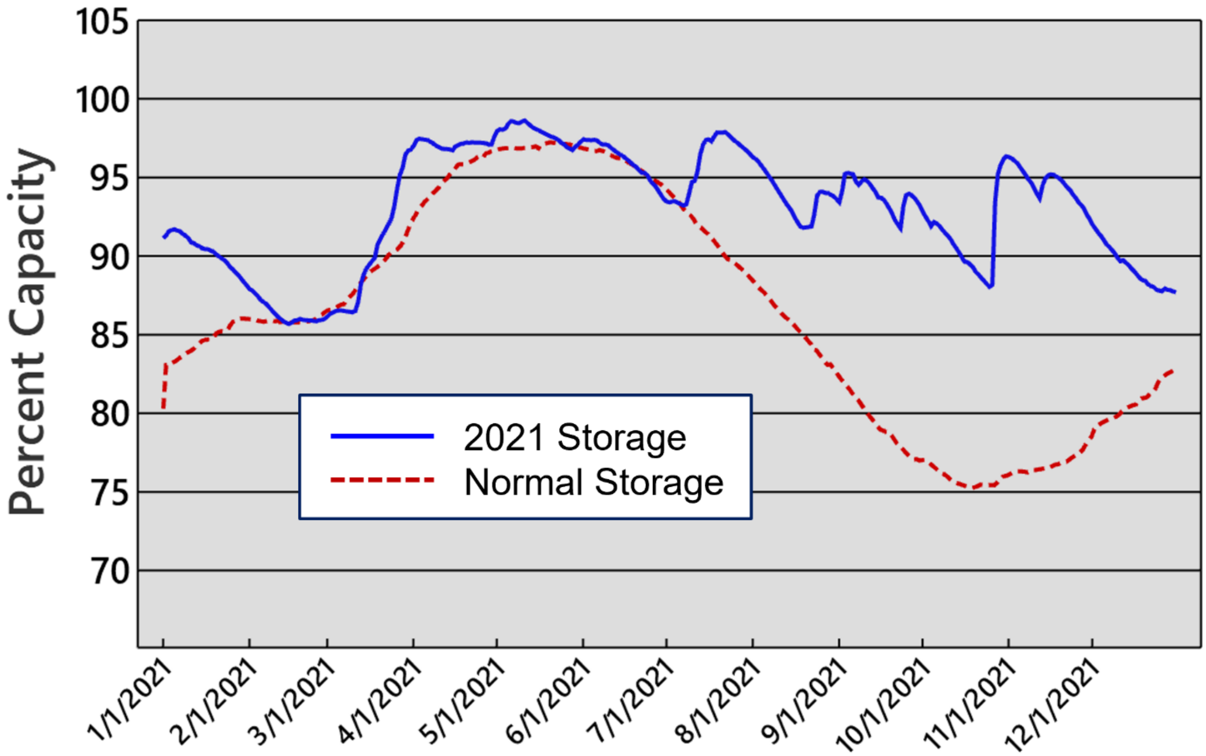


Figure 2.4 System-wide usable storage in 2021 compared to the average historical value (1991-2020). Storage greater than 100% occurs when the water surface elevation is greater than the spillway elevation and reservoirs are spilling.

3. Water Quality

3.1 Monitoring Overview

Water quality samples are collected from designated sites at streams, reservoirs, and aqueduct locations throughout the NYC water supply (Appendix E). Routine stream samples considered in this report are collected on a fixed frequency, typically monthly schedule according to DEP's watershed water quality monitoring plan (DEP 2018). However, due to the 2021 COVID-19 pandemic, stream sample monitoring was reduced, and reductions are noted with reported results and summaries.

Historically, reservoir samples are obtained from multiple sites and multiple depths with routine sampling frequencies of once per month. In previous reports, the sample period is from April through November. In 2021, the typical historic schedule was followed for Catskill/Delaware System reservoirs including West Branch, Kensico and EOH FAD basins (West Branch, Croton Falls, Boyd Corners, and Cross River). COVID-19 related sample reductions only applied to the EOH non-FAD basins (Appendix A).

To ensure an impartial comparison with past data, reservoir historic data were adjusted to reflect the months and sites collected in 2021. If the historic data did not have adequate representation (75% of 2021 sample load) that particular year was set to missing.

Aqueduct keypoint samples are collected year-round at frequencies that vary from daily, weekly, and monthly. Note that although Kensico Reservoir is usually operated as a source water, the reservoir can be bypassed so that any or all the following reservoirs can be operated as source waters: Rondout, Ashokan, and West Branch. When operating as a source, water from these reservoirs is regulated by the SWTR.

3.2 Reservoir Turbidity Patterns in 2021

Turbidity in reservoirs is comprised of both inorganic (e.g., clay, silt) and organic (e.g., plankton) particulates suspended in the water column. Turbidity may be derived from the watershed by erosion (storm runoff in particular) or generated within the reservoir itself (e.g., plankton, sediment resuspension). In general, turbidity levels are highest in the Catskill reservoirs (Schoharie and Ashokan) due to the occurrence of easily erodible lacustrine clay deposits found in these watersheds.

In 2021, apart from Schoharie and the West Basin of Ashokan, turbidity levels in the Catskill/Delaware System reservoirs were close to their median historic levels (Figure 3.1). A key to boxplots is provided in Appendix D. Elevated turbidity at Schoharie was associated with two rain events in mid-July, and Tropical Storms Henri and Ida in early September followed by multiple rain events in September, October, and early November. The West Basin of Ashokan was impacted by these same rain events as well as additional events in late March and in early and late May. In contrast, turbidity levels were below historic median concentrations in the east Basin of Ashokan due to dividing weir and release operations and due to the natural sedimentation of particles as water moves from the West Basin to the east. While 2021 rainfall amounts were well above average in all Catskill/Delaware watersheds, the watersheds of the Delaware System lack the easily erodible clays of the Catskill watersheds. Hence all Delaware System reservoirs including West Branch, which typically receives >95% of its water from the Delaware System, maintained low turbidity levels throughout the year. Low turbidity inputs from Rondout and from the East Basin of Ashokan explain the low turbidity levels observed at Kensico, the terminal reservoir of the Catskill/Delaware System. Turbidity in all monitored Croton System reservoirs was close to their historic annual median levels (Figure 3.1). However, this observation is based on limited sampling that did not capture some of the rain events that occurred during the year.

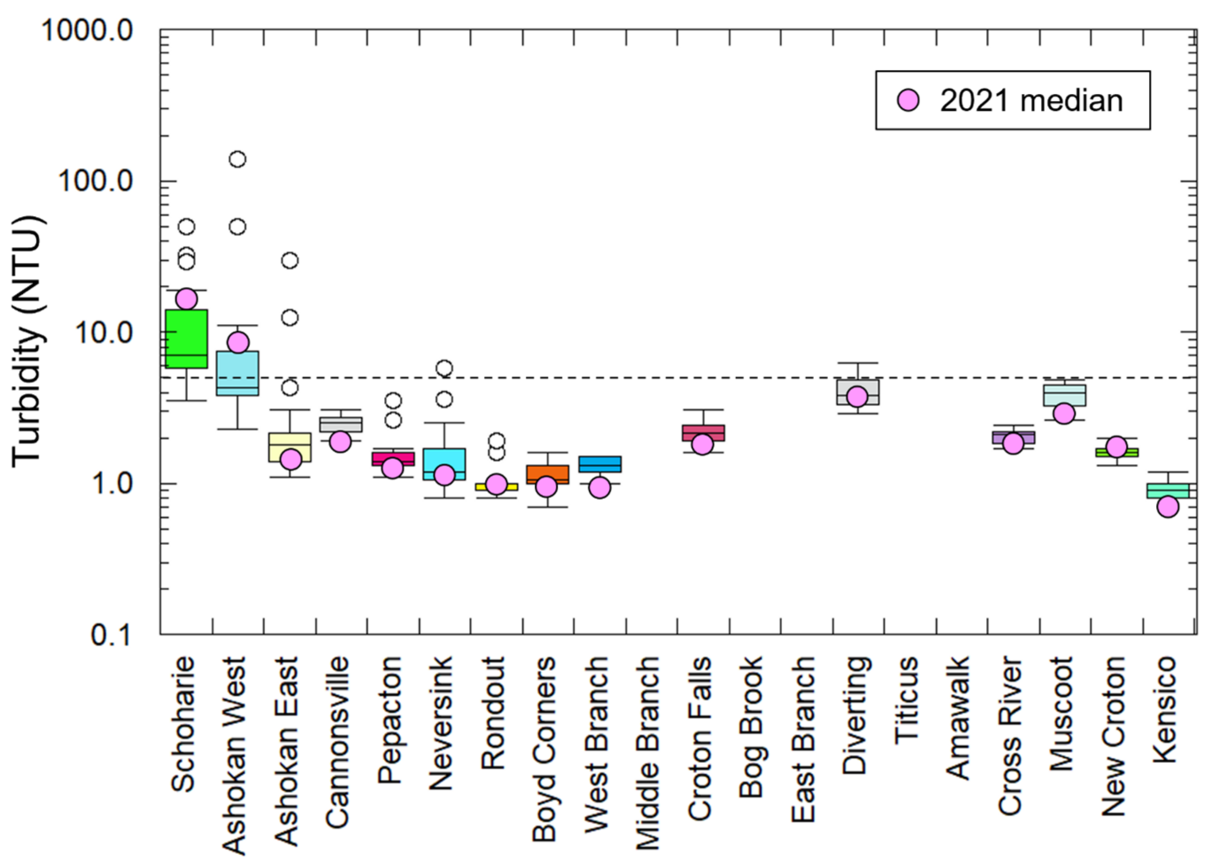


Figure 3.1 Annual median turbidity in NYC water supply reservoirs (2021 vs. 2011-2020), with the 2021 values displayed as a solid dot and outliers as open circles. The dashed line represents the SWTR standard for source water as a reference.

3.3 Coliform-Restricted Basin Assessments in 2021

Coliform bacteria serve as indicators of potential pathogen contamination. To protect the City's water supply, the New York City Watershed Rules and Regulations (WR&R) limit potential sources of coliform bacteria in the watershed area of water bodies classified as restricted. These regulations require the City to perform an annual review of its reservoir basins to make "coliform-restricted" determinations.

Coliform-restricted determinations are governed by four sections of the regulations: Sections 18-48(a)(1), 18-48(c)(1), 18-48(d)(1), and 18-48(d)(2). Section 18-48(c)(1) applies to terminal basins that include Kensico, West Branch, New Croton, Ashokan, and Rondout reservoirs. The coliform-restricted assessments of these basins conform to compliance with federally imposed limits on fecal coliforms collected from waters within 500 feet of the reservoir's aqueduct effluent chamber. Section 18-48(a)(1) applies to non-terminal basins and specifies that coliform-restricted assessments of these basins be based on compliance with New York State ambient water quality standard limits on total coliform bacteria (6 NYCRR Parts 701 and 703).

3.3.1 Terminal Basin Assessments

Table 3.1 provides coliform-restricted assessments for the five terminal reservoir basins. The results are based on 2021 fecal coliform data from a minimum of five samples each week over two consecutive six-month periods. If 10% or more of the coliform samples measured have values >20 fecal coliforms $100 mL^{-1}$ and the source of the coliforms is determined to be anthropogenic (Section 18-48(d)(2)), the basin is classified as a "coliform-restricted" basin. All terminal reservoirs had fecal coliform counts below the 10% threshold and met the criteria for non-restricted basins for both six-month assessment periods in 2021.

Table 3.1 Coliform-restricted basin status as per Section18-48(c)(1) for terminal reservoirs in 2021.

Reservoir basin	Effluent keypoint	2021 assessment
Kensico	DEL18DT	Non-restricted
New Croton	CROGH[1]	Non-restricted
Ashokan	EARCM[2]	Non-restricted
Rondout	RDRRCM[2]	Non-restricted
West Branch	CWB1.5	Non-restricted

[1]Data from the corresponding alternate site used when the sample could not be collected at the primary site listed.
[2]Data from the elevation tap that corresponds to the level of withdrawal are included one day per week, and all other samples are collected at the specified effluent keypoint.

3.3.2 Non-Terminal Basin Assessments

Section 18-48(a)(1) of the WR&R requires that non-terminal basins be assessed according to 6 NYCRR Part 703 for total coliform. These New York State regulations are specific to the class of the reservoir. A minimum of five samples per month are required in each basin to be included in the assessment. If both the median value and more than 20% of the total coliform counts for a given month exceed the values ascribed to the reservoir class, then the results exceed the reservoir class standard, and the non-terminal reservoir is designated as restricted. Table 3.2 provides a summary of the 2021 coliform-restricted calculation results for the non-terminal reservoirs and Appendix F includes the details for coliform monthly medians and the percentage of values exceeding the relevant standard.

In 2021, seven reservoirs had no exceedances for the Part 703 total coliform standard for the 17 reservoirs evaluated (Table 3.2). The highest number of exceedances occurred in Schoharie Reservoir.

Total coliform bacteria originate from a variety of natural and anthropogenic (human-related) sources. However, Section 18-48(d)(1) states the source of the total coliforms must be proven to be anthropogenic before a reservoir can receive coliform-restricted status. No other data were collected that could definitively indicate an anthropogenic source.

Table 3.2 Coliform-restricted calculations for total coliform counts on non-terminal reservoirs in 2021.

Reservoir	**Class[1]**	**Standard: Monthly Median / >20% (Total coliforms 100 mL[1])**	**Months that exceeded the standard /months of data**
Amawalk	A	2400/5000	0/2
Bog Brook	AA	50/240	0/2
Boyd Corners	AA	50/240	3/8
Cross River	A/AA	50/240	1/8
Croton Falls	A/AA	50/240	3/8
Diverting	AA	50/240	3/3
East Branch	AA	50/240	2/2
Kirk Lake	B	2400/5000	0/2
Lake Gilead	A	2400/5000	0/2
Lake Gleneida	AA	50/240	0/1
Middle Branch	A	2400/5000	0/3
Muscoot	A	2400/5000	0/5
Titicus	AA	50/240	1/2
Cannonsville	A/AA	50/240	5/8
Pepacton	A/AA	50/240	4/8
Neversink	AA	50/240	1/8
Schoharie	AA	50/240	6/7

[1] The reservoir class for each water body is set forth in 6 NYCRR Chapter X, Subchapter B. For those reservoirs that have dual designations, the higher standard was applied.

3.4 Reservoir Fecal and Total Coliform Patterns in 2021

Fecal coliform bacteria are more specific than total coliform in that their source is the gut of warm-blooded animals while total coliforms include both fecal coliforms and other coliforms that typically originate in water, soil, and sediments.

Reservoir fecal coliform results are presented in Figure 3.2 and reservoir total coliform results in Figure 3.3. According to the filtration avoidance criteria of the Surface Water Treatment Rule (SWTR), fecal coliform concentrations must be ≤ 20 fecal coliforms $100mL^{-1}$ or total coliform concentrations must be ≤ 100 total coliforms $100mL^{-1}$ in at least 90% of the measurements from the last six months at the sample point immediately prior to the first point of disinfectant application. While this criterion does not apply to other sampling locations, lines at 20 fecal coliforms $100mL^{-1}$ and 100 total coliforms $100mL^{-1}$ are provided on the plots in this section as a point of reference. The centerline in the boxplot represents the median of the 75th

percentile values rather than the 50th percentile or median of annual values. If a calculated annual 75th percentile results in a censored value or zero, it was estimated using the robust regression on statistics method (ROS) of Helsel and Cohn (1988).

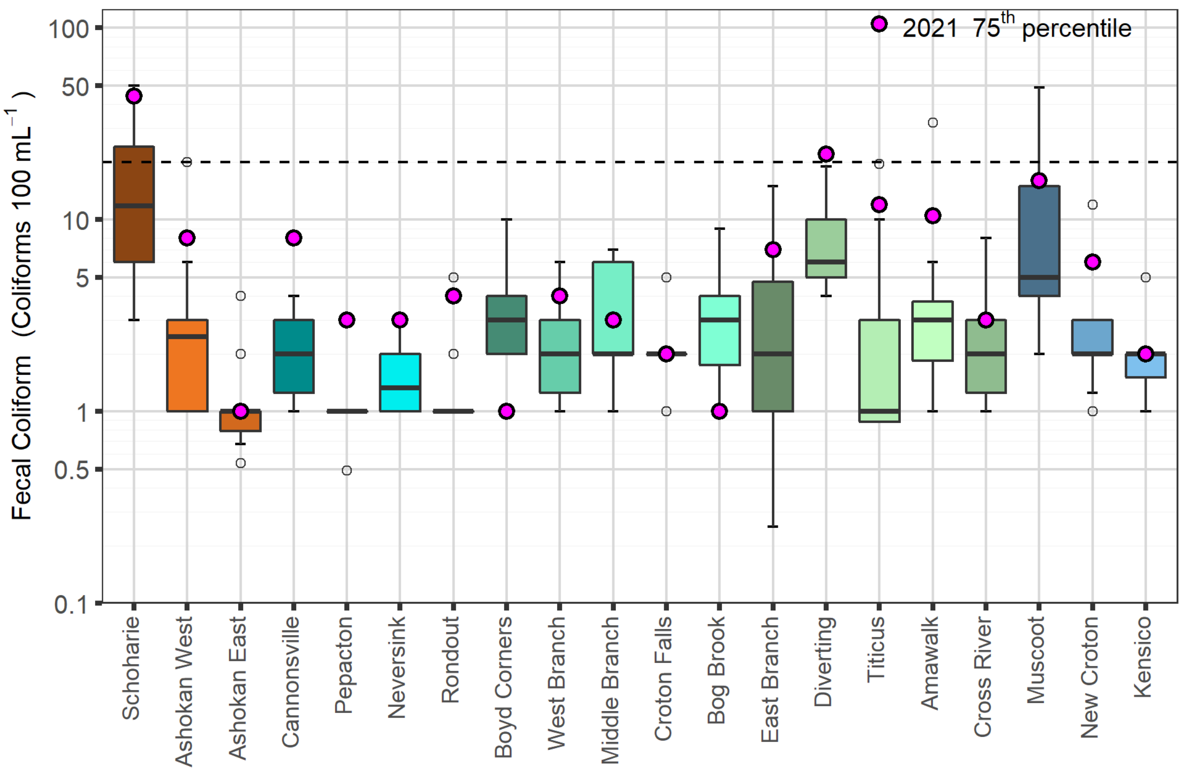


Figure 3.2 Annual 75th percentile of fecal coliforms in NYC water supply reservoirs (2021 vs. 2011-2020), with the 2021 values displayed as a solid dot and outliers as open circles. The dashed line represents the SWTR standard for source water as a reference.

In 2021, fecal and total coliform were very high compared to historic median 75th percentile levels in most of the NYC water supply reservoirs and controlled lakes (Figure 3.2, Figure 3.3, Table 3.3). The highest counts were observed following wet periods in July and in the period from September to November. Typical coliform counts were observed at Ashokan's East Basin due in part to operational changes (i.e., Shandaken tunnel shutdown, dividing weir and release operations) as well as natural processes such as predation, die-off, photolysis, and sedimentation as water moves through the West Basin to the east. These processes and the relatively low coliform inputs from Ashokan East were the likely factors that helped to maintain the typically low fecal coliform levels in Kensico in 2021.

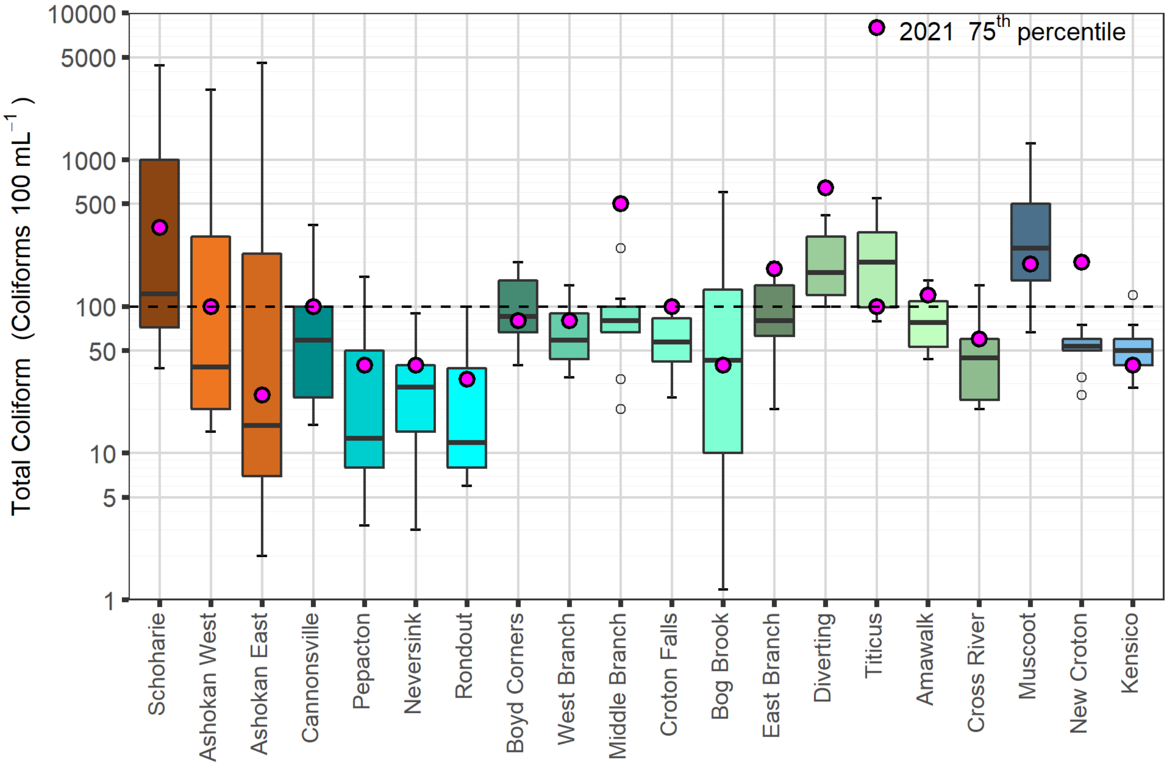


Figure 3.3 Annual 75th percentile of total coliforms in NYC water supply reservoirs (2021 vs. 2011-2020), with the 2021 75th percentile values displayed as a solid dot and outliers as open circles. The dashed line represents the SWTR standard for source water as a reference.

Table 3.3 Summary statistics for coliforms in NYC controlled lakes (coliforms 100mL^{-1}).

Lake	Historical total coliforms (75th percentile 2011-2020)	Current total coliforms (75th percentile 2021)	Historical fecal coliforms (75th percentile 2011-2020)	Current fecal coliforms (75th percentile 2021)
Gilead	20	120	1	7
Gleneida	19	40	1	1
Kirk	83	200	3	10

3.5 Phosphorus-Restricted Basin Assessments in 2021

The phosphorus-restricted basin status determination for 2021 is presented in Figure 3.4 and Table 3.4. Status is determined from two consecutive five-year assessments (2016-2020 and 2017-2021) using the methodology described in Appendix G. Reservoirs and lakes with a geometric mean total phosphorus (TP) concentration that exceeds the benchmarks in the WR&R for both assessments are classified as restricted.

There were no changes in phosphorus-restricted status from the classifications presented in the previous year's report. All West of Hudson reservoirs and three East of Hudson reservoirs retained their non-restricted classification (Table 3.4). Figure 3.4 graphically shows the phosphorus-restricted basin status of the City's reservoirs and controlled lakes. Geometric means for individual years that contributed to the assessments are shown in Appendix G. Some of the sample reductions in the East of Hudson reservoirs in 2021 resulted in high geometric means due to a limited number of samples late in the season when these reservoirs experienced oxygen depletion and consequent phosphorus release from the sediments.

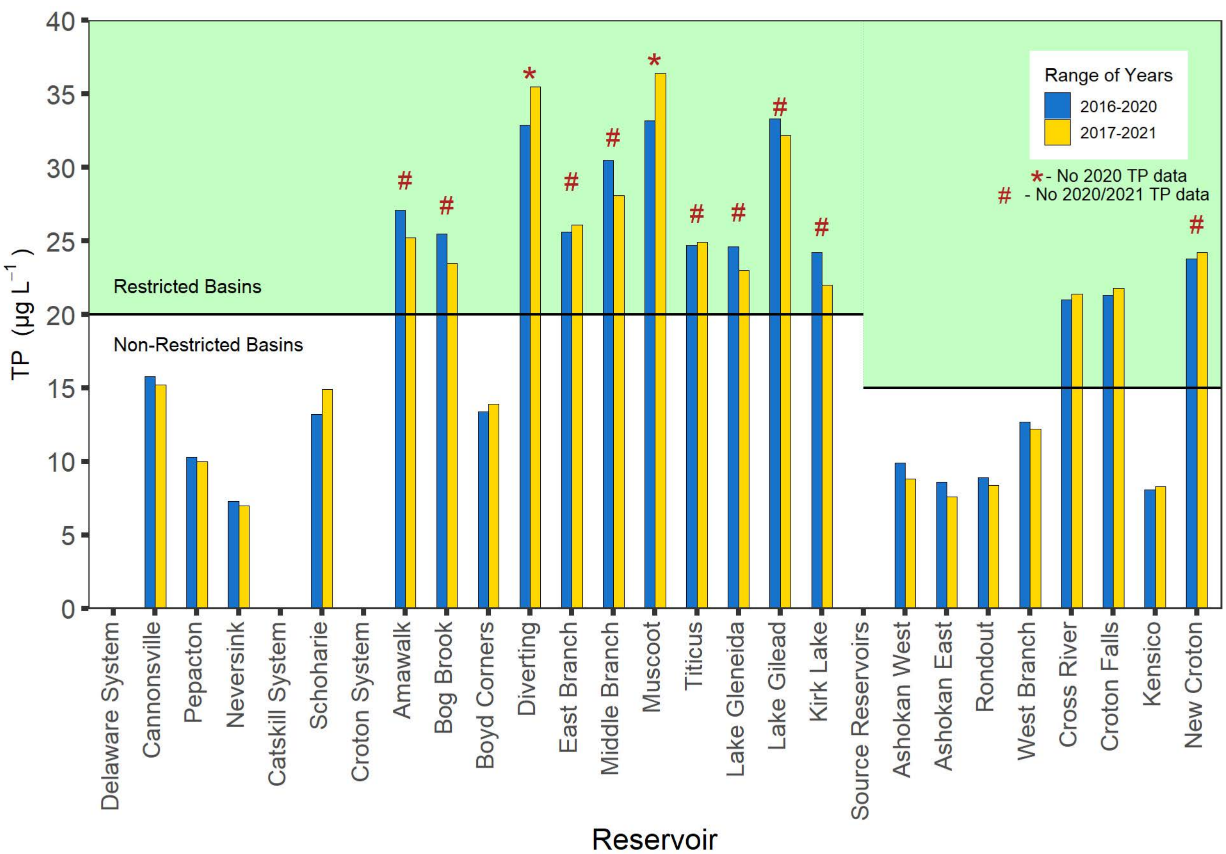


Figure 3.4 Phosphorus-restricted basin assessments. The horizontal solid lines at 20 µg L^{-1} and 15 µg L^{-1} represent the trophic guidance value for non-source and source waters, respectively.

Table 3.4 Phosphorus-restricted basin status for 2021.

Reservoir basin	2016-2020 Assessment[1] (µg L^{-1})	2017-2021 Assessment[1, 2] (µg L^{-1})	Phosphorus restricted status[3]
Non-Source Waters (Delaware System)			
Cannonsville	15.8	15.2	Non-restricted
Pepacton	10.3	10.0	Non-restricted
Neversink	7.3	7.0	Non-restricted
Non-Source Waters (Catskill System)			
Schoharie	13.3	14.9	Non-restricted
Non-Source Waters (Croton System)			
Amawalk	27.4	25.2	Restricted
Bog Brook	25.9	23.5	Restricted
Boyd Corners	13.4	13.9	Non-restricted
Diverting	33.2	35.5	Restricted
East Branch	25.7	26.1	Restricted
Middle Branch	30.9	28.1	Restricted
Muscoot	33.3	36.4	Restricted
Titicus	24.8	24.9	Restricted
Lake Gleneida	24.9	23.0	Restricted
Lake Gilead	33.7	32.2	Restricted
Kirk Lake	24.4	22.0	Restricted
Source Waters (all systems)			
Ashokan East	8.7	7.6	Non-restricted
Ashokan West	9.9	8.8	Non-restricted
Cross River	21.0	21.4	Restricted
Croton Falls	21.5	21.8	Restricted
Kensico	8.1	8.3	Non-restricted
New Croton	24.0	24.2	Restricted
Rondout	8.9	8.4	Non-restricted
West Branch	12.7	12.2	Non-restricted

[1]Arithmetic mean of annual geometric mean total phosphorus concentration for 5-year period with S.E. (standard error of the mean) added to account for interannual variability.

[2] Reservoirs and lakes with sample reductions in 2020 were based on the calculation of a 4-year value (2016-2019) or (2017-2019, 2021). Reservoirs and lakes with sample reductions in 2020 and 2021 were based on the calculations of a 3-year value (2016-2019) or (2017-2019) if there were fewer than 3 surveys in 2021.

[3]The guidance value for non-source waters is 20 µg L^{-1} and for source waters is 15 µg L^{-1}.

3.6 Reservoir Total Phosphorus Patterns in 2021

Total phosphorous (TP) levels in the Delaware reservoirs, including West Branch and Kensico, were generally within their historic ranges (Figure 3.5). In the Catskill System, rain events elevated TP concentrations in Schoharie and in the West Basin of Ashokan. TP remained low in Ashokan's East Basin due to sedimentation in the West Basin and the diversion of particulate phosphorus out of the West Basin through the release channel. In the Croton System, TP levels were elevated in nearly all the reservoirs driven primarily by rain events in July and from multiple rain events occurring from September to November (Figure 3.5, Table 3.5).

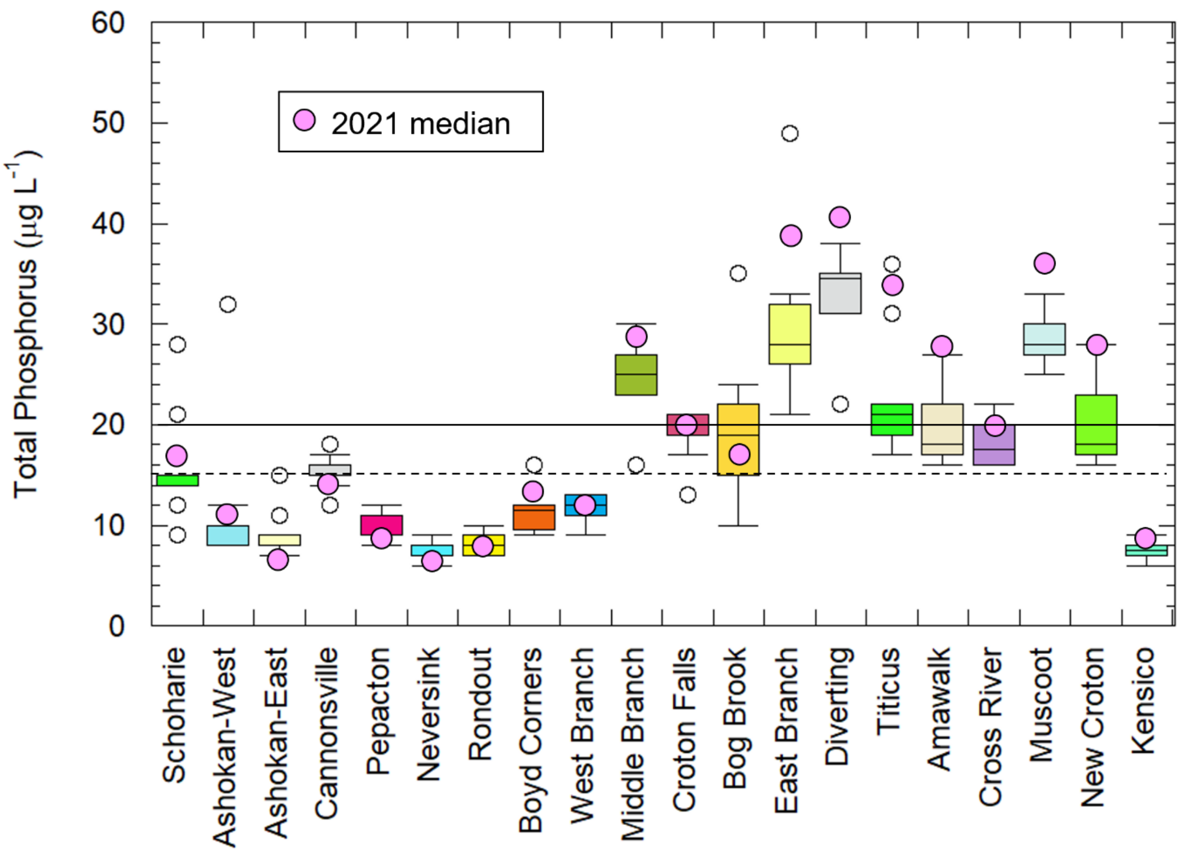


Figure 3.5 Annual median total phosphorus in NYC water supply reservoirs (2021 vs. 2011-2020), with the 2021 median values displayed as a solid dot and outliers as open circles. The horizontal dashed line at 15 µg L^{-1} refers to the NYC Total Maximum Daily Load (TMDL) guidance value for source waters. The horizontal solid line at 20 µg L^{-1} refers to the NYSDEC ambient water quality guidance value for reservoirs other than source waters.

Table 3.5 Total phosphorus summary statistics for NYC controlled lakes (μg L^{-1}).

Lake	Median Total Phosphorus (2011-2020)	Median Total Phosphorus (2021)
Gilead	19	21
Gleneida	16	15
Kirk	29	44

3.7 Reservoir Comparisons to Benchmarks in 2021

The New York City reservoirs and water supply system are subject to the federal SWTR standards, New York State ambient water quality standards, and DEP's own guidelines. Water quality data for 2021 for the terminal reservoirs are evaluated by comparing the results to the water quality benchmarks listed in Table 3.6. Note that the benchmark values in this table are not necessarily applicable to all individual samples and medians described herein (e.g., SWTR limits for turbidity and fecal coliforms apply only to the source water point of entry to the system) and different values apply to Croton reservoirs than to Catskill/Delaware System reservoirs. Placing the data in the context of these benchmarks assists in assessing water quality status of the system and helps in identifying issues.

Comparisons of 2021 reservoir sample results to benchmark values are provided in Appendix H. Highlights of the benchmark comparisons for terminal reservoirs from 2021 include the following.

pH

Reservoir samples were generally in the circumneutral pH range (6.5-8.5) in 2021. In the Croton System, exceedances were from values above pH 8.5, with the most exceedances in Croton Falls Reservoir. West Branch Reservoir was an exception, as all samples outside the circumneutral range were below pH 6.5, reflecting the characteristics of water transferred from the Delaware System.

The West of Hudson reservoirs had a few exceedances above a pH of 8.5, with the majority in Cannonsville and Pepacton, an indicator of algal blooms. Most exceedances for WOH reservoirs were below a pH of 6.5. All pH values outside the circumneutral range for Kensico were below a pH of 6.5, reflecting the influence of water transferred from West of Hudson reservoirs.

Table 3.6 Reservoir and controlled lake benchmarks as listed in the WR&R (DEP 2019a).

Analyte	Basis[1]	Croton System		Catskill/Delaware System	
		Annual Mean	Single Sample Maximum	Annual Mean	Single Sample Maximum
Alkalinity (mg L^{-1})	(a)	≥40.00		≥10.00	
Ammonia-N (mg L^{-1})	(a)	0.05	0.10	0.05	0.10
Dissolved chloride (mg L^{-1})	(a)	30.00	40.00	8.00	12.00
Chlorophyll *a* (mg L^{-1})	(a)	0.010	0.015	0.007	0.012
Color (Pt-Co units)	(b)		15		15
Dominant genus (ASU mL^{-1})	(c)		1000		1000
Fecal coliform (coliforms $100mL^{-1}$)	(d)		20		20
Nitrite + Nitrate (mg L^{-1})	(a)	0.30	0.50	0.30	0.50
pH (units)	(b)		6.5-8.5		6.5-8.5
Phytoplankton (ASU mL^{-1})	(c)		2000		2000
Dissolved sodium (mg L^{-1})	(a)	15.00	20.00	3.00	16.00
Soluble reactive phosphorus (µg L^{-1})	(c)		15		15
Sulfate (mg L^{-1})	(a)	15.00	25.00	10.00	15.00
Total dissolved solids (mg L^{-1})[2]	(a)	150.00	175.00	40.00	50.00
Total organic carbon (mg L^{-1})[3]	(a)	6.00	7.00	3.00	4.00
Total dissolved phosphorus (µg L^{-1})	(c)		15		15
Total phosphorus (µg L^{-1})	(c)		15		15
Total suspended solids (mg L^{-1})	(a)	5.00	8.00	5.00	8.00
Turbidity (NTU)	(d)		5		5

[1](a) WR&R (Appendix 18-B) – based on 1990 water quality results, (b) NYSDOH Drinking Water Secondary Standard, (c) DEP Internal standard/goal, (d) NYSDOH Drinking Water Primary Standard.
[2]Total dissolved solids was estimated by multiplying specific conductivity by 0.65 (van der Leeden 1990).
[3]Dissolved organic carbon was used in this analysis since total organic carbon is not routinely analyzed at all sites.

Phytoplankton

Phytoplankton sampling summary statistics for 2021 are provided in Appendix H. There were few exceedances of counts for the single sample maximum of 2,000 ASU mL^{-1} for total phytoplankton. In 2021, there were a total of 13 NYSDEC Harmful Algal Blooms (HABs) Program notifications (NYSDEC 2021) (2021 Archived HABs Notices). NYSDEC categorizes confirmed blooms for water sampling results as those with confirmed presence of cyanobacteria that may produce toxins or other harmful compounds. Cannonsville Reservoir and Kirk Lake had five reported blooms (August 10 – October 13 and July 11 – October 8, respectively); Kensico, Croton Falls, and Rondout reservoirs had one bloom reported (June 2, June 9, and July 6, respectively).

Chlorophyll and Dissolved Organic Carbon

Chlorophyll *a* concentration is a surrogate measure of algal biomass. Among the reservoirs sampled for chlorophyll *a* in 2021, Boyd Corners and Croton Falls had no exceedances, Cross River and New Croton had one exceedance, and West Branch had two exceedances of the single sample maximum. The four samples collected on Muscoot all exceeded the single sample maximum and the annual mean standard of 10 $\mu g\ L^{-1}$ was greatly exceeded (42.5 $\mu g\ L^{-1}$).

There was a single exceedance of the single sample maximum for dissolved organic carbon (DOC) in Kensico at site 8 near the Bear Gutter stream inflow in 2021 after a rain event. West Branch had three exceedances that were close to the single sample maximum of 4.0 mg L^{-1} at site 4, which is in the northeast basin, separated from the main basin by the Route 301 causeway. These exceedances occurred in September and November. For headwater reservoirs, both Cannonsville and Neversink had two exceedances and Schoharie had seven exceedances representing 8% of all samples collected.

Chloride

In the Delaware System, only Cannonsville exceeded the single sample mean chloride concentration (44% of all samples collected) and the annual mean standard. Pepacton slightly exceeded the annual mean standard of 8.0 mg L^{-1}. Of the Croton System reservoirs sampled in 2021, Croton Falls had the highest number of samples that exceeded the single sample maximum of 40 mg L^{-1} (100%) and annual mean benchmark of 30 mg L^{-1} (70.8 mg L^{-1}). Cross River also exceeded both standards with 78% of samples above the single sample maximum and annual mean of 39.7 mg L^{-1}. All samples collected in New Croton exceeded the single sample maximum and the annual mean was 64.4 mg L^{-1}. West Branch Reservoir exceeded the annual mean benchmark chloride value of 8 mg L^{-1} (16.9 mg L^{-1}) and 60% of the 15 samples collected exceeded the single sample maximum. This was a slight increase when compared with the previous year. Kensico Reservoir exceeded the single sample maximum value for 46% of samples and slightly exceeded the annual mean value. All chloride samples were well below the health secondary standard of 250 mg L^{-1}.

Turbidity

Among the Delaware System reservoirs, few samples exceeded the single sample maximum for Cannonsville, Pepacton, and Neversink, and there were no exceedances in Rondout. As is historically the case for the Catskill reservoirs, Schoharie had the highest number of single sample maximum exceedances of the 5 NTU benchmark value for turbidity (86%) and

Ashokan West Basin had the second highest number (65%). Turbidity was generally low in the Croton System. There were no exceedances of the turbidity standard in West Branch, and a low number of exceedances of the single sample maximum for Croton Falls, Cross River, and New Croton (7%, 8%, and 2% of all samples, respectively). There were no exceedances of the 5 NTU turbidity value in routine monitoring samples for Kensico Reservoir in 2021.

Nutrients

In 2021 for the Delaware System, Cannonsville had the greatest number of single sample maximum exceedances of 15 µg L^{-1} (42% of all samples, all depths, and 46% of samples collected in the epilimnion at a depth of 3 m), Pepacton had fewer exceedances (13% overall, 15% in the epilimnion), and Neversink had no exceedances of the benchmark value of 15 µg L^{-1} for total phosphorus (TP). For the Catskill System, Ashokan East Basin had few exceedances (3% for all samples, with no exceedances in the epilimnion), Ashokan West Basin had 32% exceedances (all samples, with 25% in the epilimnion). In the Croton System, TP exceedances were highest in New Croton (91% for all samples, 100% in the epilimnion), followed by Cross River (90%) and Croton Falls (66%). West Branch with influences from the local watershed and the Delaware System had few exceedances (19%). Kensico Reservoir had one sample (1%) that exceeded the benchmark value for TP.

For nitrate/nitrite for reservoirs sampled in 2021, only Croton Falls and New Croton had exceedances of the single sample maximum value. None of the reservoirs sampled in 2021 exceeded the annual mean benchmark for nitrate/nitrite of 0.30 mg L^{-1}.

Fecal Coliform Bacteria

In 2021, fecal coliform bacteria were low in reservoirs throughout the system. There were no exceedances of the single sample maximum in Rondout, Croton Falls, Ashokan East Basin, West Branch, and Kensico. The highest number of exceedances was in Schoharie Reservoir (45% of samples). Fecal coliform counts exceeded the single sample maximum of 20 fecal coliforms 100mL^{-1} for 8% of samples in Ashokan West Basin and 10% of samples in New Croton. In the Delaware system, Cannonsville had an exceedance of 10%, while Pepacton had 1% and Neversink had 4%.

3.8 Reservoir Trophic Status in 2021

Trophic state indices (TSI) are commonly used to describe the productivity of lakes and reservoirs. Three trophic state categories — oligotrophic, mesotrophic, and eutrophic — are used to separate and describe water quality conditions. Oligotrophic waters are low in nutrients, low in algal growth, and tend to have high water clarity. Eutrophic waters, on the other hand, are high in nutrients, high in algal growth, and low in water clarity. Mesotrophic waters are intermediate. The indices developed by Carlson (1977) use commonly measured variables (i.e., chlorophyll *a*, TP, and Secchi transparency) to delineate the trophic state of a body of water. TSI based on chlorophyll *a* concentration is calculated as:

TSI = 9.81 x (ln (CHLA)) + 30.6

where CHLA is the concentration of chlorophyll *a* in $\mu g\ L^{-1}$

The Carlson TSI ranges from approximately 0 to 100 (there are no upper or lower bounds) and is scaled so that values under 40 indicate oligotrophic conditions, values between 40 and 50 indicate mesotrophic conditions, and values greater than 50 indicate eutrophic conditions. A low trophic state is desirable because such reservoirs produce better water quality at the tap. Trophic state indices are generally calculated from data collected in the photic zone of the reservoir during the growing season (May through October). In 2021, the full complement of chlorophyll *a* samples were collected from the Catskill/Delaware System as well as from the EOH FAD basins. Sample availability for the EOH non-FAD basins is described at the start of this chapter.

Historical (2011-2020) annual median TSI based on chlorophyll *a* concentration is presented in boxplots for all reservoirs in Figure 3.6. This analysis generally indicates that all West of Hudson reservoirs (including Kensico and West Branch) and East of Hudson reservoir Boyd Corners usually fall into the mesotrophic category. East of Hudson reservoirs Croton Falls and Cross River tend to fall into the meso-eutrophic to eutrophic range. Comparisons to historic data were made using only the months collected from each reservoir in 2021.

In 2021, TSI was close to historic median levels in both Ashokan basins and low in Schoharie Reservoir (Figure 3.6). The low TSI at Schoharie can be explained by the elevated surface water turbidity associated with runoff events in July and September, which likely prevented or greatly inhibited algal photosynthesis. Except for Neversink TSI levels in the Delaware System reservoirs (including West Branch and Kensico) were mostly at or below historic median levels and generally correlated with annual median TP concentrations. Slightly higher chlorophyll was observed at Neversink in June through August and in October. Depending on the month, these seasonal increases corresponded to storm-related phosphorus increases and/or to higher surface water temperatures. TSI at Kensico was equivalent to its lowest in the past 10 years despite elevated water temperatures, slightly elevated total (TP) and dissolved phosphorus (TDP) and low turbidity in the surface waters. However, the excess phosphorus was almost always as dissolved organic phosphorus (TDP - soluble reactive phosphorus) and/or particulate phosphorus (TP - TDP), forms generally not readily utilized by phytoplankton. Additional factors contributing to the low TSI could be related to the operation of the reservoir in 2021 and to the proximity of sampling dates to rainfall events which may cause phytoplankton to disperse. During the growing season (May-October) Kensico was operated in "float" mode which means that most water from the Delaware System does not enter the reservoir. As a result, inputs to Kensico were almost solely from the Catskill System where low chlorophyll results were observed in 2021.

TSI trends varied in the Croton System. TSI was higher than historic levels at EOH FAD basins Boyd Corners and Croton Falls but was lower at Cross River. Although total and dissolved phosphorus were elevated in Boyd Corners much of the year, TSI was only elevated in July and August, during the only extended period of the growing season when the reservoir was not spilling, suggesting that the TSI increase may be related to a reduction in water movement and increased residence time. Croton Falls TSI was elevated in September and October corresponding to elevated phosphorus from runoff associated with Hurricane Ida on September 1. Chlorophyll *a* samples were greatly reduced at most EOH non-FAD basins and not collected at all in most reservoirs in 2021. Although TSI was very high at Muscoot Reservoir, data was only available from July 20 when the reservoir was experiencing an *Aphanizomenon* bloom. Only data from September and October is shown for New Croton Reservoir in Figure 3.6 with results suggesting relatively average productivity for that period.

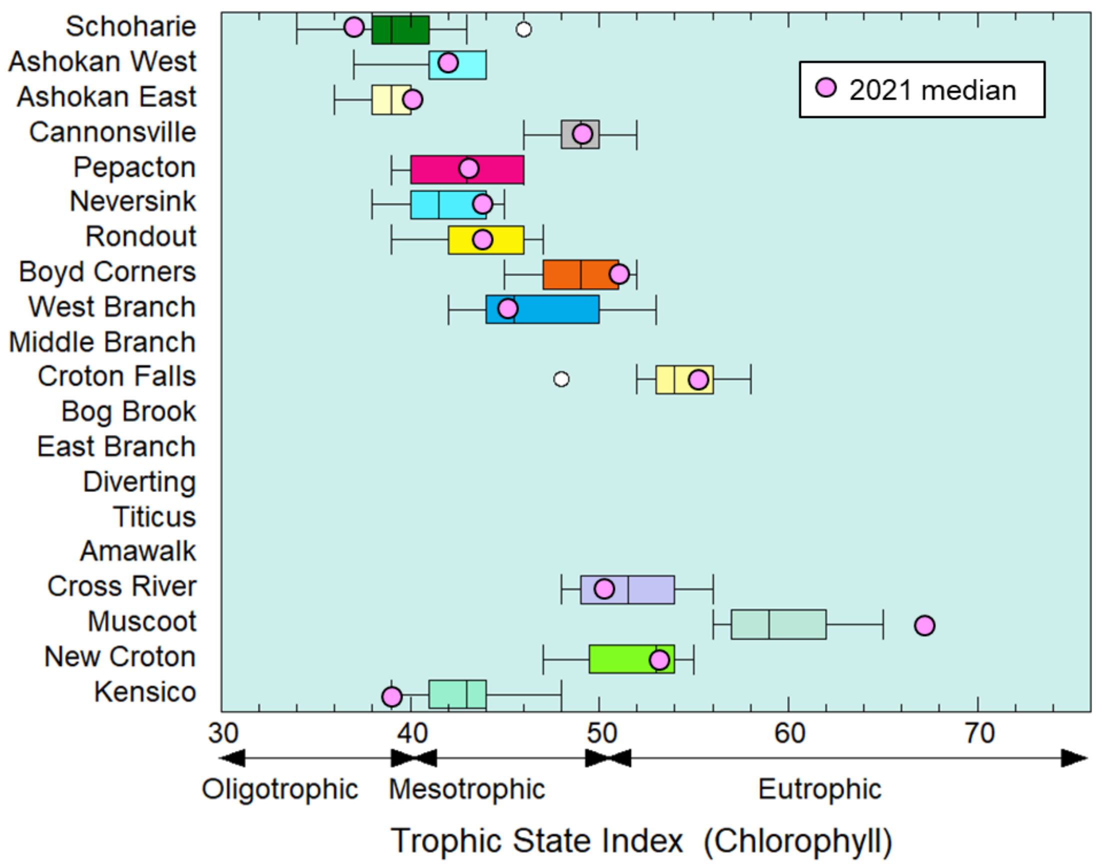


Figure 3.6 Annual median Trophic State Index (TSI) in NYC water supply reservoirs (2021 vs. 2011-2020), with the median displayed as a solid dot and outliers as open circles. In general, data were obtained from epilimnetic depths at multiple sites. Sample frequency is described in section 3.1. TSI is based on chlorophyll *a* concentration.

3.9 Water Quality in the Major Inflow Streams in 2021

The stream sites discussed in this section are listed in Table 3.7, with locations shown in Figure 3.7. These stream sites were chosen because they are immediately upstream from the six Catskill/Delaware System reservoirs and five of the Croton reservoirs. They represent the bulk of the water entering the reservoirs from their respective watersheds. The exception is New Croton Reservoir, whose major inflow is from the Muscoot Reservoir release. Kisco River and Hunter Brook are tributaries to New Croton Reservoir and represent water quality conditions in the New Croton watershed.

Water quality in these streams was assessed by examining those analytes considered to be the most important for the City's water supply. For streams, these are turbidity and fecal coliform bacteria (to maintain compliance with the SWTR), and TP (to control nutrients and eutrophication).

The 2021 results presented here are based on routine grab samples generally collected once a month, but also include additional samples from locations (Esopus Creek at Boiceville, West Branch Delaware River at Beerston, and Neversink River near Claryville) where ongoing studies include fixed frequency samples that would be comparable to the routine samples and increase the number of samples for the year. The 2021 results are plotted by collection date and superimposed on the historic monthly boxplots which are centered on the 15th of the month. As noted elsewhere in this report, there were reductions in the 2021 water quality monitoring programs during the COVID-19. The figures in this section show the 2021 results with a boxplot of historical (2011-2020) monthly values for comparison.

Table 3.7 Site codes and site descriptions for the major inflow streams.

Site code	Site description
S5I	Schoharie Creek at Prattsville, above Schoharie Reservoir
E16i	Esopus Creek at Boiceville bridge, above Ashokan Reservoir
CBS	West Branch Delaware River at Beerston, above Cannonsville Reservoir
PMSB	East Branch Delaware River below Margaretville WWTP, above Pepacton Reservoir
NCG	Neversink River near Claryville, above Neversink Reservoir
RDOA	Rondout Creek at Lowes Corners, above Rondout Reservoir
WESTBR7	West Branch Croton River, above Boyd Corners Reservoir
EASTBR	East Branch Croton River, above East Branch Reservoir
MUSCOOT10	Muscoot River, above Amawalk Reservoir
CROSS2	Cross River, above Cross River Reservoir
KISCO3	Kisco River, input to New Croton Reservoir
HUNTER1	Hunter Brook, input to New Croton Reservoir

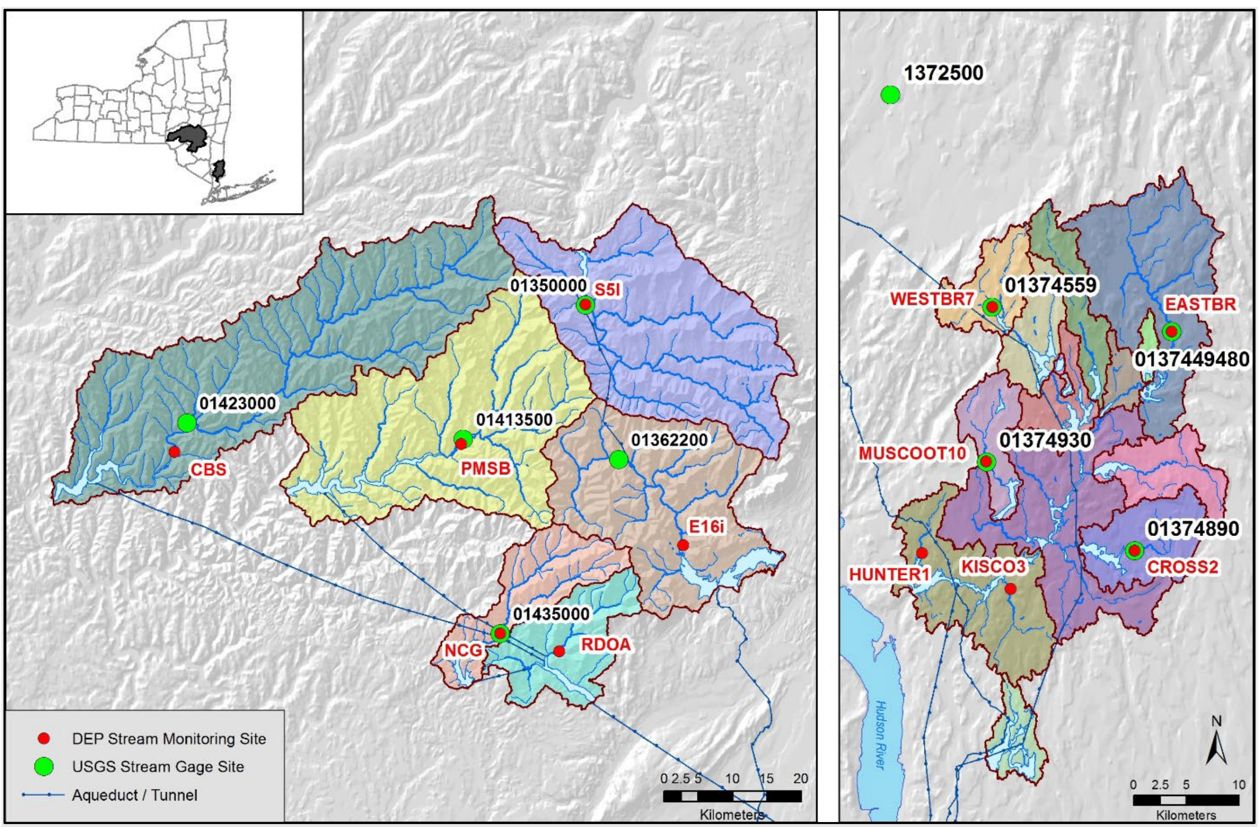


Figure 3.7 Locations of major inflow stream water quality sampling sites and USGS gage stations used to calculate areal-normalized streamflow values (see Section 2.3).

Turbidity

Catskill System streams Schoharie Creek (S5I) and Esopus Creek (E16I) exceeded their historical 75th percentiles for turbidity during much of the year (Figure 3.8). The December 24-25 rain-on-snow event from the prior year as well as numerous rain events, particularly in the second half of the year, caused flows (Figure 2.3) and turbidity to spike on multiple occasions. The Delaware System watersheds generally experienced the same rain events as the Catskill System but except for July and sometimes August, turbidity levels were within or close to their historical interquartile ranges. Turbidity is generally lower in the Delaware System because surficial materials in these watersheds are typically not as erodible as the surficial lake-bed clays of the Catskill System. High July turbidities were associated with a very wet 20-day period from June 29 to July 18 when cumulative precipitation amounts ranged from 8.07 to 11.37 inches. Turbidity spiked to 40 NTU at the West Branch Delaware River at Beerston (CBS) on August 23 after a minor rain event (1.06 inches) one day prior. Although samples were limited in the EOH system, Cross River (CROSS2) and Kisco River (KISCO3) turbidities were within historical monthly interquartile ranges. Turbidity was mostly low throughout the year in the few Croton System streams that were sampled in 2021. Snowmelt-related excursions outside the historical 75th percentile were observed at the West Branch of the Croton River (WESTBR7), but these results were still relatively low ranging to 3 NTU.

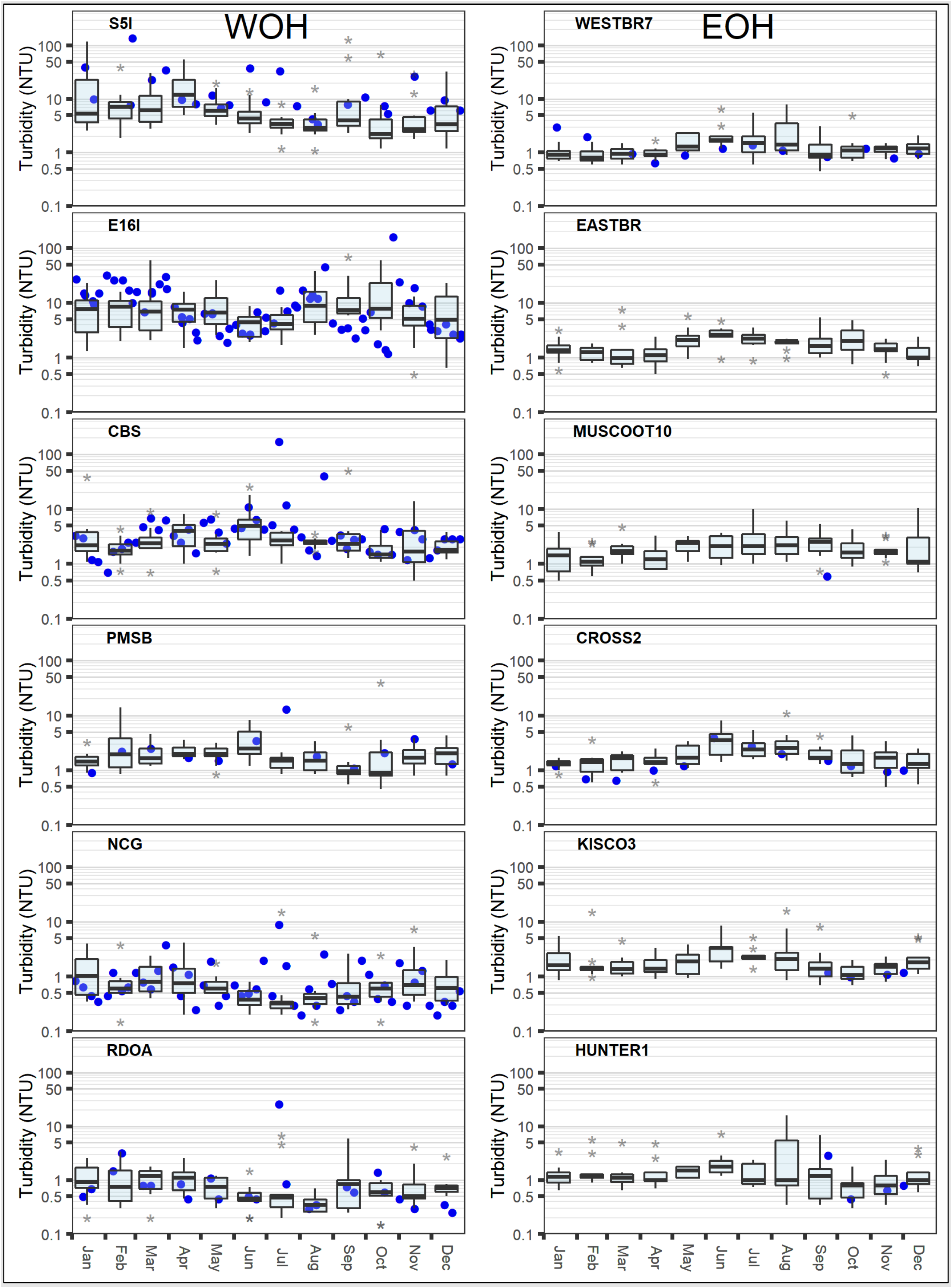


Figure 3.8 2021 turbidity values from routine stream samples with a monthly boxplot of the historic (2011-2020) routine monthly samples. Note the y-axis is a log scale.

Total Phosphorus

The 2021 total phosphorus (TP) concentrations (Figure 3.9) generally followed the same patterns observed for turbidity and are likely explained by rain events and the rain-on-snow event discussed in the turbidity section. Several notable exceptions to the positive turbidity-phosphorus correlation were observed from August to October at WESTBR7. Here turbidity levels were close to their historical monthly medians while TP concentrations were close or well above their historical 75th percentiles. Much of the phosphorus was dissolved (including soluble reactive phosphorus) which may have both anthropogenic (i.e., septic effluent) or natural sources (e.g., animal feces or microbial breakdown of plant material). Given the low density of septic systems and the high density of forest and wetlands in this watershed it is likely that the phosphorus was from natural sources and transported by the high runoff events common during this period.

Fecal Coliform Bacteria

Fecal coliform bacteria in the WOH main inflow streams often exceeded their historical monthly ranges in 2021 (Figure 3.10). Like turbidity and TP results, high fecal coliform counts were frequently associated with the high number of rain events in 2021 as well as the December 2020 rain-on-snow event. The highest fecal coliform counts (and turbidity and TP concentrations) were often observed when samples were collected soon after a storm that was preceded by a period of relatively dry conditions. Such was the case for RDOA, NCG, PMSB and E16I in July. Fecal coliform results were usually lower or within historical monthly ranges in the EOH streams coinciding with the low rainfall and flows during the first half of the year. Even during the second half of the year, with wet periods occurring in July, late August, September, and October, fecal coliform counts remained close to their historic ranges. The most prominent exception occurred at WESTBR7 with a result of 750 fecal coliform $100mL^{-1}$ in late October. This sample was collected the day after a 3-day rain total of 4.82 inches. A fecal coliform benchmark of 200 coliforms $100mL^{-1}$ relates to the NYSDEC water quality standard for fecal coliforms (which is a monthly geometric mean of five samples) (6NYCRR §703.4b). Of the major inflow stream samples collected in 2021, three (NCG, PMSB and RDOA) had one result greater than or equal to 200 coliforms $100mL^{-1}$ while WESTBR7 had two results which exceeded this benchmark. All excursions can be attributed to rain events and the resulting runoff.

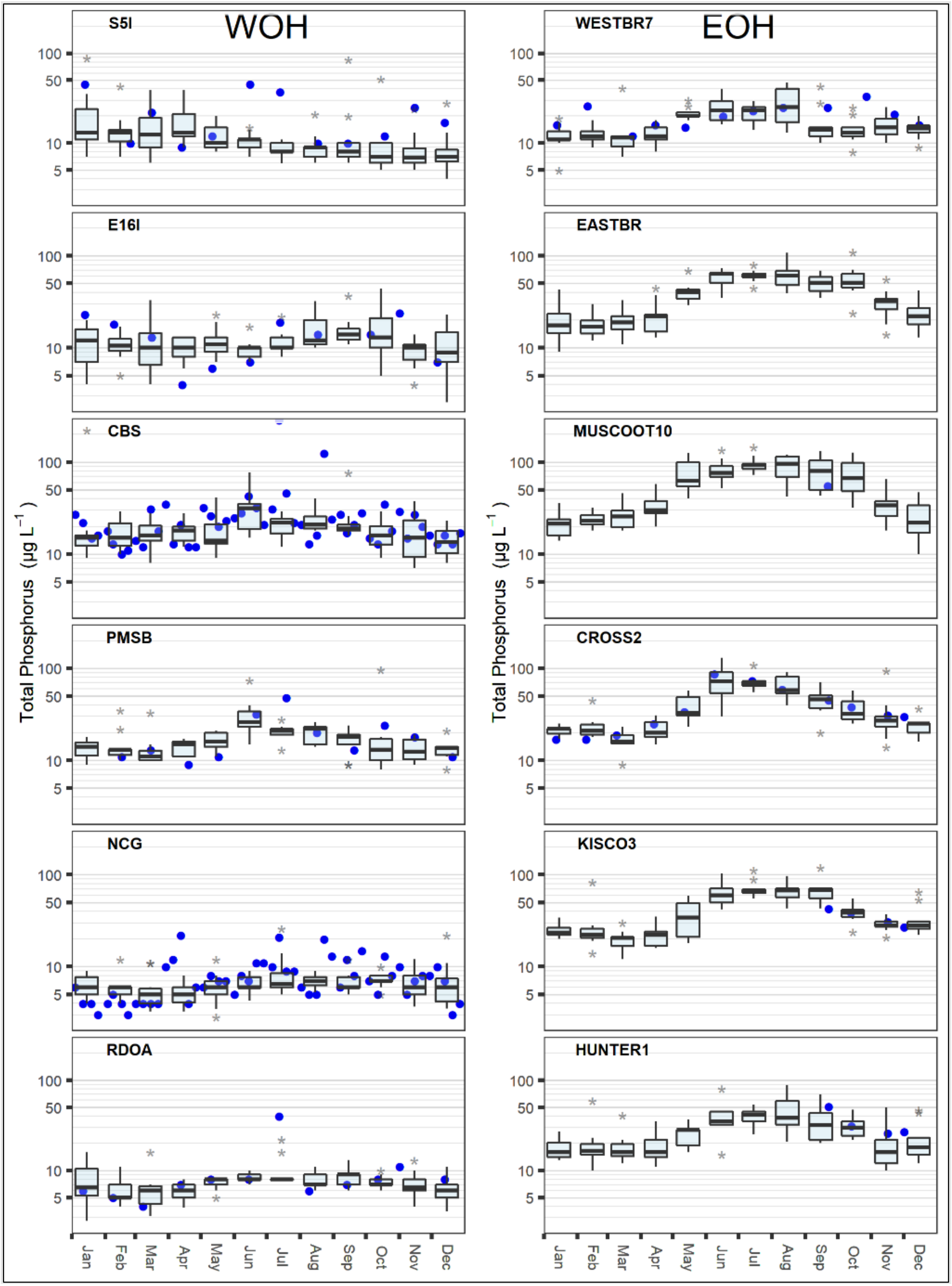


Figure 3.9 2021 total phosphorus values from routine stream samples with a monthly boxplot of the historic (2011-2020) routine monthly samples. Note the y-axis is a log scale.

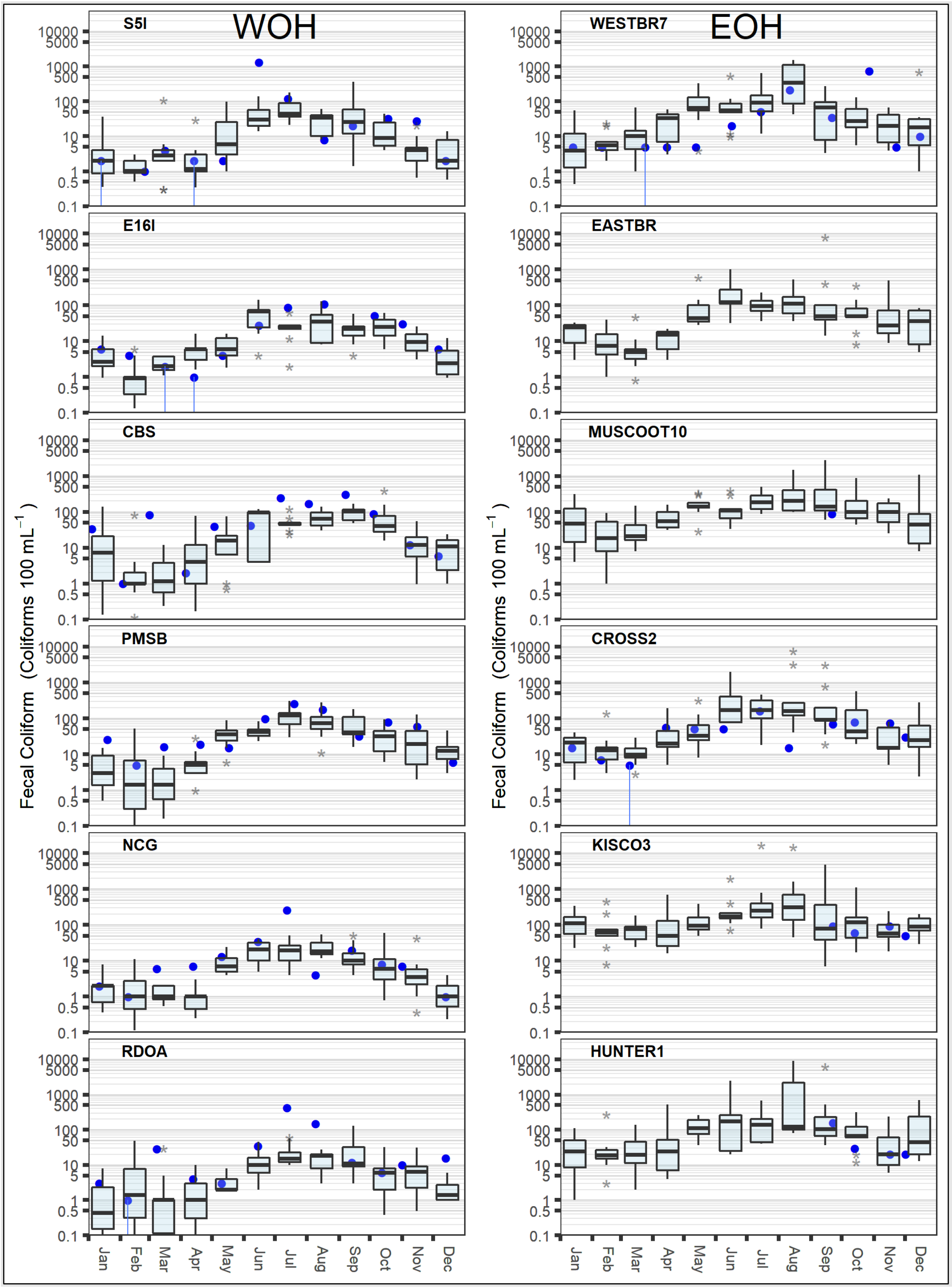


Figure 3.10 2021 fecal coliform values from routine stream samples with a monthly boxplot of the historic (2011-2020) routine monthly samples. Note the y-axis is a log scale.

Environmental Protection

3.10 Stream Comparisons to Benchmarks in 2021

Selected water quality benchmarks have been established for reservoirs and reservoir stems (any watercourse segment which is a tributary to a reservoir and lies within 500 feet of the full reservoir) in the WR&R (DEP 2019a). In this section, the application of these benchmarks has been extended to 40 streams and reservoir releases to evaluate stream status in 2021. The benchmarks are provided in Table 3.8.

Table 3.8 Stream water quality benchmarks as listed in the WR&R (DEP 2019a). The benchmarks are based on 1990 water quality results.

Analyte	Croton System		Catskill/Delaware Systems	
	Annual Mean	Single Sample Maximum	Annual Mean	Single Sample Maximum
Alkalinity (mg $CaCO_3L^{-1}$)	N/A	$\geq$40.00	N/A	$\geq$10.00
Ammonia-N (mg L^{-1})	0.1	0.2	0.05	0.25
Dissolved chloride (mg L^{-1})	35	100	10	50
Nitrite+Nitrate (mg L^{-1})	0.35	1.5	0.4	1.5
Organic Nitrogen [1]	0.5	1.5	0.5	1.5
Dissolved sodium (mg L^{-1})	15	20	5	10
Sulfate (mg L^{-1})	15	25	10	15
Total dissolved solids (mg L^{-1})[2]	150	175	40	50
Total organic carbon (mg L^{-1})[3]	9	25	9	25
Total suspended solids	5	8	5	8

[1] Organic nitrogen is not analyzed currently.
[2] Total dissolved solids are estimated by multiplying specific conductivity by 0.65 (van der Leeden et al. 1990).
[3] Dissolved organic carbon was used in this analysis since TOC is not routinely analyzed at all sites.

Comparison of stream results to these benchmarks is presented in Appendix I along with site descriptions, which appear next to the site codes. Note that the Catskill/Delaware System criteria are applied to the release from West Branch Reservoir (WESTBRR) since that release usually is affected by Delaware System water. Below is a discussion of selected sites and analytes. Please note that sampling in 2021 was limited due to COVID-19 safety protocols so 2021 results will not necessarily be comparable to past years.

Alkalinity

Alkalinity is a measure of water's ability to neutralize acids and is largely controlled by the abundance of carbonate rocks/surficial materials in a watershed and by the amount of precipitation the watershed receives. Elevated precipitation, as in 2021, lowers alkalinity by diluting the cations that contribute to alkalinity. Sufficient alkalinity ensures a stable pH in the

6.5 to 8.5 range, generally considered a necessary condition for a healthy ecosystem. Monitoring of alkalinity is also considered important to facilitate water treatment processes such as chemical coagulation, water softening, and corrosion control.

Watersheds of the Catskill/Delaware System vary in their capacity to neutralize acids. Low buffering capacity is typical of the surficial materials in the Ashokan, Rondout, and Neversink watersheds and streams from these watersheds were below the alkalinity single sample benchmark of 10 mg L^{-1} in 75 of 99 samples collected in 2021. Higher buffering capacity is generally observed in the Cannonsville, Pepacton, and Schoharie watersheds. Despite increased precipitation, only 11 of 156 stream samples in these watersheds were below the 10 mg L^{-1} benchmark. A benchmark of 40 mg L^{-1} is used for the Croton System streams; the higher benchmark reflects the much higher natural buffering capacity of this region. However, less buffering capacity does occur in the Boyd Corners and West Branch watersheds and together with increased precipitation in 2021, caused 46 of 48 stream samples from those watersheds to fall below 40 mg L^{-1}. In contrast, there was only one excursion below 40 mg L^{-1} in the remaining Croton watersheds.

Chloride

The Catskill/Delaware System annual mean benchmark of 10 mg L^{-1} was met or exceeded in 10 of the 24 streams monitored in the Catskill/Delaware System with the highest mean, 28.1 mg L^{-1}, occurring at site NK6 on Kramer Brook in the Neversink watershed. In contrast to Kramer Brook, chloride concentrations in two additional monitored streams in the Neversink watershed, Aden Brook (NK4) and the Neversink River (NCG), were quite low, averaging 3.5 and 3.0 mg L^{-1}, respectively. The Kramer Brook watershed is very small (<1 square mile), is bordered by a state highway and contains pockets of development, all of which contribute to the relatively high chloride levels. The single sample Catskill/Delaware chloride benchmark of 50 mg L^{-1} was exceeded once during the winter in three streams with concentrations ranging from 50.7 mg L^{-1} at Kramer Brook to 75.2 mg L^{-1} at Platte Kill (P-21).

Other Catskill/Delaware System streams which exceeded the annual mean chloride benchmark included Bear Kill at S6I (16.4 mg L^{-1}) and Schoharie Creek at S5I (10.5 mg L^{-1}) , both located within the Schoharie watershed; Trout Creek at C-7 (17.2 mg L^{-1}), Loomis Brook at C-8 (16.0 mg L^{-1}), and the West Branch of the Delaware River at CBS (14.1 mg L^{-1}), all tributaries to Cannonsville Reservoir; and Chestnut Creek at RGB (11.3 mg L^{-1}), a tributary to Rondout Reservoir. Three Pepacton streams, Platte Kill at P-21 (14.3 mg L^{-1}), Tremper Kill at P-13 (12.6 mg L^{-1}) and, the East Branch of the Delaware River at PMSB (12.5 mg L^{-1}), exceeded the average annual benchmark in 2021. Average annual chloride was also elevated at the outflow from the West Branch Reservoir release at WESTBRR (13.7 mg L^{-1}). In general, higher chloride concentrations correlate with the percentage of impervious surfaces (e.g., roads, parking lots) in the watersheds (Mayfield and Van Dreason 2019).

The Croton System annual mean chloride benchmark of 35 mg L^{-1} was exceeded in 12 of 13 monitored Croton streams. Only Gypsy Trail Brook, a tributary to West Branch Reservoir was below the annual mean benchmark with a mean concentration of 24.3 mg L^{-1} in 2021. Annual means exceeding the benchmark ranged from 35.4 mg L^{-1} in the West Branch of the Croton River at WESTBR7 to 175.5 mg L^{-1} in Michael Brook at MIKE2. The mean 2021 chloride concentration for all 13 Croton streams was 56.2 mg L^{-1}, substantially higher than the streams of the Catskill/Delaware System, which together averaged 9.7 mg L^{-1}. The single sample chloride benchmark is 100 mg L^{-1} for streams of the Croton System. In 2021, this benchmark was commonly exceeded at Michael Brook at MIKE2. Historically, additional streams exceeded this benchmark and likely did in 2021 as well. However, since COVID-19 protocols resulted in fewer samples, and in some cases no samples collected, we were unable to quantify exceedances as fully as years past. Road salt is considered the primary source of chloride in these systems, while secondary sources include septic system leachate, water softening brine waste, and wastewater treatment plant effluent. The much greater chloride concentrations in the Croton System are due to higher road and population densities in these watersheds. Given the common co-occurrence of chloride and sodium, it was not surprising that sodium benchmarks were exceeded in much the same pattern as chloride (Appendix I).

Total Dissolved Solids

Total dissolved solids (TDS) is a measure of the combined content of all inorganic and organic substances in the filtrate of a sample. Although TDS is not analyzed directly by DEP, it is commonly estimated in the water supply industry using measurements of specific conductivity. Conversion factors used to compute TDS from specific conductivity relate to the water type (International Organization for Standardization 1985, Singh and Kalra 1975). For NYC waters, specific conductivity was used to estimate TDS by multiplying specific conductivity by 0.65 (van der Leeden et al. 1990).

In 2021, 14 of 24 Catskill/Delaware streams had at least one value greater than the TDS single sample maximum of 50 mg L^{-1}. Apart from Esopus Creek (E16I), these same streams also exceeded the TDS annual mean benchmark of 40 mg L^{-1}. TDS in Catskill/Delaware streams was strongly correlated with chloride with chloride accounting for 92 percent of the variation in TDS (Figure 3.11). All excursions of the single sample maximum were associated with chloride concentrations that exceeded approximately 10.7 mg L^{-1}.

Like the Catskill/Delaware streams, Croton stream TDS was strongly correlated to chloride concentrations (Figure 3.12). The much higher Croton TDS is mostly due to greater road density and deicer usage in the Croton watersheds. The TDS single sample maximum of 175 mg L^{-1} and the annual mean benchmark of 150 mg L^{-1} was exceeded in 10 of 13 monitored Croton streams in 2021. Three stream sites, LONGPD1, CROFALLSVC and MIKE2, exceeded the standard throughout the year.

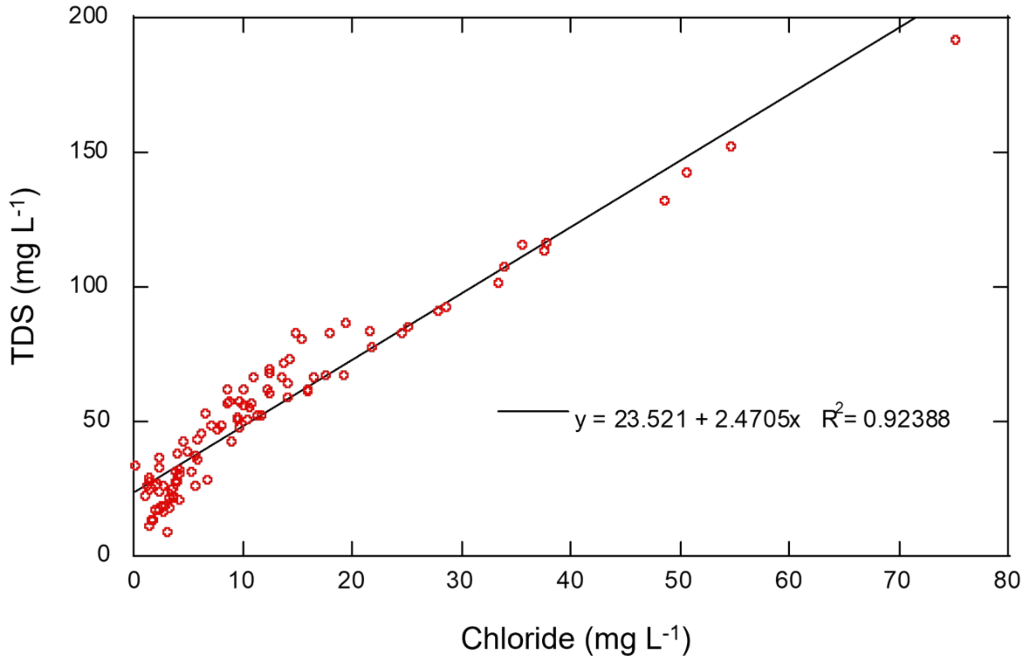


Figure 3.11 Total Dissolved Solids (TDS) versus chloride for Catskill/Delaware System streams in 2021.

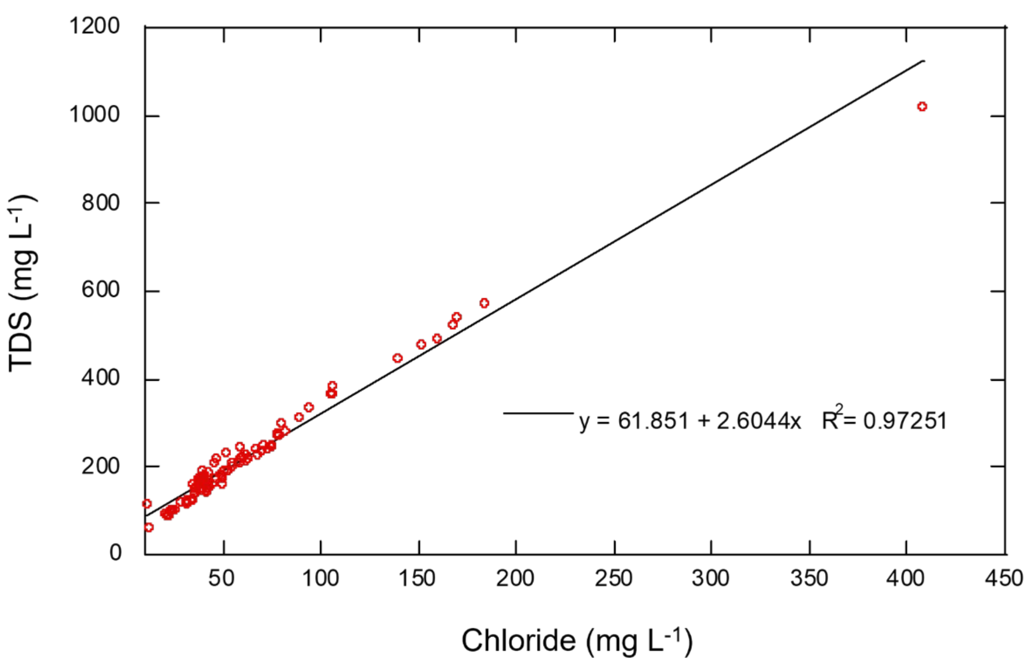


Figure 3.12 Total Dissolved Solids (TDS) versus chloride for Croton System streams in 2021.

Nitrogen

Nitrogen results were generally in compliance with benchmarks in the Catskill/Delaware System in 2021. No stream exceeded the single sample nitrate benchmark of 1.5 mg L^{-1}. The mean annual benchmark of 0.40 mg L^{-1} was only exceeded at the West Branch of the Delaware River at CBS (0.49 mg L^{-1}). Likely sources for nitrate are fertilizers associated with the relatively high agricultural activity in this basin and multiple wastewater treatment plants that discharge to the river.

Michael Brook at MIKE2 (3.55 mg L^{-1}) and the Kisco River at KISCO3 (0.58 mg L^{-1}), were the only Croton streams to exceed the nitrate annual mean benchmark of 0.35 mg L^{-1} in 2021. The single sample nitrate benchmark of 1.5 mg L^{-1} was also exceeded at Michael Brook in nine of 12 monthly samples with the highest concentration, 7.18 mg L^{-1}, occurring in August. Possible nitrogen sources are plentiful given the relatively high development in the Michael Brook and Kisco River watersheds, including inputs from local wastewater treatment plants.

All ammonia results complied with the single sample ammonia benchmark of 0.25 mg L^{-1} and the mean ammonia annual benchmark of 0.05 mg L^{-1} in the Catskill/Delaware System in 2021. Ammonia was only detected in 16 of 258 samples (all streams combined) with detected concentrations relatively low, ranging from 0.02 to 0.05 mg L^{-1}. Three Croton streams exceeded the ammonia single sample maximum of 0.20 mg L^{-1} in 2021. A result of 0.22 mg L^{-1} was observed at the release from Diverting Reservoir (DIVERTR) in October. Although ammonia data was not collected from the reservoir in 2021, the elevated value in the release is likely related to the release of ammonia from anoxic reservoir sediments in late summer/autumn. A result of 0.21 mg L^{-1} was observed at the Boyd Corners release (BOYDR) in February. At the time of sampling, flow in the release was near its historic low, allowing ammonia to concentrate. Michael Brook (MIKE2) exceeded the benchmark in February (0.23 mg L^{-1}) and in August (2.35 mg L^{-1}), likely associated with relatively high development in this watershed.

Sulfate

Neither the single sample maximum (15 mg L^{-1}) nor the annual mean (10.0 mg L^{-1}) benchmarks for sulfate were exceeded in the Catskill/Delaware streams in 2020. Individual sample results ranged from 2.2 to 7.1 mg L^{-1} with a collective average of 3.6 mg L^{-1}. Croton stream results were all below the Croton System single sample maximum of 25 mg L^{-1} in 2021. However, Michael Brook (MIKE2) exceeded the annual mean benchmark of 15 mg L^{-1} with an average of 17.6 mg L^{-1}. Quarterly concentrations ranged from 13.3 in May to 22.1 in February. The Michael Brook watershed has a relatively high population density and sulfate is a common ingredient in personal care products (e.g., soaps, shampoos, and toothpaste) and mineral supplements. Note that USEPA does not consider sulfate to be a health risk and has only established a secondary maximum contaminant level of 250 mg L^{-1} as a benchmark for aesthetic consideration (i.e., salty taste).

Dissolved Organic Carbon

Dissolved organic carbon (DOC) was used in this analysis instead of total organic carbon since the latter is not routinely analyzed as part of the DEP monitoring program. Previous work has shown that DOC constitutes most of the organic carbon in stream and reservoir samples. The DOC single sample benchmark of 25 mg L^{-1} and annual mean benchmark of 9.0 mg L^{-1} were not surpassed by any stream in the Catskill/Delaware or Croton systems in 2021. In the Catskill/Delaware System, single samples ranged from 0.6 to 9.5 mg L^{-1} and stream annual means ranged from 1.2 to 3.5 mg L^{-1}. DOC is generally higher in the Croton System compared to the Catskill/Delaware System (although still well below benchmarks) due to a higher occurrence of wetlands in the Croton watersheds. Mean DOC in the Croton System ranged from 3.5 to 6.2 mg L^{-1} in 2021, and the highest single sample DOC, 10.6 mg L^{-1}, occurred at the West Branch of the Croton River (WESTBR7). DOC concentrations were elevated compared to previous years throughout the NYC water supply in 2021, particularly following large rain events in July and October.

3.11 Water Quality Evaluation for New York State (MOU Addendum E)

In September 1997, the New York State Department of Environmental Conservation (DEC) and DEP finalized a Memorandum of Understanding (MOU) governing several aspects of enforcement protocols in the New York City water supply watersheds. For the past 25 years DEP has submitted annual reports to fulfill the requirements for describing the results of the Addendum E analysis along with any other documentation of water quality concerns. Going forward, this section will include the information needed to satisfy the requirement of the Addendum E report, so that a separate stand-alone annual report is no longer required.

3.11.1 Data Analysis

The means of the analytes required for Addendum E were calculated for each site and compared to the stream water quality guidance values listed in Table 3.9. Values below the detection limit were converted to one-half the detection limit for the purpose of calculating mean values. The median is used for total coliform and the geometric mean is used for the fecal coliform evaluations. Coliform values listed as “CONF” in the dataset were not used in the summary statistics for each sampling site because they could not be converted into a numerical value. To calculate the compliance of streams with the Addendum E pH standards ($6.5 \leq pH \leq 8.5$) this protocol converts pH values to hydrogen ion concentrations, calculates the mean, and compares the mean to the pH standards also expressed as hydrogen ion concentrations (*i.e.*, $3.1623 \times 10^{-7} \geq [H^+] \geq 3.1623 \times 10^{-9}$).

Table 3.9 Water Quality Guidance Values used to compare routine stream monitoring data for Addendum E.

Parameter	Guidance Value
pH $[H^+]$	$6.5 \leq pH \leq 8.5$ $[3.1623 \times 10^{-9} \leq [H^+] \leq 3.1623 \times 10^{-7}]$
fecal coliform bacteria	200 CFU $100mL^{-1}$
total coliform bacteria	2400 CFU $100mL^{-1}$
total phosphorus	50 µg L^{-1}
dissolved oxygen	6 mg L^{-1}
total ammonia (NH_3+NH_4-N)	2 mg L^{-1}
nitrate-nitrite (NO_3+NO_2-N)	10 mg L^{-1}

3.11.2 Water Quality Results

In 2021, 525 samples were collected at 75 sites, analyzed, and later compared to water quality guidance values. Table 3.10 lists sites where either the mean value contravened water quality standards, or if data from a site included more than two "spikes" in one or more of the seven parameters tested. A "spike" is defined by Addendum E as an ambient water quality concentration found to be above the guidance value by three standard deviations of the mean at a given site. There were 11 sites at which the mean value contravened the Table 1 guidance values, and four sites exceeded the spike threshold. The number of spikes at a site for each analyte are listed in the fifth column of Table 3.10. For information regarding biomonitoring impairment ratings during 2021, see Section 3.13.

Table 3.10 Routine stream sampling sites with contraventions of water quality guidelines in 2021.

Reservoir Basin	Site	Mean contravened water quality guidelines	Analytes exceeding spike threshold	Number exceeding spike threshold	Spike threshold contra-vention
Kensico Basin					
Kensico	E9	Dissolved oxygen	N/A	N/A	N/A
	MB-1	TP	Fecal coliform	1	N
		TP	Total coliform	1	N
	N5-1	TP	Fecal coliform	1	N
		TP	Total coliform	1	N
New Croton System					
Amawalk	MUSCOOT10	Dissolved oxygen	N/A	N/A	N/A
		TP	none	0	N
Catskill System					
Ashokan	AEHG	pH (acid)	none	0	N
	ASCHG	pH (acid)	none	0	N
Schoharie	SBKHG	pH (acid)	none	0	N
Delaware System					
Neversink	NCG	pH (acid)	Ammonia	3	Y
		pH (acid)	Fecal coliform	1	N
		pH (acid)	TP	1	N
	NK4	pH (acid)	Ammonia	1	N
		pH (acid)	Fecal coliform	1	N
		pH (acid)	pH (acid)	1	N
		pH (acid)	TP	1	N
	NK6	pH (acid)	none	0	N
Rondout	RRHG	pH (acid)	none	0	N

N/A = not applicable; there is no spike threshold for dissolved oxygen.

3.12 Zebra Mussel Monitoring

DEP has been monitoring all 19 New York City reservoirs for the presence of zebra mussel (*Dreissena polymorpha*) larvae (veligers), as well as settlement of juvenile zebra mussels. Sampling locations remained the same in 2021 as in 2020, with the addition of multi-plate colonization substrates being deployed in Amawalk, Muscoot, and New Croton reservoirs. West of Hudson reservoirs were not monitored in 2020 or 2021.

In 2020, veligers were found only in Lake Mahopac, and adults have only been found in Lake Mahopac and the Muscoot River up to about 1 kilometer downstream of Lake Mahopac. Rainfall totals exceeding 6 inches, according to the National Weather Service, in August-early September 2021 most likely transported both veligers and rafting adult zebra mussels into Amawalk Reservoir. The first attached adult zebra mussels recorded in the NYC water supply were found in Amawalk Reservoir on the multi-plate sampling apparatus in September 2021. Signage was created and placed at all access points to warn anglers of their presence as part of the effort to contain their spread. In addition, an outreach email message was created and sent to all DEP access permit holders with a concise but thorough description of the issue and recommendations to help prevent their spread.

A survey conducted in Amawalk Reservoir in November 2021 revealed the presence of settled adults on naturally occurring substrate near the inflow of the Muscoot River and on the dam face near the spillway. Furthermore, attached adults were found in the release channel below the spillway and within the natural stream channel below the release channel. Data suggested that downstream movement of zebra mussels from Lake Mahopac was dependent on the elevation of the lake and its spill status. This suggestion was confirmed in 2021; the only time veligers were detected in samples downstream of Lake Mahopac was during or following periods of elevated streamflow.

A shoreline survey conducted in chest waders in December 2021 for attached zebra mussels in downstream Muscoot Reservoir was inconclusive. DEP was not able to access the most relevant substrates due to the loose nature of the alluvial sediments where the Muscoot River enters Muscoot Reservoir.

3.13 Stream Biomonitoring

Biomonitoring assessments are made following protocols developed by the New York State Stream Biomonitoring Unit (SBU) (NYSDEC 2014). Five metrics, each a different measure of biological integrity, are calculated and averaged to produce a Biological Assessment Profile (BAP) score ranging from 0-10. These scores correspond to four levels of impairment (non-impaired, 7.5-10; slightly impaired, 5-7.5; moderately impaired, 2.5-5; severely impaired, 0-2.5). The five metrics used in the analysis are total number of taxa (SPP or species richness); total Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) taxa (EPT richness); Hilsenhoff Biotic Index for taxa tolerance to organic pollution (HBI), Percent Model Affinity (PMA), and since 2012, Nutrient Biotic Index-Phosphorus (NBI-P).

In 2021, DEP collected samples from 20 stations in 14 streams throughout New York City’s watershed (for site locations, see Appendix J). Some samples were analyzed twice as replicates. The mean values of those replicates are used when data are presented in figures in this section. The EOH, Schoharie Creek (Catskill) and Batavia Kill (Catskill) surveys were conducted later in the season than originally planned (September 29 and 30, October 4, 8, and 15) due to wet summer and autumn weather.

East of Hudson – Croton System

Of the six Croton System sites assessed in 2021, only one was considered moderately impaired (site 112). The remaining five sites scored as slightly impaired (Figure 3.13). While five of the sites had BAP scores lower than their respective period of record means, one of the sites (142) scored higher. The lower-than-average ratings at sites 102, 134, 142, and 146 are likely the results of the wet weather, high flows, streambed disruption and late season surveys. DEP will continue to monitor at these sites.

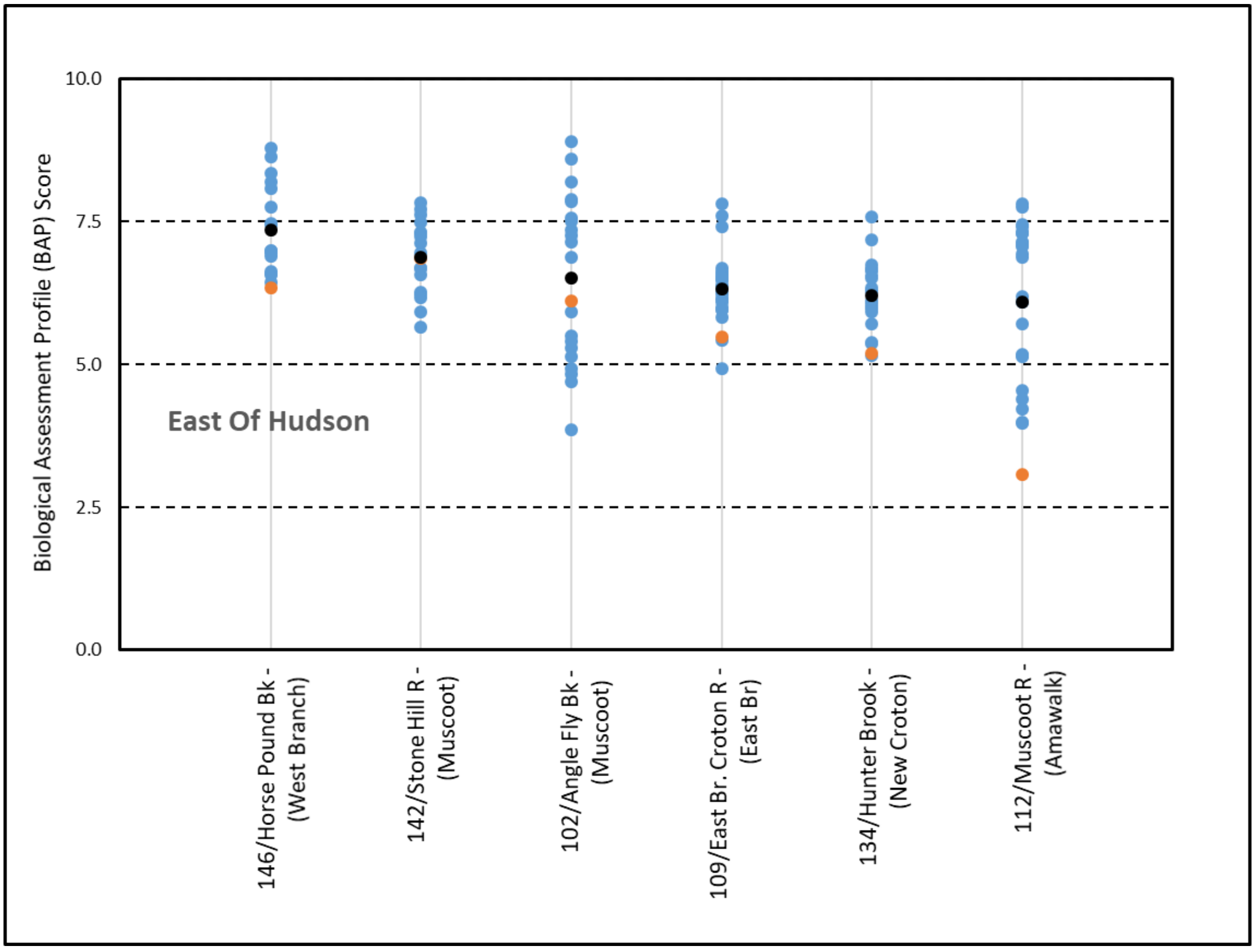


Figure 3.13 Biological Assessment Profile scores for East of Hudson biomonitoring sites sampled in 2021, arranged by mean score from highest to lowest. Black dots represent the mean score, orange dots the 2021 score, and blue dots the pre-2021 scores. The watershed is indicated in parentheses.

The assessment at Angle Fly Brook (Site 102) showed a fifth survey year of increased BAP score which, after the 2015 decline to 3.96, narrowly missed bringing the site back into the slightly impaired status (Figure 3.14). DEP will continue to monitor this site in 2022. BAP scores for the period of record for each site are shown in Figure 3.15.

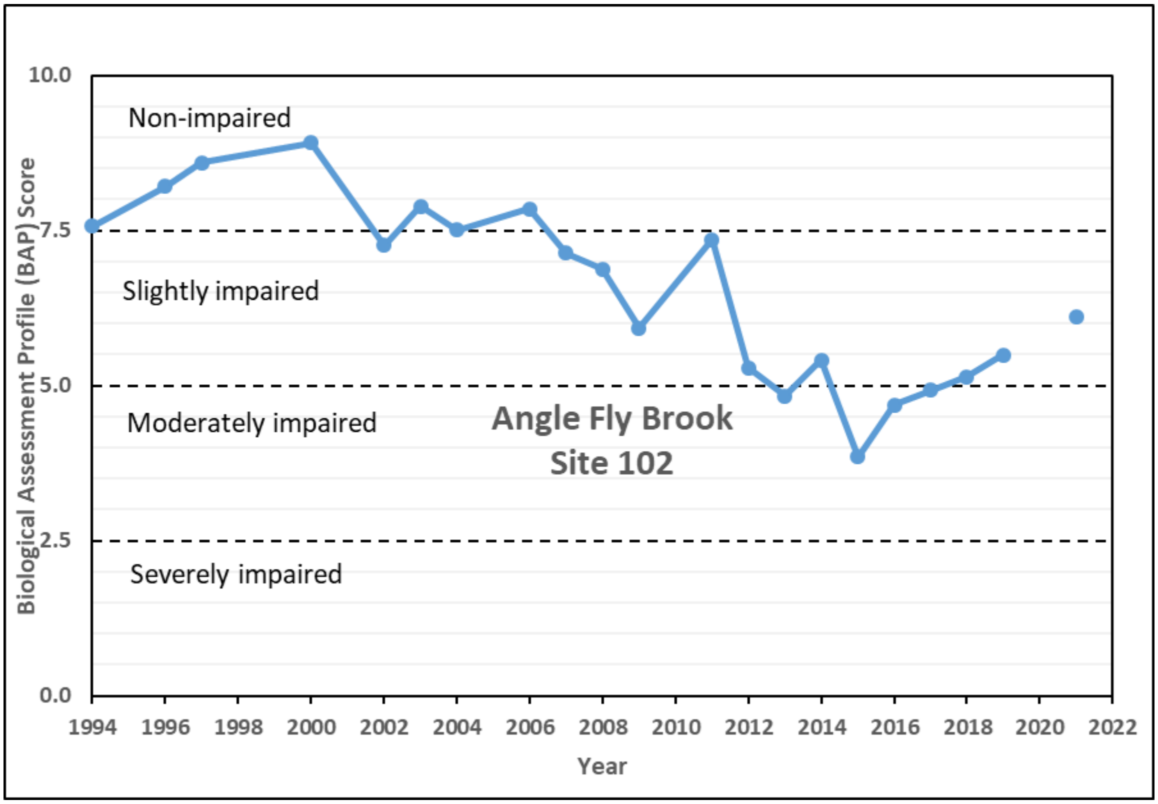


Figure 3.14 1994-2021 BAP scores for the Angle Fly Brook Site 102 showing continued increased rating.

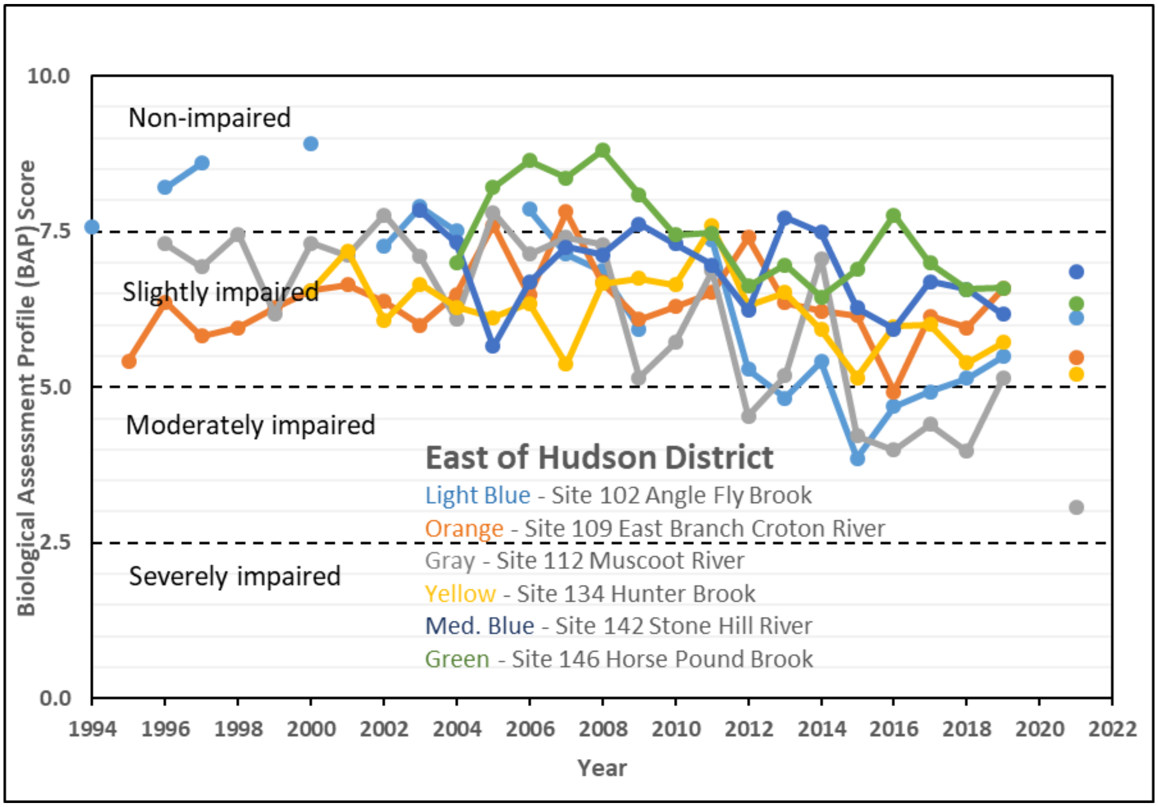


Figure 3.15 1994-2021 BAP scores for all 2021 sample sites within the East of Hudson District.

West of Hudson - Catskill/Delaware System

Of the seven Catskill System sites assessed in 2021, four were considered slightly impaired with the remaining three (215, 227 and 229) considered non-impaired (Figure 3.16). Among the four slightly impaired sites, two (202 and 204) were considered just shy of non-impaired. While four of the seven sites had BAP scores lower than their respective period of record means (202, 204, 216 and 229), the remaining sites (206, 215 and 227) scored higher than their period of record means. Additionally, those sites scored higher than during the previous sampling year while, except for site 216, the remaining sites remained relatively unchanged. It should be noted that while site 216 showed a significant BAP score drop it is located upstream of site 204 which showed only a slight drop. The difference in the change in Ashokan and Schoharie BAP scores may be the result of the timing of the site surveys. Ashokan watershed sites were surveyed very early in the sampling process while the Schoharie watershed sites were surveyed at the tail end of the survey schedule. The lower scores found in the Schoharie sites is most likely the results of the wet weather, high flows, streambed disruption and late season surveys. BAP scores for the period of record for each site are shown in Figure 3.17. DEP will continue to monitor at all these sites.

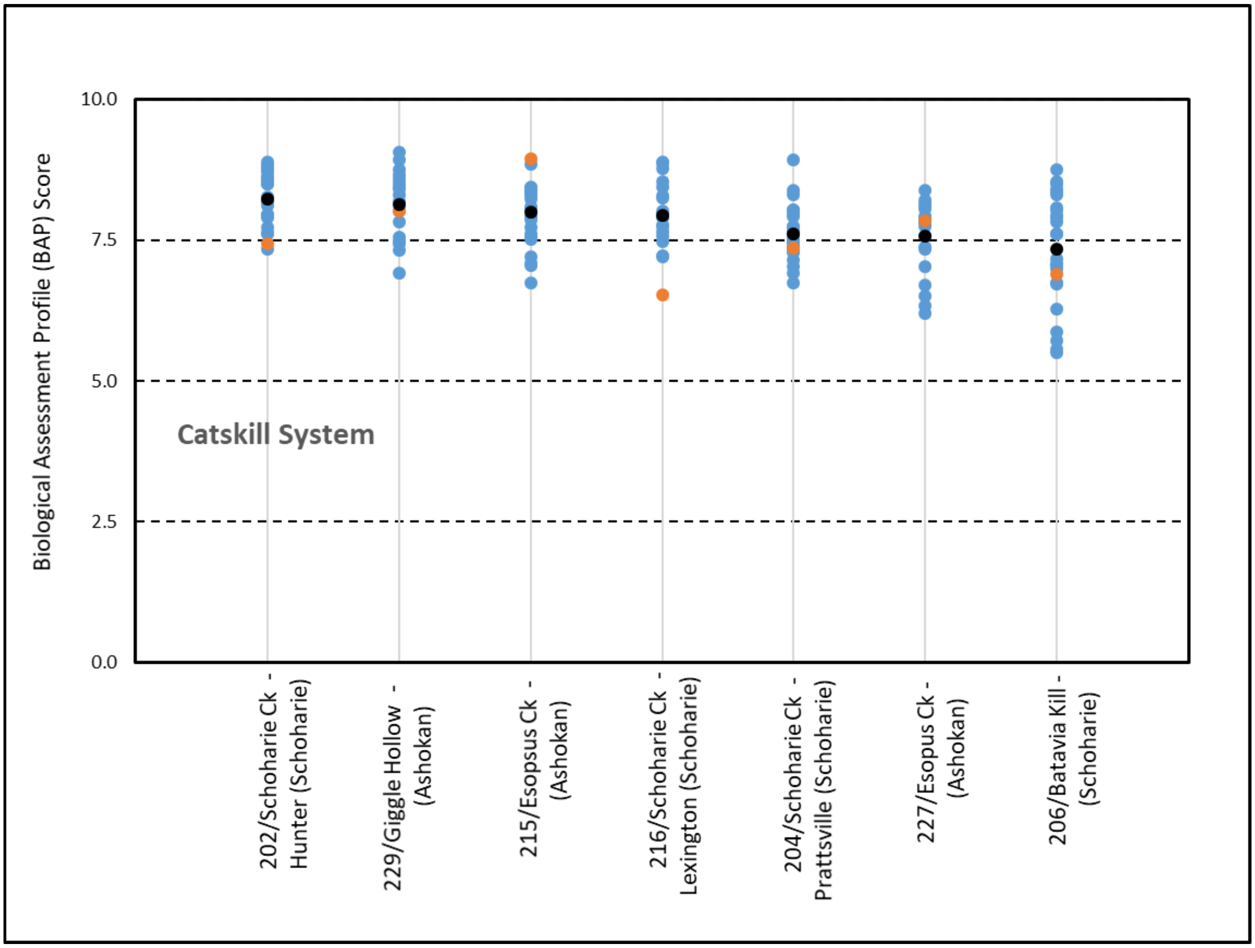


Figure 3.16 Biological Assessment Profile scores for the Catskill System biomonitoring sites sampled in 2021, arranged by mean score from highest to lowest. Black dots represent the mean score, orange dots the 2021 score, and blue dots the pre-2021 scores. The watershed is indicated in parentheses.

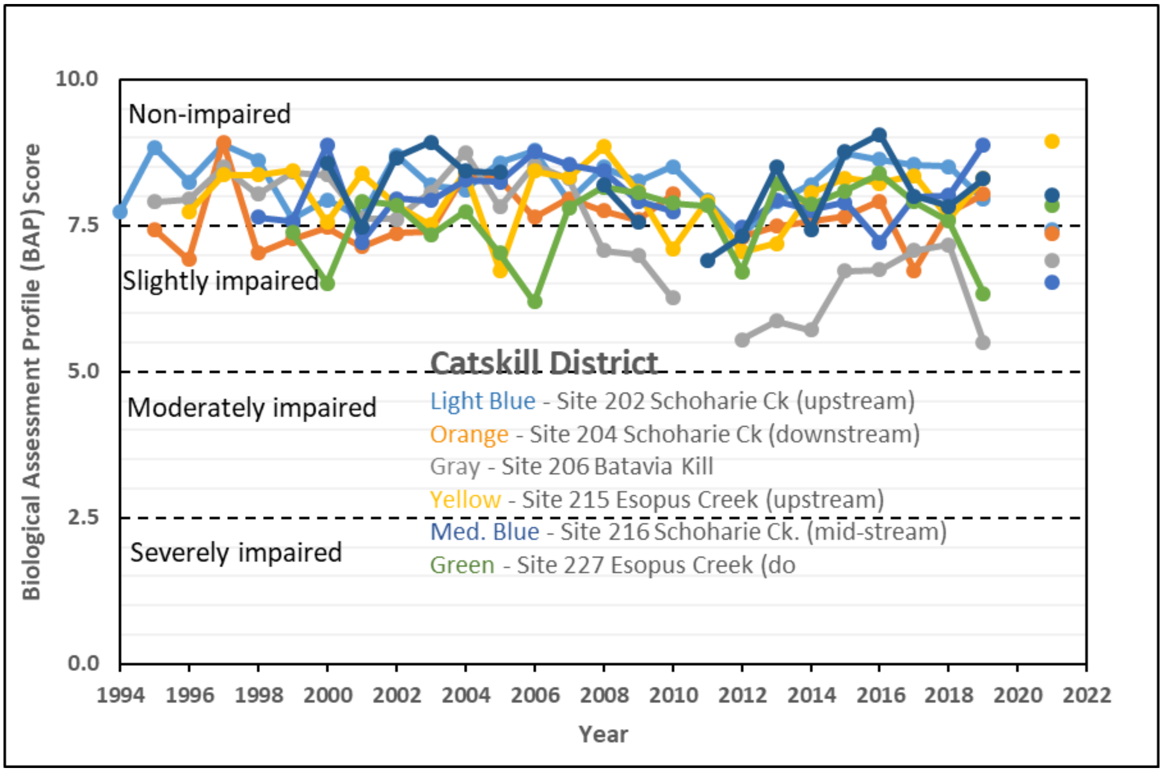


Figure 3.17 1994-2021 BAP scores for all 2021 sample sites within the Catskill District.

Of the seven Delaware System sites assessed in 2021, four were considered slightly impaired (sites 301, 304, 307 and 321). However, sites 304 and 321 were just below the non-impaired threshold. The remaining three sites (316, 320 and 330) were assessed to be non-impaired. While five sites (301, 307, 320, 321 and 330) of the seven had BAP scores lower than their respective period of record means, three of those the sites (320, 321 and 330) had scores that changed just a relatively small amount (Figure 3.18). Additionally, three of the sites (sites 304, 316, and 321) scored higher than during the previous sampling year (2019) and three sites (307, 320 and 330) stayed relatively unchanged with a BAP score decreases of less than 0.5. Site 301 dropped in its BAP score. However, site 301 is the upstream site of the West Branch of the Delaware River and both downstream sites appear fine. DEP will continue to monitor at this site. BAP scores for the period of record for each site are shown in Figure 3.19.

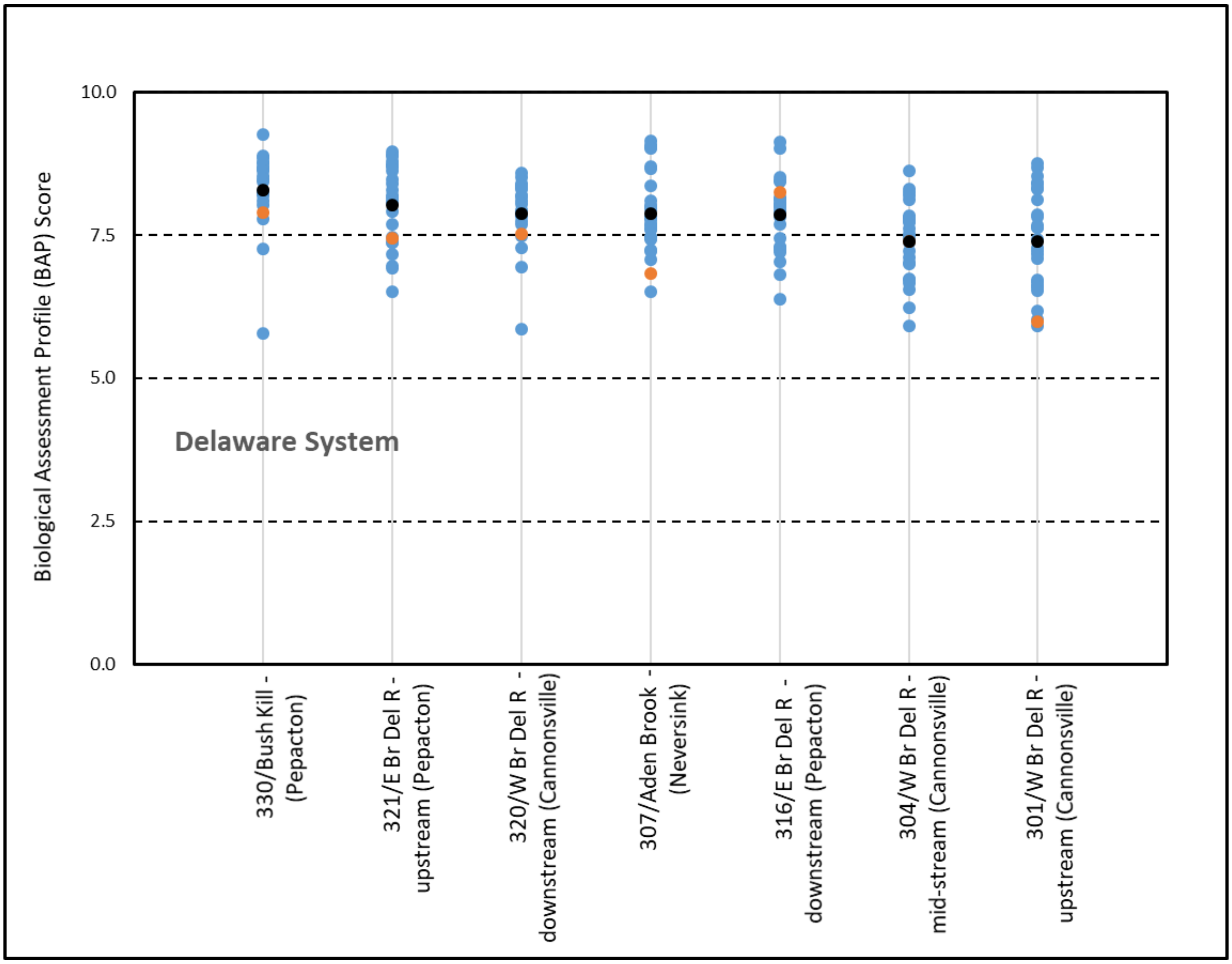


Figure 3.18 Biological Assessment Profile scores for the Delaware System biomonitoring sites sampled in 2021, arranged by mean score from highest to lowest. Black dots represent the mean score, orange dots the 2021 score, and blue dots the pre-2021 scores. The watershed is indicated in parentheses.

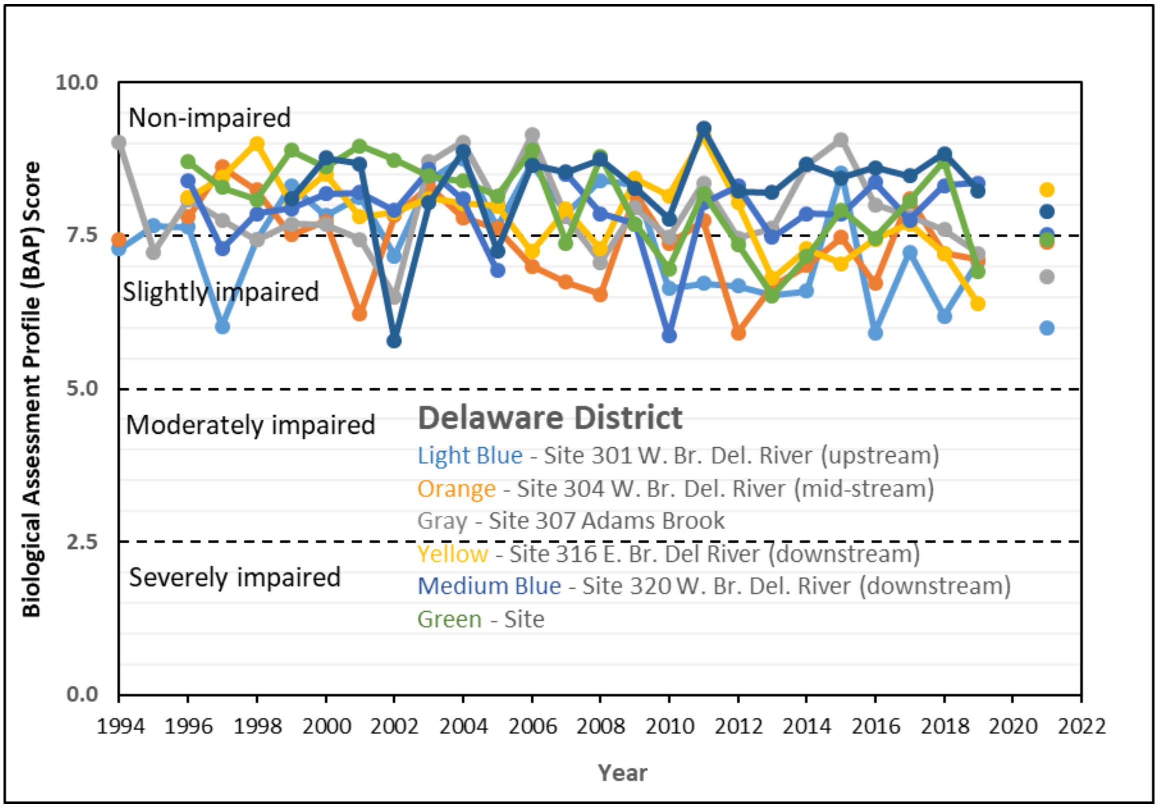


Figure 3.19 1994-2021 BAP scores for all 2021 sample sites within the Delaware District.

3.14 Supplemental Contaminant Monitoring

3.14.1 Volatile (VOC) and Semi volatile Organic (SVOC) Compounds

To supplement required distribution system monitoring, DEP collects one sample at key sites throughout the upstate watersheds during the last quarter of the year to test for many volatile and semi volatile organic compounds as well as the herbicide glyphosate. The list of compounds is provided in Appendix K and the sites sampled are provided below in Table 3.11. All samples were shipped to a contract lab for analysis. In 2021, only one compound at one site was detected above its detection limit. Methyl chloride was detected at the Neversink Reservoir elevation tap NR2 at a concentration of 0.67 µg L^{-1} well below the NYCRR MCL of 5 µg L^{-1} for principal organic contaminants.

Environmental Protection

Table 3.11 Sampling sites for VOC, SVOC, and glyphosate monitoring.

Site Code	Site Description	Reason for Site Selection
	East of Hudson	
CROGH	Croton Gate House	Croton Aqueduct intake
DEL10	Delaware Shaft 10	Delaware intake on West Branch
DEL18DT	Delaware Shaft 18	Delaware intake on Kensico
	West of Hudson	
EARCM (EM)	Ashokan Intake	Represents Ashokan water
NRR2CM (NR2)	Neversink Intake	Represents Neversink water
PRR2CM (PR1)	Pepacton Intake	Represents Pepacton water
SRR2CM	Schoharie Intake monitoring site	Schoharie water entering Esopus
RDRRCM	Rondout Intake	Represents Rondout water
WDTOCM (CR2)	West Delaware Tunnel Outlet	Represents Cannonsville water

If a diversion is off-line at the collection time, the sample is drawn from the upstream reservoir elevation tap that corresponds to the tunnel intake depth as if that reservoir were on-line. In 2021, sampled elevation taps are indicated in parentheses.

3.14.2 Metals Monitoring

Supplemental, noncompliance sampling of the Catskill, Delaware, and East of Hudson systems is conducted to determine background concentrations for a variety of metals as outlined in Table 3.13 and Table 3.14. These metals are monitored at the keypoint sites listed in Table 3.12.

In 2021, sampling was reduced as per COVID-19 protocols. Instead of the normal four samples, the following sites were sampled once: CR2 (elevation tap alternate for WDTOCM), EM (elevation tap alternate for EARCM), NR2 (elevation tap alternate for NRR2CM), PRR2CM, RDRRCM, and SRR2CM. CROGH was sampled twice and CATALUM three times. The usual four samples were collected at keypoints associated with Kensico and West Branch.

Table 3.12 Keypoint sampling sites for trace and other metal occurrence monitoring.

Reservoir Basin	Site(s)
West of Hudson	
Catskill System	
Ashokan	EARCM[1]
Schoharie	SRR2CM[1]
Delaware System	
Cannonsville	WDTOCM[1]
Pepacton	PRR2CM[1]
Neversink	NRR2CM[1]
Rondout	RDRR2CM[1]
East of Hudson	
Kensico	CATALUM, DEL17, DEL18DT, DEL19LAB
New Croton	CROGH[1], CROGH1CM[2]
West Branch	DEL9, DEL10, CWB1.5

[1]Elevation tap samples will be collected when the reservoir is offline.
[2]Only sampled when blending of Croton waters occurs.

Data are reviewed on an annual basis and compared to the Health (Water Source) standard as stipulated in USEPA National Primary and Secondary Drinking Water Standards (Table 3.13) and the New York State Department of Environmental Conservation, Water Quality Regulations, Title 6, Chapter X, Part 703.5 (Table 3.14).

Table 3.13 USEPA National Primary and Secondary Drinking Water Quality Standards.

Analyte	Primary Standard ($\mu g\ L^{-1}$)	Secondary Standard ($\mu g\ L^{-1}$)
Silver (Ag)		100
Aluminum (Al)		50-200
Arsenic (As)	10	
Barium (Ba)	2,000	
Beryllium (Be)	4	
Cadmium (Cd)	5	
Chromium (Cr)	100	
Copper (Cu)	1,300	1,000
Iron (Fe)		300
Mercury (Hg)	2	
Manganese (Mn)		50
Nickel (Ni)		
Lead (Pb)	15	
Antimony (Sb)	6	
Selenium (Se)	50	
Thallium (Tl)	0.5	
Zinc (Zn)		5,000

Table 3.14 Water quality standards for metals from NYSDEC Title 6 regulations.

Analyte	Type	Standard ($\mu g\ L^{-1}$)
Silver (Ag)	H(WS)	50
Arsenic (As)	H(WS)	50
Barium (Ba)	H(WS)	1,000
Cadmium (Cd)	H(WS)	5
Chromium (Cr)	H(WS)	50
Copper (Cu)	H(WS)	200
Mercury (Hg)	H(WS)	0.7
Manganese (Mn)	H(WS)	300
Nickel (Ni)	H(WS)	100
Lead (Pb)	H(WS)	50
Antimony (Sb)	H(WS)	3
Selenium (Se)	H(WS)	10

In 2021, most metal sample results were well below state and federal benchmarks. Antimony, arsenic, beryllium, cadmium, chromium, lead, mercury, selenium silver, and thallium were non-detect in all samples.

Nickel was detected on one occasion at CROGH (1.2 µg L^{-1}) and at SRR2CM (1.2 µg L-^{1}), well below the NYSDEC regulation (Title 6, Chapter X, Part 703.5) of 100 µg L^{-1}. Barium was detected in all 35 samples, ranging from 8.8 µg L^{-1} at CATALUM to 33.6 µg L^{-1} at CROGH. Copper was detected in 18 of 35 samples with concentrations ranging from 1.1 µg L^{-1} to 19.0 µg L^{-1} due to plumbing fixtures at the various keypoint monitoring locations. Zinc was detected in 3 of 34 samples ranging from 13.9 at DEL19LAB to 20.2 µg L^{-1} at CATALUM. Iron was detected in 30 of 35 samples with concentrations ranging from 30 µg L^{-1} at DEL10 to 869 µg L^{-1} at SRR2CM. The SRR2CM result and a result of 407 µg L^{-1} at EM exceeded the USEPA secondary standard of 300 µg L^{-1} for iron while all detected barium, copper, and zinc results were well below their respective standards.

Standards for manganese and aluminum were occasionally surpassed in 2021. The manganese secondary standard of 50 µg L^{-1} was exceeded once at EM (64 µg L^{-1}) and once at SRR2CM (141 µg L^{-1}), while the aluminum secondary standard of 50 µg L^{-1} was exceeded at DEL9 (53.5 µg L^{-1}), CATALUM (74 µg L^{-1}), NR2 (118 µg L^{-1}), PRR2CM (202 µg L^{-1}) and, EM (369 µg L^{-1}). While iron, aluminum, and manganese exceedances may pose aesthetic concerns (e.g., taste, staining), they are not considered a health risk. Moreover, all these sample locations are well upstream of the NYC distribution system. Samples from the Catskill/Delaware System site in closest proximity to distribution, DEL19LAB, were below the benchmarks, ranging from 10.5 to 23.1 µg L^{-1} for aluminum, <30 to 53 µg L^{-1} for iron (the "<" designates the analytical detection limit), and 12 to 25 µg L^{-1} for manganese. The Croton keypoint, CROGH, was also below or equivalent to benchmarks, ranging from <10 to 12 µg L^{-1} for aluminum, from 72 to 74 µg L^{-1} for iron and from 34 to 50 µg L^{-1} for manganese.

3.15 Special Studies

Special studies were initiated when a water quality concern was raised or to better understand monitoring and management alternatives. Investigations in the Kensico basin are reported in Chapter 4.

3.15.1 **Septic to Sewer Conversion Evaluation**

DEP completed a monitoring program to determine if the conversion of onsite septic systems to a centralized sewer collection system would have a statistically significant impact upon water quality downstream of the project area. Project areas were established within and/or near the communities of Bloomville (Wright Brook), Tannersville (Sawmill Creek), and Margaretville (Bull Run), NY with monitoring locations above and below the area converted to a sewer system. Dissolved organic carbon, coliform bacteria, chloride, nutrients, and field-measured analytes were monitored monthly, since they could potentially indicate onsite septic system contributions to the local watershed. Flow at the project areas was not monitored, so nearby US Geological Survey gages were used as surrogates for flow conditions. The three approaches utilized to determine if there was a statistical difference between the pre- and post-conversion periods were 1) comparing all pre- and post-conversion data, 2) subsetting the data into three-month seasonal periods, and 3) separating data based upon flow conditions.

Evaluation of pre- versus post-construction conversion focused upon water quality changes downstream of the project area to determine if there was a statistically significant improvement in water quality. The upstream monitoring locations' primary purpose was to evaluate whether the watershed was impacting conditions downstream of the project area and masking potential changes in water quality. Overall, statistical significance increased as analytical results were increasingly partitioned by flow threshold and season, but at the expense of the number of analytical results utilized to calculate the statistical significance. Also, the ability to determine detectable water quality improvements downstream of the project areas were obscured by trends originating in the watershed upstream of the project area. Two recommendations were made to increase the likelihood of detecting statistically significant differences for future monitoring projects: 1) monitoring should focus on baseflow conditions when groundwater contributions represent the greatest percentage of the stream flow; and 2) ample time must be allowed for monitoring to account for interannual variation in water year. The complete report, "Monitoring and statistical analysis to evaluate changes to local stream water quality related to the conversion of onsite septic systems to a centralized wastewater collection system" is available upon request.

3.15.2 Taste and Odor Sampling

Taste and odor (T&O) compounds such as geosmin (GSM) and 2-methyisoborneol (MIB) can be detected in drinking water at concentrations as low as 10 ng/L. DEP monitors consumer complaints in the distribution system via the 311 system, and water quality calls are categorized based on the type of water quality complaint. When GSM or MIB concentrations are greater than the 10 ng/L threshold, musty water quality consumer complaint calls can increase. DEP uses water quality consumer complaint data in conjunction with GSM and MIB data to monitor and manage T&O events. DEP has been monitoring for GSM and MIB in the Croton System since autumn 2019.

In 2021, a total of 761 samples were collected at a total of 48 sites with most monitoring occurring at New Croton Reservoir. While concentrations of MIB at the New Croton Reservoir gatehouses increased in the late autumn period in 2019 and 2020, this trend did not continue in 2021. In 2021, gatehouse (CRO1B, CRO1T, CRO143, CRO163, CRO183) and diversion (CROGH) MIB concentrations remained elevated throughout the winter and did not subside until March 2021. Unlike previous years, as temperature increased and the reservoir stratified in mid-May, concentrations of MIB started to increase into the summer months. MIB concentrations remained elevated throughout the summer and eventually peaked on August 2, 2021, with a concentration of 550 ng/L MIB detected at CRO183. This peak in MIB concentration coincided with chlorination testing taking place upstream of the Croton Filtration Plant which required withdrawal of water from the Croton Lake Gatehouse. Shortly after water was diverted from the Croton Lake Gatehouse, consumer complaints spiked but resolved when diversion was decreased. Trends of higher MIB concentrations in New Croton Reservoir continued through August 2021 until Tropical Storm Ida inundated the watershed with large rainfall amounts on September 1-2, 2021. Following the storm, concentrations of MIB continued to decrease into autumn and then remained undetectable until the end of the year.

In support of pump station operations, DEP also collected and analyzed 16 total samples from the Croton Falls and Cross River valve chambers. All samples at Croton Falls Reservoir were below detection limit for GSM and MIB. At Cross River there were four detections ranging from 6.8 - 9.1 ng/L GSM and 9.6 - 109.3 ng/L MIB.

3.15.3 Croton Falls Rinse Operation

In 2021 DEP conducted a pilot study that involved transferring Delaware System water to the Croton System to improve water quality. Specifically, Rondout Reservoir water was delivered to West Branch Reservoir via the Rondout-West Branch Tunnel, and West Branch water was delivered to Croton Falls Reservoir via the West Branch Croton River. The goal was to improve Croton Falls water quality in advance of the 2022 Rondout-West Branch Tunnel bypass connection. DEP chose specific conductance as the analyte to assess the displacement of Croton water with Delaware System water within the Croton Falls Reservoir. Profile measurements were collected at one-meter intervals at least every two weeks during the operation.

The operation began in late July, after the thermocline was well established in Croton Falls Reservoir. Delaware system water blended with Croton water which remained confined to upper third of the water column at Croton Falls site 1.1 in the main basin. Monitoring locations located within the two smaller basins showed no displacement of water. Remnants of Hurricane Ida effectively ended the operation on September 1 because Delaware System water contributions were overwhelmed by contributions from the local watershed. Recommendations from this pilot included: 1) initiate operation prior to establishment of the Croton Falls Reservoir thermocline; 2) focus on in-situ analytes that can provide characteristics throughout the entire water column at multiple locations within the Croton Falls Reservoir main basin; and 3) evaluate potential impacts to downstream reservoirs. The complete Croton Falls Rinse Operation After Action Report (DEP 2022) is available upon request.

3.15.4 Emerging Contaminant Monitoring

DEP screened for per- and polyfluoroalkyl substance (PFAS) compounds as part of a larger emerging contaminant project conducted in 2019 (DEP 2019b). In 2021, and as a follow up to this work, DEP conducted quarterly monitoring at the Catskill-Delaware and Croton source water monitoring locations and annual monitoring at Kensico tributaries E9, E10, E11, and Kensico Reservoir limnology Site 6 (6BRK0).

Consistent with 2019 and 2020, the outflow of Kensico Reservoir (DEL18DT) had no detections of the PFAS compounds tested. Monitoring of the outflow of New Croton Reservoir (CROGH) resulted in the detection of four of the 14 compounds tested (Table 3.15). Detections were at or slightly above the MRL (0.0020μgL^{-1}) for these four compounds, as they were in 2019 and 2020, except for PFBS which was only previously detected in December 2020. Although not drinking water, results were below the New York State Drinking Water Standards for PFOS and PFOA (0.010 μgL^{-1} each). Results were also below the New York State Ambient Water Quality Guidance Values for PFOS (0.0027 μgL^{-1}) and PFOA (0.0067 μgL^{-1}) during all four quarters.

The results for **s**amples collected at the three tributary sites (E9, E10, and E11) and one limnology site (6BRK0) in August 2021 are provided in Table 3.16. Limnology site 6BRK0 had a detection of perfluorooctanoic acid (PFOA) at 0.0022 ug/L which was slightly above the method reporting limit of 0.002 ug/l. Tributaries E9, E10, and E11 had detections of five, nine, and seven PFAS compounds, respectively. The compounds detected in the streams were consistent with previous monitoring except for PFBS, which was not detected at E9 in 2021. Concentrations of the compounds during this August 2021 sampling were also in the range of quarterly data from 2019, with E10 concentrations one to three orders of magnitude higher than E9 and E11. In 2021, PFOA continued to be the compound with the maximum value at E9, and PFOS continued to result in the maximum concentration at E10. However, the compound with the maximum result at E11 has been different for each sampling event.

Table 3.15 PFAS results from New Croton Reservoir outflow (CROGH), 2021 (μgL^{-1}).

PFAS compound	Feb 10	May 11	August 3	November 3
Perfluorobutanesulfonic acid (PFBS)	0.0020	0.0020	<0.0020	<0.0020
Perfluorohexanoic acid (PRHxA)	0.0020	0.0021	0.0020	0.0022
Perfluorooctanoic acid (PFOA)	0.0030	0.0030	0.0029	0.0031
Perfluoroctanesulfonic acid (PFOS)	0.0024	0.0024	0.0022	0.0023
Remaining 10 compounds	**<0.0020**	**<0.0020**	**<0.0020**	**<0.0020**

Table 3.16 PFAS results for stream sites E9, E10 and E11 and limnology site 6BRK0, August 3, 2021 (μgL^{-1}).

PFAS compound	E9	E10	E11	6BRK0
N-ethyl perfluorooctanesulfonamidoacetic acid	<0.0020	<0.0020	<0.0020	<0.0020
N-methyl perfluorooctanesulfonamidoacetic acid	<0.0020	<0.0020	<0.0020	<0.0020
Perfluorobutanesulfonic acid (PFBS)	<0.0020	0.043	0.0060	<0.0020
Perfluorodecanoic acid (PFDA)	<0.0020	0.0036	<0.0020	<0.0020
Perfluorododecanoic acid (PFDoA)	<0.0020	<0.0020	<0.0020	<0.0020
Perfluoroheptanoic acid (PFHpA)	0.0037	0.11	0.022	<0.0020
Perfluorohexanesulfonic acid (PFHxS)	0.0020	0.68	0.029	<0.0020
Perfluorohexanoic acid (PFHxA)	0.0040	0.20	0.034	<0.0020
Perfluorononanoic acid (PFNA)	<0.0020	0.11	0.015	<0.0020
Perfluorooctanesulfonic acid (PFOS)	0.0058	1.2	0.034	<0.0020
Perfluorooctanoic acid (PFOA)	0.0093	0.39	0.032	0.0022
Perfluorotetradecanoic acid (PFTA)	<0.0020	<0.0020	<0.0020	<0.0020
Perfluorotridecanoic acid (PFTrDA)	<0.0020	<0.0020	<0.0020	<0.0020
Perfluoroundecanoic acid (PFUnA)	<0.0020	**0.0063**	**<0.0020**	**<0.0020**

4. Kensico Reservoir

4.1 Kensico Reservoir Overview

Kensico Reservoir in Westchester County is the terminal reservoir for the City's raw source water from the Catskill/Delaware water supply. Protection of this reservoir is critically important to prevent water quality degradation and to maintain the Filtration Avoidance Determination. To ensure this goal is met, DEP has a routine water quality monitoring strategy for Kensico aqueducts, streams, and the reservoir that is documented in the Watershed Water Quality Monitoring Plan (WWQMP) (DEP 2018). The sampling site locations are shown in Figure 4.1. The WWQMP prescribes monitoring to maintain compliance with all federal, state, and local regulations; enhance the capability to make current and future predictions of watershed conditions and reservoir water quality; and ensure delivery of the best water quality to consumers through ongoing high frequency surveillance.

Table 4.1 summarizes the approximate number of water quality samples collected within the Kensico watershed during 2021. All Kensico Reservoir aqueduct compliance monitoring was maintained throughout the COVID-19 pandemic. DEP was unable to monitor at the Pleasantville Alum Plant (CATALUM) when the aqueduct was shut down for maintenance during the beginning and end of 2021. All COVID-19 monitoring reductions that occurred in 2021 were implemented after consultation with the NYSDOH.

Table 4.1 Summary of Kensico watershed water quality samples collected in 2021.

Kensico sampling programs	**Turbidity**	**Fecal Coliform**	***Giardia/ Crypto- sporidium***	**Phyto- plankton**	**Other Analyses**
Keypoint effluent	2,194/366*	365	52	165	2445
Keypoint influent	446	444	88	90	2991
Reservoir	701	418		91	2449
Streams	141	141	96		1365

*2,194 samples collected for compliance, and 366 samples collected for process control

Since compliance with the Safe Drinking Water Act Surface Water Treatment Rule (SWTR) (USEPA 1989) is required to maintain the Filtration Avoidance Determination, fecal coliform and turbidity are critical aspects of Kensico water quality monitoring. Fecal coliform and turbidity results during 2021 consistently met compliance requirements for water leaving Kensico Reservoir. The predominantly low fecal coliform results are in large part due to the ongoing success of the Waterfowl Management Program discussed in Section 4.4.1 in greater detail.

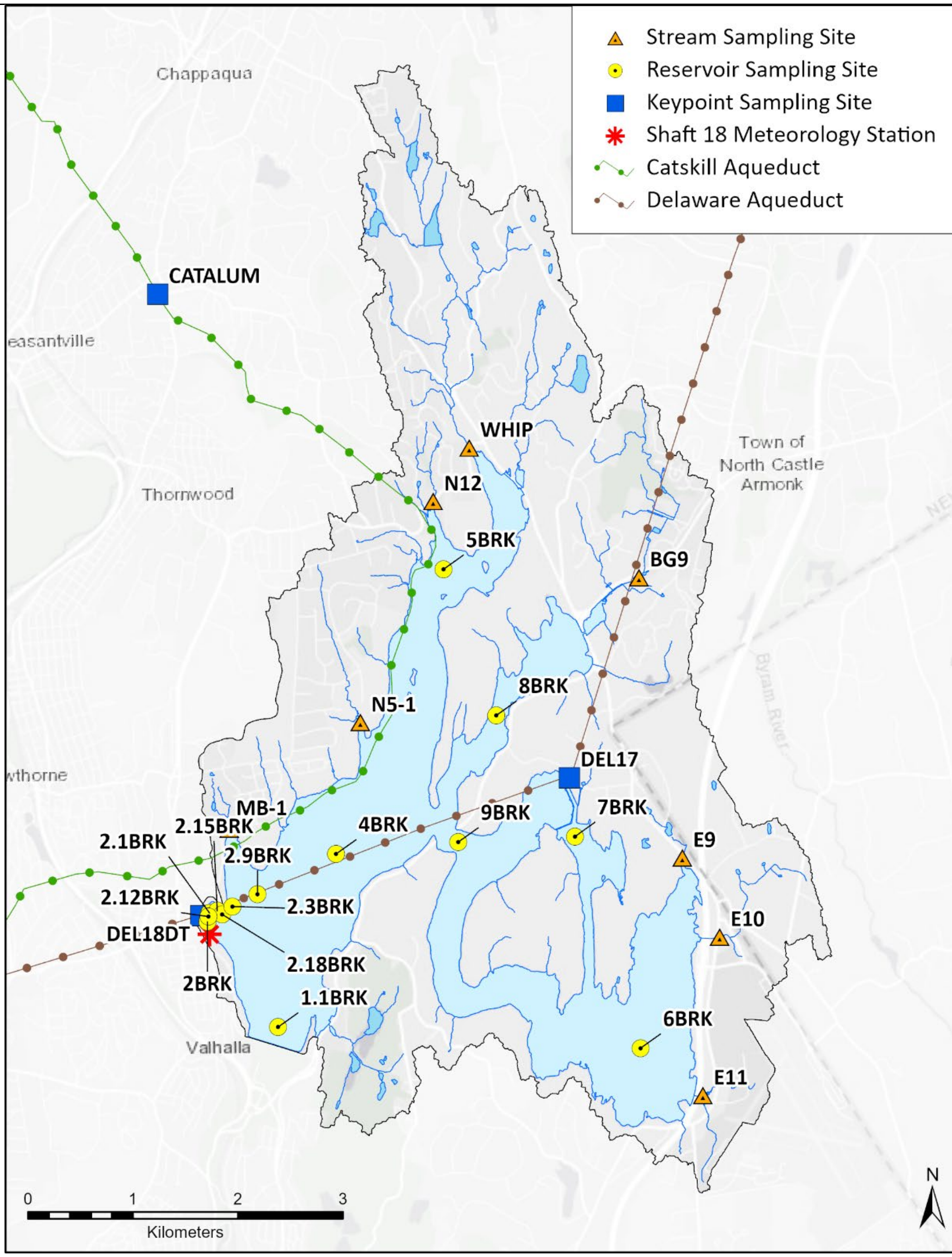


Figure 4.1 Kensico Reservoir showing limnological, hydrological, and keypoint sampling sites, meteorology stations, and aqueducts.

4.2 Reservoir Raw Water Quality Compliance

DEP routinely conducts water quality compliance monitoring at the Kensico Reservoir aqueduct keypoints. The CATALUM and DEL17 influent keypoints represent water entering Kensico Reservoir from the upstate reservoirs of the Catskill/Delaware System via the Catskill and Delaware aqueducts, respectively. The monitoring for CATALUM and DEL17 includes requirements defined by the Catskill Influent Chamber and Delaware Aqueduct (DEL17) SPDES permits, NY-026-4652 and NY-026-8224 respectively. The DEL18DT effluent keypoint represents Kensico Reservoir water entering the Delaware Aqueduct Shaft 18 facility at a point just prior to disinfection, after which the water travels down to Hillview Reservoir and into the distribution system. Table 4.2 outlines the routine grab sample monitoring that occurred at three aqueduct keypoint locations for 2021.

Analytical results from all three keypoint locations are used as an indicator of water quality entering and discharging from Kensico Reservoir. These data are utilized to optimize operational strategies to ensure the delivery of the best quality water leaving the reservoir. Operational strategies are also informed by the continuous monitoring instrumentation for temperature, pH, conductivity, and turbidity at all three locations in near-real time.

Table 4.2 Water quality monitoring for Kensico Reservoir aqueduct keypoints via routine grab samples for 2021.

Site	Fecal* and Total Coliforms, Turbidity, Specific Conductivity, Scent, Apparent Color	Field, pH, and Temperature	Turbidity*	Phytoplankton	UV_{254}	TP	DOC	Alkalinity, Ammonia, NOx, Orthophosphate, TDP, Total Suspended Solids,	Anions (SO4, Cl), Major Metals (Ca, K, Na, Mg), Trace Metals, Fe, Mn, Hg
CATALUM	5D	5D		W	W	W	W	M	Q
DEL17	5D	5D		W	W	W	W	M	Q
DEL18DT	7D	7D	4H	3D	W	M	W	M	Q

4H – Sampled every four hours
7D – Sampled seven days per week
5D – Sampled five days per week.
3D – Sampled three times per week
W – Sampled Weekly
*for SWTR Compliance
M – Sampled Monthly
Q – Sampled Quarterly

Annual median and single sample maximum for turbidity and fecal coliform are included as a partial assessment of the overall water quality for 2021 and can be compared to the previous year (Table 4.3). Assessment of individual 2021 routine grab samples for each of the Kensico aqueduct locations was conducted graphically (Figure 4.2, Figure 4.3, and Figure 4.4) by comparing results to Surface Water Treatment Rule (SWTR) limits. Influent sites (DEL17 and CATALUM) are not subject to the SWTR limits, so the SWTR limit line is provided for reference purposes.

Table 4.3 Kensico keypoint fecal coliform and turbidity metric results.

Analyte	Kensico Sampling Location	Median		Single Sample Maximum	
		2020	2021	2020	2021
Fecal coliform (coliforms $100mL^{-1}$)	CATALUM	<1	<1	24	E4
	DEL17	1	1	33	E120
	DEL18DT	1	1	55	E82
Turbidity (NTU)	CATALUM	1.5	1.8	55	9.6
	DEL17	0.8	0.8	1.5	3.1
	DEL18DT	0.8	0.8	1.3	2.1

The 2021 turbidity and fecal coliform metrics were similar to 2020, except for the single sample maximums (SSM) for CATALUM turbidity and DEL18DT and DEL17 fecal coliform. CATALUM SSM for turbidity was significantly less than the 2020 turbidity SSM result that was associated with the Catskill Aqueduct restart after a 10-week shutdown to remove biofilm growth within the aqueduct. CATALUM 2021 turbidity concentrations were typically less than 2.5 NTU except during mid- to end-March 2021 and late-June to mid-July 2021 (Figure 4.3). Both turbidity increases were associated with operational changes at Ashokan Reservoir including increased transfer of water from the Ashokan West to East Basin in March and the direct transfer of Ashokan West Basin water to Kensico Reservoir in June-July to increase storm event capture capacity for late-summer storms.

For DEL17 and DEL18DT, all turbidity results were less than 5 NTU, and elevated continuous monitoring readings were associated with Hurricane Ida on September 1, 2021, where DEL17 reached a maximum of nearly 5 NTU and DEL18DT reached a maximum of 2.8 NTU. Elevated fecal coliform results were also typically associated with storm events originating in the Ashokan watershed (Figure 4.2 and Figure 4.4). The SWTR requires that no more than 10% of source water samples exceed 20 fecal coliform 100 mL^{-1} over the previous six-month period. In 2021, fecal coliform results exceeding 20 fecal coliform 100 mL^{-1} were primarily associated with Hurricane Ida and a late October 2021 storm event. In 2021, the maximum percent of fecal coliform samples with greater than 20 fecal coliform 100 mL^{-1} for any consecutive six- month period was 3.28 % (Figure 4.4).

All three keypoint sites remained non-restricted for 2021 because less than 10% of all fecal coliform samples were greater than 20 fecal coliforms $100mL^{-1}$ (Section 3.3.1). In 2021, Kensico water quality was well within the SWTR requirements for both fecal coliforms and turbidity.

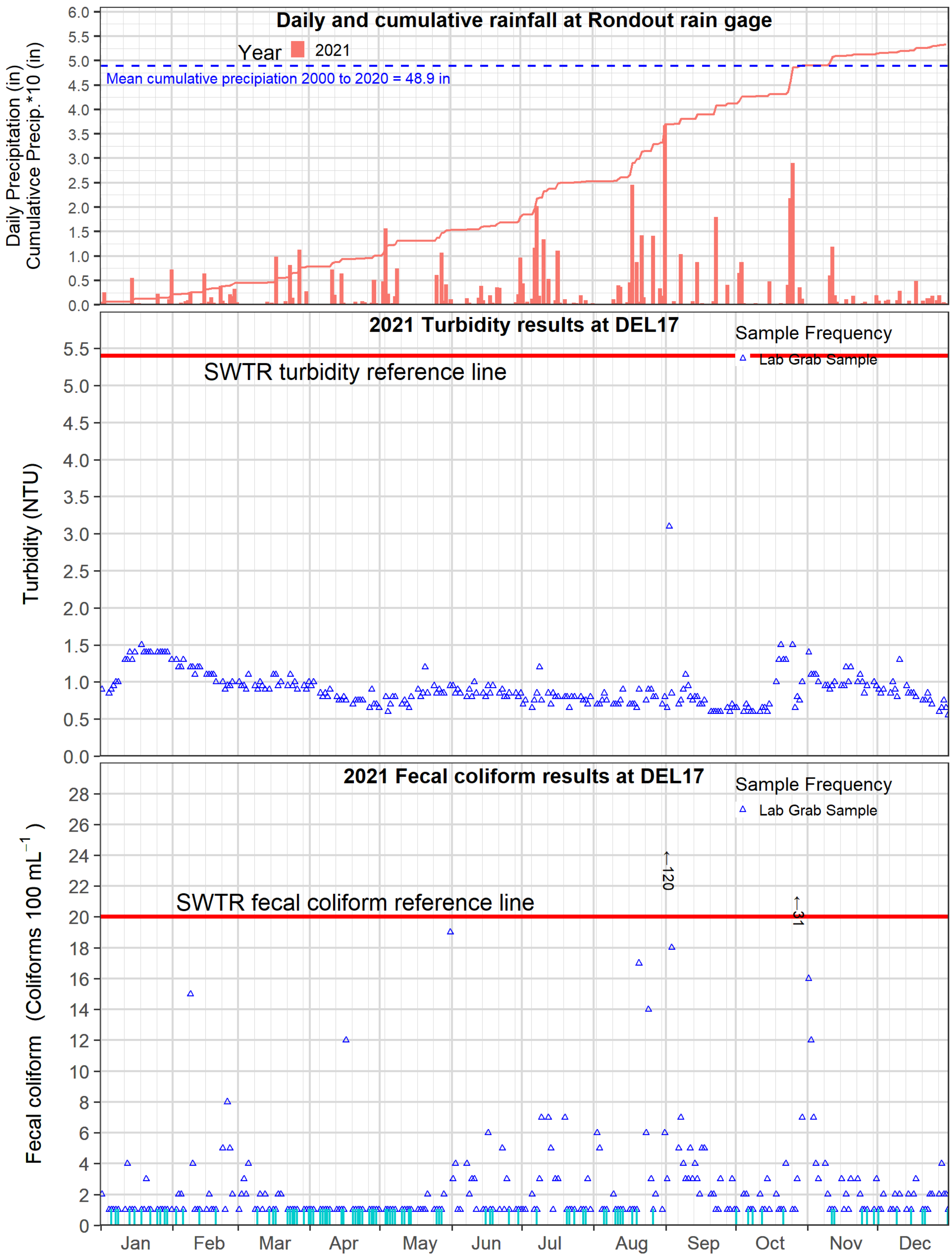


Figure 4.2 Five-day-per-week turbidity and fecal coliform grab samples at DEL17. Drop lines indicate censored values.

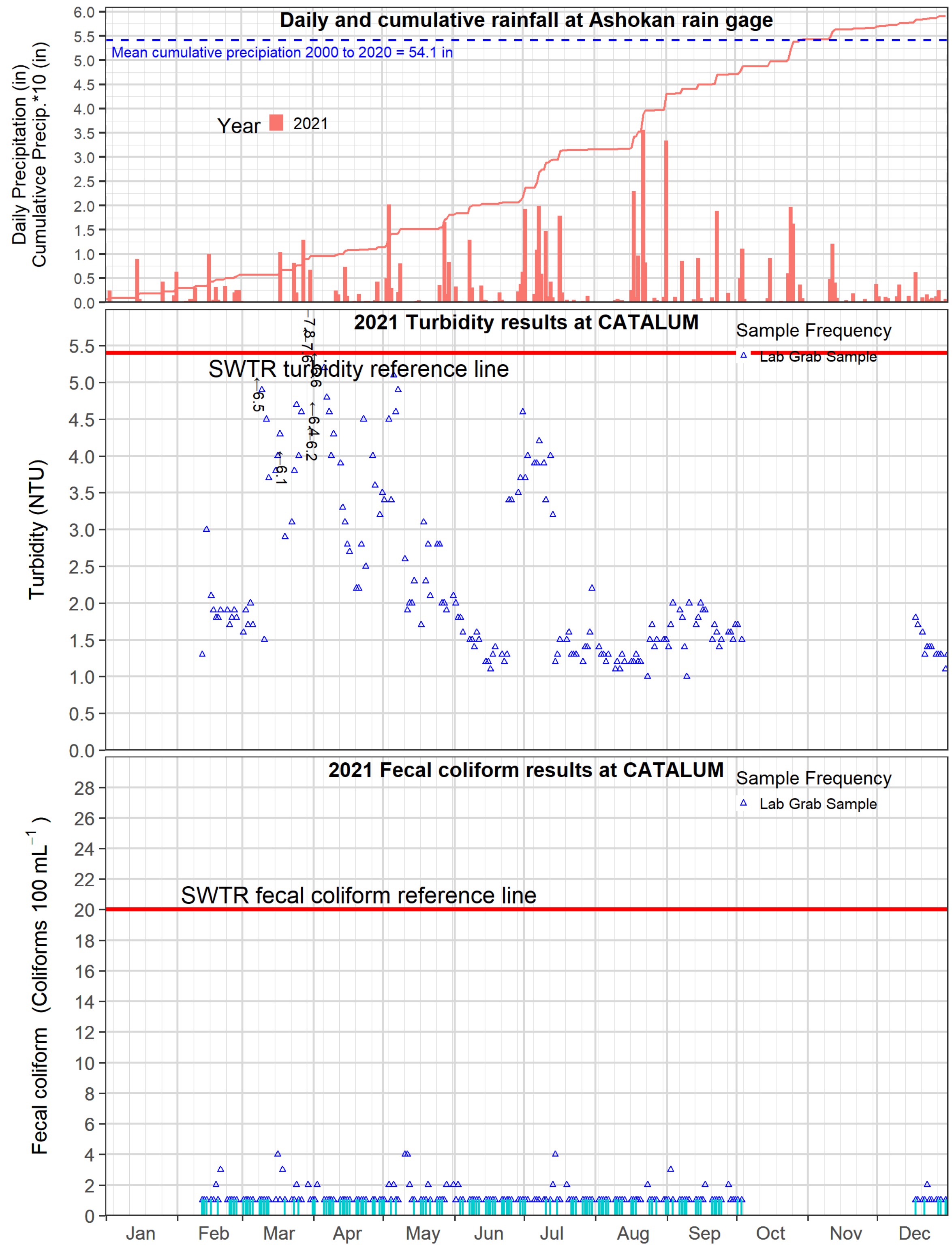


Figure 4.3 Five-day-per-week turbidity and fecal coliform grab samples at CATALUM. Drop lines indicate censored values.

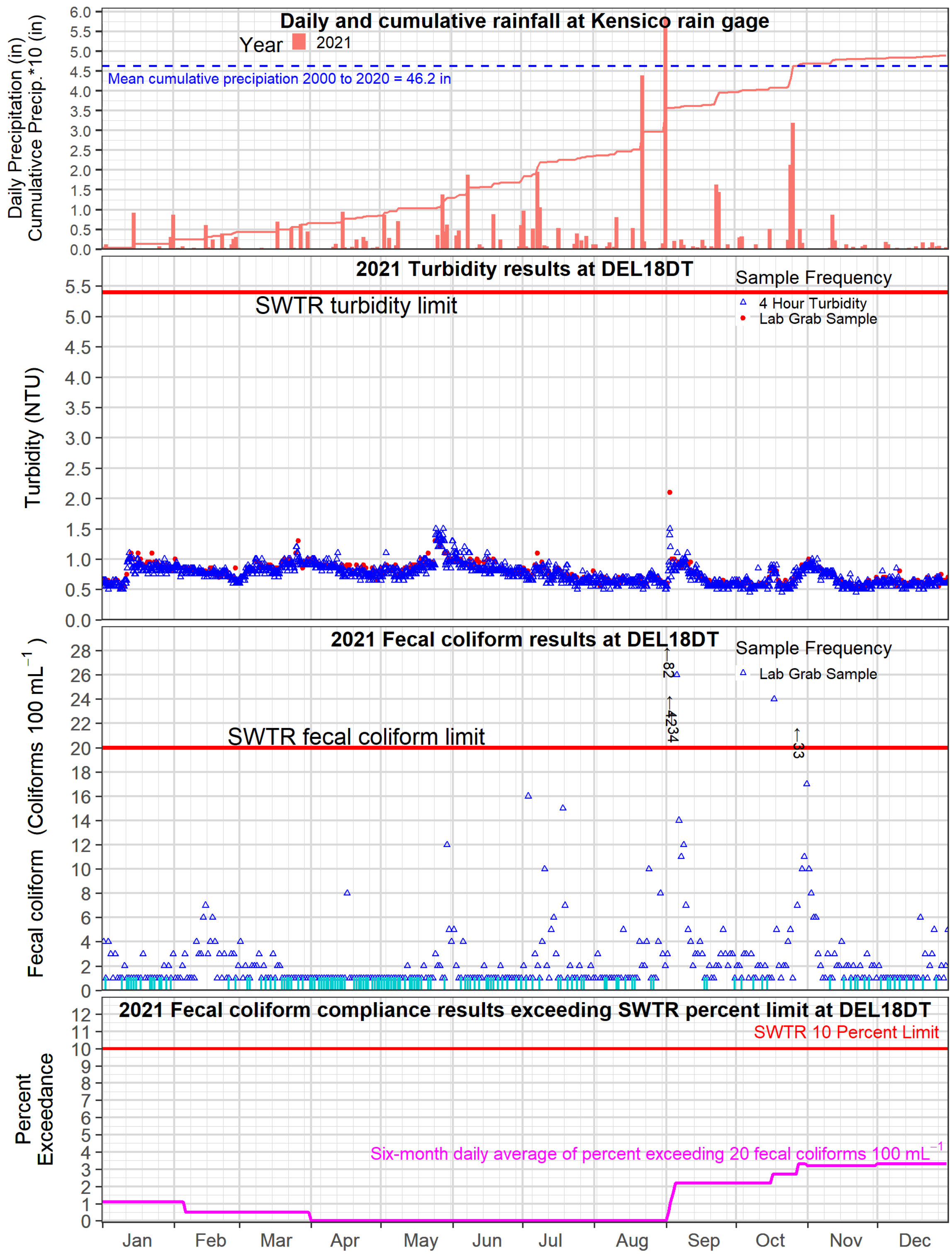


Figure 4.4 Seven-day-per-week turbidity and fecal coliform grab samples at DEL18DT. Drop lines indicate censored values.

4.3 Kensico Watershed Monitoring and Turbidity Curtain Inspections

4.3.1 Kensico Watershed Monitoring

DEP continues to conduct a fixed-frequency monitoring program at stream and reservoir sites in the Kensico watershed with turbidity and fecal coliform being the primary analytes of focus in this section. Routine samples were collected from eight perennial streams and seven locations within Kensico Reservoir. Additional sites were monitored to evaluate potential impacts within the watershed and reservoir (Figure 4.1).

Kensico perennial stream have continuous flow measurement structures at each location. WHIP (Whippoorwill Creek) and BG9 (Bear Gutter) are determined via a rating curve. E11 (Stream E11), E10 (Stream E10), MB-1 (Malcolm Brook), and N5-1 (Stream N5-1) are determined via a V-notch weir. N12 (Stream N12) and E9 (Stream E9) are determined via an H-flume that accommodates a wider range of flows. With each watershed having a different drainage area and BMP type, the hydrograph can be shaped differently and same-day monitoring occurring at a different position on the hydrograph. The nearby USGS flow gage Cross River near Cross River provides an estimate of flow conditions within the Kensico watershed (Figure 2.3). Turbidity and fecal coliform 2021 routine monitoring results for these streams were typically near or below the previous 10-year monthly median concentrations except when monitoring was influenced by storm event flow (Figure 4.5). All samples collected during May, June, and October 2021 with elevated concentrations, as compared to the 10-year median, were almost always associated with storm events. One instance not associated with a storm event was January 2021 at N12 when an elevated fecal coliform concentration was associated with a quick decrease in flow conditions.

For all Kensico Reservoir 2021 routine monitoring turbidity grab samples, the annual median turbidity concentration was 0.8 NTU (Figure 3.1) with individual results ranging from 0.35 to 4.1 NTU (Figure 4.6). Figure 4.6 shows interpolated concentrations, where shading and contour lines are an estimate of turbidity concentrations and may not fully represent actual concentrations in those portions of the reservoir. The highest turbidity concentrations occurred at profile location 5BRK which is heavily influenced by incoming Catskill System water (CATIC). The impacts of the December 2020 rain-on-snow event on the Ashokan watershed were observed into early May 2021 until Ashokan Reservoir water temperature increased enough to facilitate settling of clay particles from the water column. Two other late summer/early autumn storms caused a minimal increase within Kensico Reservoir. The remnants of Hurricane Ida (September 1, 2021) resulted in a minimal turbidity increase at the main basin monitoring locations but led to a localized event near the Delaware Shaft 18 facility. The late October 2021 storm event increased turbidity concentrations at the bottom of the profiles at 1.1BRK and 6BRK. Fecal coliform results were also generally low; the 75th percentile in 2021 was 2 fecal coliform 100mL^{-1} (Figure 3.2) with approximately 52 percent of the monthly reservoir grab samples resulting in no detectable fecal coliforms and one result greater than 20 fecal coliform 100mL^{-1};

associated with the remnants of Hurricane Ida. Fecal coliform results cannot be plotted as a contour plot because of the number of censored values.

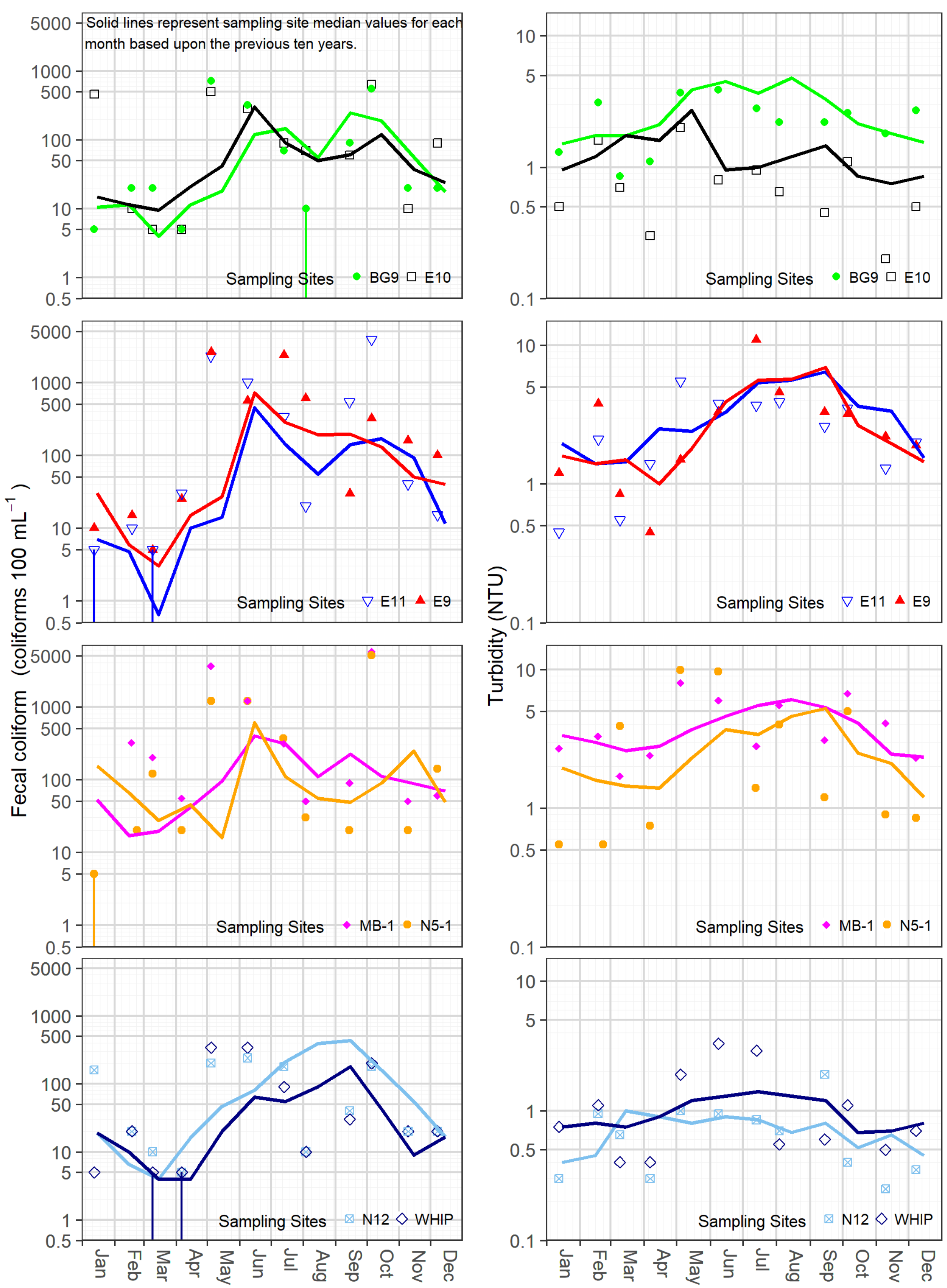


Figure 4.5 Routine Kensico stream monitoring results compared to previous ten-year median.

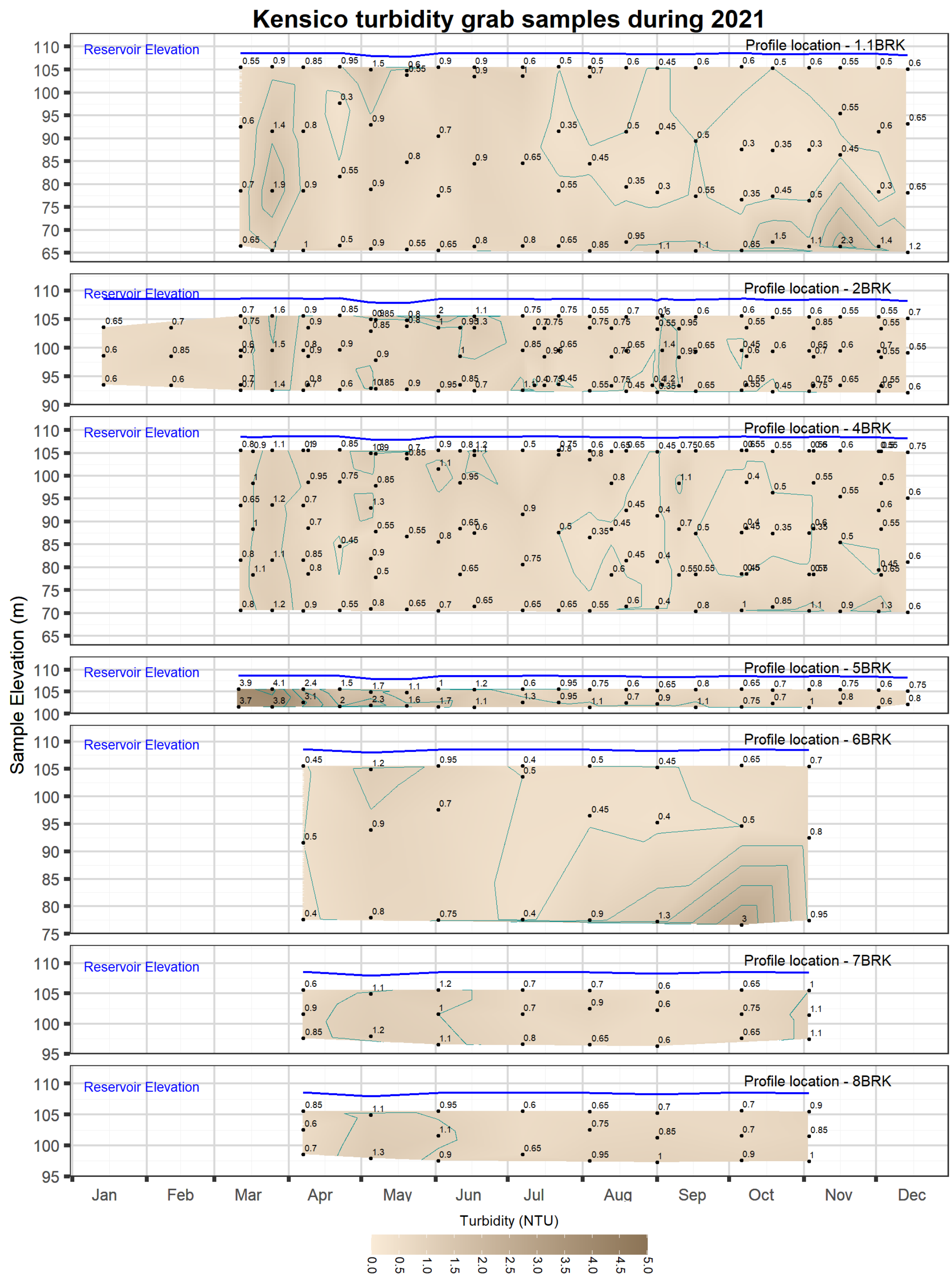


Figure 4.6 Kensico Reservoir turbidity grab sample results for 2021 with analytical measurements marked as points overlaying an interpolated concentration map.

4.3.2 Turbidity Curtain Inspection

The three turbidity curtains in the Catskill Upper Effluent Chamber cove (CATUEC) are designed to redirect water from the CATUEC cove into the main waterbody of Kensico Reservoir and minimize impacts of storm events by local streams. Since September 2012, with the activation of the Catskill/Delaware Ultraviolet Light Disinfection Facility, the CATUEC chamber has been off-line because there is insufficient pressure head to drive water from the chamber to the UV Treatment facility. During a typical year, DEP visually inspects the turbidity curtains at least monthly from fixed shore locations around the cove as part of the ongoing maintenance of the curtains. Due to the COVID-19 pandemic, no inspections were performed during 2021. During a normal year, when inspections indicate that maintenance is required, Bureau of Water Supply Systems Operations is notified, and operations staff perform the appropriate repairs or adjustments.

4.4 Wildlife Management

4.4.1 Waterfowl Management

The Waterfowl Management Program (WMP) was designed to study the relationship between trends in seasonal bird populations on the reservoirs and fecal coliform concentrations both within the reservoirs and at the keypoint water sampling locations. The objective of the program is to minimize fecal coliform loading to the reservoirs from roosting birds during the migratory season.

Migratory populations of waterbirds utilize NYC reservoirs as temporary staging areas and wintering grounds and can contribute to increases in fecal coliform loadings during the autumn and winter, primarily from direct fecal deposition in the reservoirs. These waterbirds generally roost nocturnally and occasionally forage and loaf diurnally on the reservoirs, although most foraging activity occurs away from the reservoirs. In the past, avian fecal samples collected from both Canada geese (*Branta canadensis*) and ring-billed gulls (*Larus delawarensis*) revealed that fecal coliform concentrations are relatively high per gram of feces (Alderisio and DeLuca 1999). This is consistent with data from water samples collected over several years near waterbird roosting and loafing locations, demonstrating that fecal coliform levels correspond to waterbird populations at several NYC reservoirs (DEP 2002). As seasonal waterbird population counts increased during the avian migratory and wintering periods, fecal coliform bacteria levels also increased. Continued implementation of avian dispersal measures has led to reduced waterbird counts and fecal coliform levels, allowing DEP to maintain compliance with the federal Surface Water Treatment Rule (SWTR).

Historic water quality monitoring data collected at the two main water influent and effluent facilities at Kensico demonstrated that higher levels of fecal coliform bacteria were leaving the reservoir than what was contributed through aqueducts from the upstate reservoirs (DEP 1992). It was apparent then that a local source of fecal coliform bacteria was impacting

Kensico. One of DEP's Watershed Protection Program objectives was to identify and mitigate all potential sources of fecal coliform bacteria at Kensico Reservoir. Implementation of waterbird dispersal actions starting in autumn 1993 demonstrated an immediate and marked decline in bacteria. Based on these data, DEP determined that waterbirds were the most important contributor to seasonal fecal coliform bacteria loads to Kensico.

The WMP includes standard bird management techniques at several City reservoirs that were approved by the U.S. Department of Agriculture's Animal and Plant Health Inspection Service's Wildlife Services (USDA), and in part under registration and permit by the U.S. Fish and Wildlife Service (USFWS) and a permit with the New York State Department of Environmental Conservation (NYSDEC). DEP maintains an annual depredation permit from the USFWS to manage avian species and a NYSDEC Possession and Collection Permit to manage mammalian populations for water quality improvements. Additional federal and state permits have been acquired for the protection of endangered and threatened species that inhabit the reservoirs and surrounding watersheds.

Avian management techniques include non-lethal dispersal actions by use of pyrotechnics, motorboats, airboats, propane cannons, active nest removals of terrestrial avian species, remote-control boats, and physical chasing. Bird deterrence measures include waterbird reproductive management, shoreline fencing, bird netting, overhead bird deterrent wires, and meadow management. Lethal avian management is only implemented at Hillview Reservoir as a last option and was implemented as needed in 2021, whereby 37 ducks were removed.

The Surface Water Treatment Rule (40 CFR 141.71(a)(1)) states that no more than 10% of source water samples can have counts that exceed 20 fecal coliforms $100mL^{-1}$ over the previous six-month period. Since the inception of the WMP, no such violation has occurred at Kensico Reservoir. The link between this success and the WMP is demonstrated by comparing source water fecal coliform levels before and after the implementation of the WMP (Figure 4.7). DEP will continue implementation of the WMP to help ensure delivery of high-quality water to City consumers.

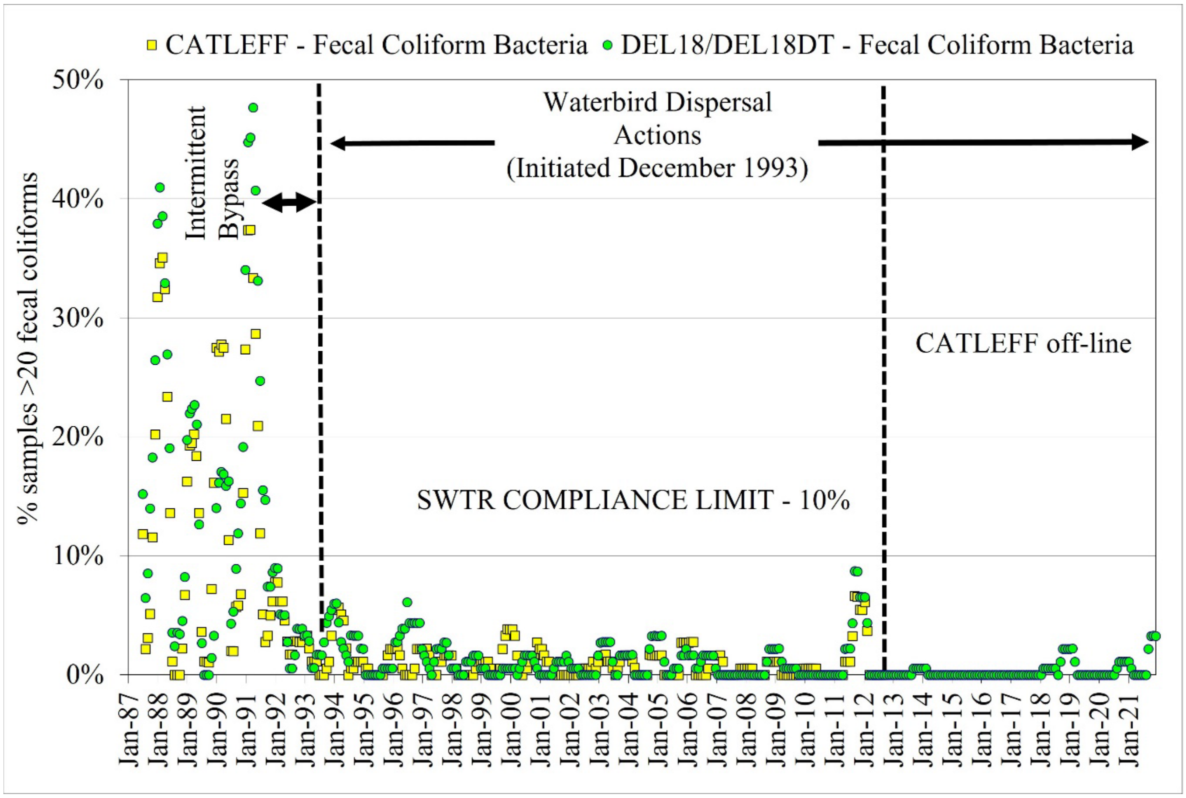


Figure 4.7 Percent of keypoint fecal coliform samples at Kensico Reservoir greater than 20 fecal coliforms $100mL^{-1}$ for the previous six-month period, 1987-2021. The first vertical dashed line indicates the year in which the WMP was implemented.

4.4.2 Terrestrial Wildlife Management

In advance of storm events that are expected to yield substantial precipitation levels, pre-storm wildlife sanitary surveys are conducted adjacent to the Delaware Shaft 18 Effluent Facility at Kensico Reservoir in the vicinity of the source water intake. All wildlife fecal excrement from birds and mammals are collected during these surveys and identified to species and disposed of in advance of the storms to prevent the feces from being washed into the reservoir.

During 2021, DEP and its contractor conducted 31 wildlife sanitary surveys in advance of significant precipitation events at Kensico Reservoir Shaft 18 in the vicinity of the water intake facility (Table 4.4). On one of 22 surveys there was no evidence of excrement observed at the collection site. Of the 885 fecal samples collected, 52% were attributed to white-tailed deer (*Odocoileus virginianus*), 1.5% to rabbits (*Sylvilagus spp.*), 0.9% to raccoons (*Procyon lotor*), and approximately 4% to other mammals. Avian species excrement included 26% from passerine bird species and 15.3% from Canada geese. One additional wildlife sanitary survey was conducted at the Catskill Effluent Cove and N5 Stream in the Kensico Main Basin on October 25, 2021 and is reported in Table 4.5.

Table 4.4 Wildlife sanitary surveys conducted adjacent to Delaware Aqueduct Shaft 18.

Date of Survey	White-tail Deer	Raccoon	Rabbit	Canada Goose	Coyote	Mink	Striped Skunk	Passerine (birds)	Domestic Dog	Other/ Unknown Mammal	Total
1/7/2021	0	0	0	0	0	0	0	0	0	0	**0**
1/15/2021	7	0	1	0	0	0	0	0	0	1	**9**
3/28/2021	16	2	3	8	0	0	0	0	0	2	**31**
4/14/2021	0	0	0	52	0	0	0	0	0	1	**53**
4/21/2021	0	0	0	8	0	0	0	0	0	0	**8**
5/4/2021	0	0	0	14	0	0	0	0	0	0	**14**
5/26/2021	0	0	0	32	0	0	0	43	0	0	**75**
6/9/2021	0	0	0	0	0	0	0	2	4	0	**6**
6/15/2021	0	0	0	0	1	0	0	8	0	0	**9**
6/22/2021	0	0	0	0	0	1	0	25	0	0	**26**
6/30/2021	0	0	0	0	0	0	0	58	0	0	**58**
7/6/2021	0	0	0	0	0	0	0	48	0	0	**48**
7/27/2021	0	0	0	0	0	0	0	3	0	0	**3**
8/2/2021	6	2	0	20	0	0	0	0	0	3	**31**
8/3/2021	52	0	0	0	0	0	0	0	0	0	**52**
8/20/2021	1	0	2	1	0	0	0	1	0	0	**5**
8/31/2021	1	0	0	0	0	0	0	1	0	2	**4**
9/15/2021	0	0	0	0	0	0	0	13	0	0	**13**
9/21/2021	2	0	1	0	0	0	0	18	0	2	**23**
9/22/2021	0	1	0	0	0	0	0	0	0	1	**2**
9/27/2021	15	1	0	0	0	0	0	0	0	0	**16**
10/4/2021	17	0	0	0	0	0	0	0	0	4	**21**
10/9/2021	32	0	2	0	0	0	0	0	0	0	**34**
10/16/2021	1	0	1	0	4	0	1	1	0	1	**9**
10/24/2021	70	0	0	0	0	0	0	0	0	5	**75**
10/25/2021	47	0	0	0	0	0	0	2	0	0	**49**
10/29/2021	15	0	0	0	0	0	0	0	0	0	**15**
11/11/2021	74	1	2	0	0	0	0	2	0	0	**79**
11/18/2021	33	1	1	0	0	0	0	9	0	1	**45**
11/21/2021	36	0	0	0	0	0	0	0	0	0	**36**
12/17/2021	35	0	0	0	0	0	0	0	0	1	**36**
Total by species	**460**	**8**	**13**	**135**	**5**	**1**	**1**	**234**	**4**	**24**	**885**
Percent by species	**52.0**	**0.9**	**1.5**	**15.3**	**0.6**	**0.1**	**0.1**	**26.4**	**0.5**	**2.7**	**100**

Table 4.5 Wildlife sanitary survey conducted at Catskill Effluent Cove and N5 Stream.

Date of Survey	Supplemental Survey locations at Kensico Reservoir	White-tail Deer	Raccoon	Coyote	Other/ Unknown Mammal	Total
10/25/2021	N5	8	37	0	0	**45**
10/25/2021	Catskill Effluent Cove	33	19	3	2	**57**
Total by species		**41**	**56**	**3**	**2**	**102**
Percent by species		**40.2**	**54.9**	**2.9**	**2.0**	**100**

4.5 Kensico Research Projects and Special Investigations

4.5.1 Bryozoans

Monitoring of bryozoan colonies in the five sluiceways at Shaft 18 continued in 2021. In addition to high definition (HD) video recordings, water quality parameters (temperature, turbidity, etc.) and operational conditions (daily flow) were documented at the time of each visit.

Due to reduced monitoring associated with COVID-19, video surveys in 2021 were limited to one in February to inform operations staff about sluiceway conditions, and two in September. The September surveys were conducted to inform operations staff of any areas that contained high concentrations of colonies which might require divers to enter the sluiceways for removal as has been done in the past.

The two September surveys, conducted after most of the growing season had passed, confirmed less growth in the sluiceways that had been closed most frequently, and more in the sluiceways that had the most flow. The review of historical data records and close collaboration with operational staff was again extremely helpful and resulted in reduced colonial growth compared to times of no gate closures. No occlusion issues were reported downstream of Shaft 18 or downstream of the CDUV plant in 2021.

4.5.2 Special Investigations in the Watershed

The following five special investigations occurred within the Kensico Reservoir watershed during 2021 and are listed below in chronological order. Each of these special investigations evaluated the potential impacts to drinking water quality. A summary of each investigation and the corresponding results are shown below.

4.5.2.1 Kensico Shoreline Stabilization Project: 2021

Kensico Reservoir shorelines around the Delaware Shaft 18 facility were identified as areas that can significantly contribute to turbidity issues, especially during periods of high northeast winds. As a result, a plan to stabilize shoreline areas on both sides of Delaware Shaft 18 was developed. Construction on the shoreline area farthest away from the intake was completed in December 2020, with construction on the shoreline adjacent to Delaware Shaft 18 ongoing. Since construction had the potential to cause and contribute to reservoir turbidity issues, an intensive monitoring plan was developed. The construction contractor was responsible for monitoring turbidity within the sheet piles and turbidity curtains that enclosed the construction area while DEP implemented a monitoring plan outside the construction zone to monitor for turbidity contraventions. DEP's monitoring consisted of the deployment of three fixed depth automated monitoring buoys outfitted with turbidity sensors deployed in the middle of the water column and another near the bottom of the reservoir if depth allowed. DEP also benefitted from data from the fixed-depth buoys on Kensico Reservoir at sites 2.9BRK and 2BRK that are part of the WWQO's routine Robotic Monitoring Program. Site 2.9BRK is located upstream of the construction area and acts as a control to give a picture of background turbidity levels in the reservoir. Site 2BRK, located directly in front of the Shaft 18 intake, allows confirmation that any turbidity issue from the construction project is settling out before reaching the intake area.

In 2021, two of the automated monitoring buoys were located at the new construction area, while one buoy remained near the original shoreline project area to monitor any post-construction issues. Figure 4.8 shows a recent overview photo of both construction areas. All these automated monitoring buoys collect turbidity data at 15-minute intervals and these data are displayed in near real time via the Water Quality Water Hub dashboard. BWS Water Quality and Operations staff constantly monitor the dashboard so that appropriate actions can be taken to ensure that elevated turbidity does not reach the Shaft 18 building. In 2021, no contraventions of the Surface Water Treatment Rule (SWTR) turbidity limit were experienced at Shaft 18. This project is expected to be complete in summer 2022.

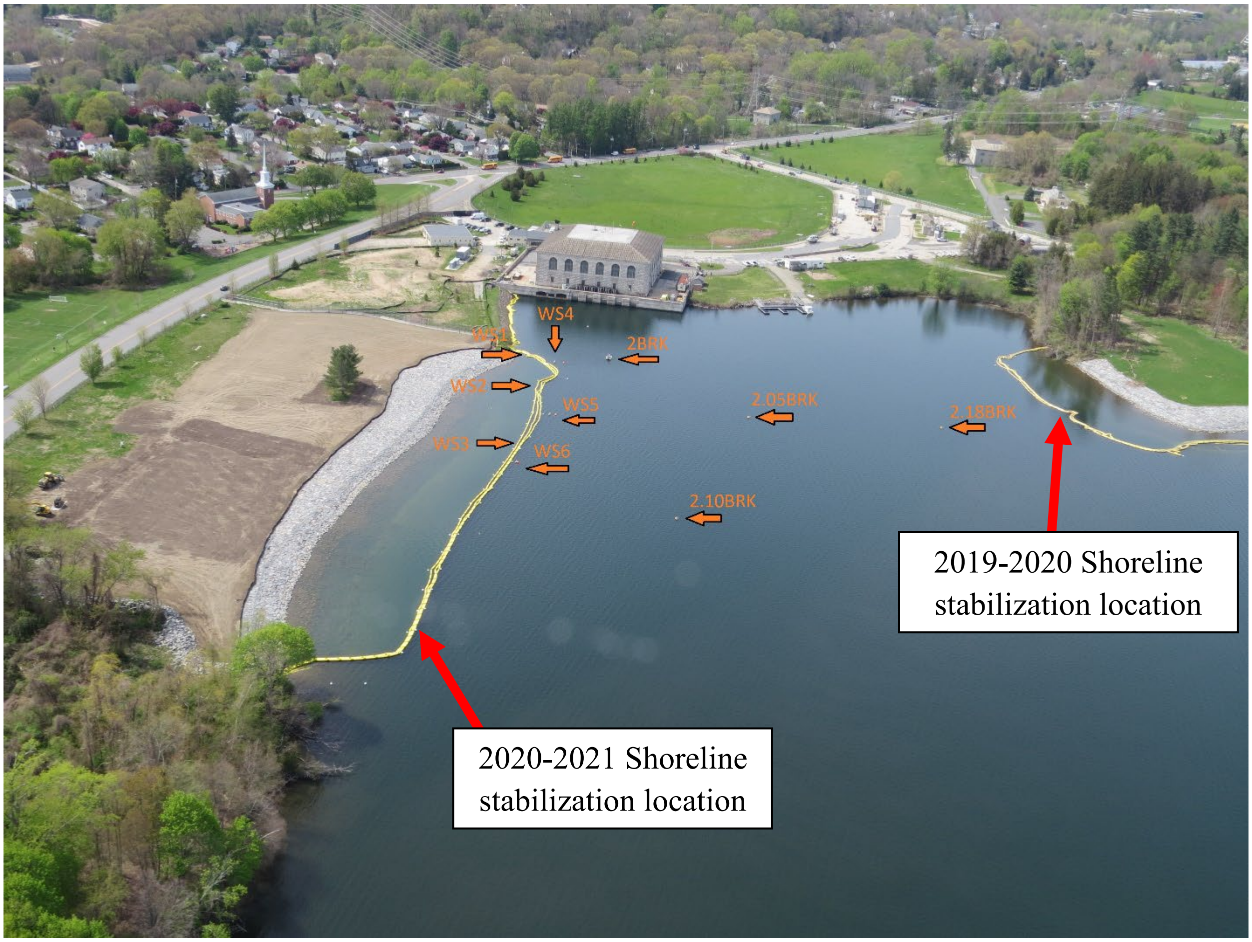


Figure 4.8 Kensico Reservoir shoreline stabilization locations.

4.5.2.2 Whippoorwill Creek Potential Septic Discharge Continued Investigation: June 2021

In 2021, DEP followed up on an investigation of elevated fecal coliform counts and human markers using microbial source tracking (MST) in Whippoorwill Creek headwaters in New Castle. DEP collected five additional samples on June 1, 2021, from the same Whippoorwill neighborhood. Fecal coliform results ranged from 340 to >3,000 coliforms $100mL^{-1}$, and MST testing again resulted in high concentrations (1.15E+03 – 1.02E+06) of the human marker, HF183, at all sites. Approximately 15 homes were suspected of potential issues and REP staff followed up with dye testing in September and October 2021. Permission was received to dye test three of these homes, and all tests were indicative of septic system failure. To date, septic system repairs have been completed at these three residences. Westchester County Department of Health (WCDOH) performed a dye test at a fourth residence, which was also indicative of a failure. DEP also contacted WCDOH via e-mail regarding possible SSTS issues at seven additional residences and is awaiting a response. In addition, at least eight other properties in the Whippoorwill subdivision are suspected of having SSTS issues. DEP contacted the owners; however, permission for dye testing was denied. The Byram Meadows subdivision is another area of potential concern, as recent water samples resulted in elevated bacteria counts during rain events and this area discharges to the Whippoorwill stream closer to Kensico Reservoir.

4.5.2.3 Tropical Storm Henri: August 2021

On August 22-23, 2021, a storm event (T.S. Henri) with approximate total of 4.36 inches of rainfall triggered storm event monitoring. The storm event occurred in two major episodes of rainfall, with the first beginning the morning on August 22 and the second about mid-morning on August 23. Autosamplers triggered early in the storm; however, they failed later and did not catch samples during or after the peak of the hydrograph. Two grab samples were collected late morning on Aug 23: MB-1 at 10:40 a.m. and N5-1 at 11:40 a.m. to represent the latter part of the event. Grab sampling at MB-1 on August 21 (prior to the storm) indicated background levels of turbidity, conductivity, and fecal coliform (5.1 NTU, 612 μScm^{-1}, and an estimated 60 fecal coliforms $100mL^{-1}$, respectively). Samples taken at N5-1 on August 22, very early in the event, were similar for these three parameters, showing only slight increase in turbidity and fecal coliforms. These initial results were similar to the routine monthly samples taken on August 3. Flows at sites N5-1 and Malcolm Brook (MB-1) showed a sharp increase in flow on August 22 with discharges reaching 24.87 cfs at N5-1 and 6.45 cfs at MB-1. When additional precipitation fell on August 23, another peak in stream discharge resulted in flows of 13.51 cfs at N5-1 and 5.22 cfs at MB-1. Fecal coliforms peaked as well, with concentrations rising to 6,500 and 14,000 fecal coliforms $100mL^{-1}$ at N5-1 and MB-1, respectively.

Microbial source tracking analysis using Bacteroidales was performed on the two grab samples collected on the morning of August 23 at MB-1 and N5-1. Both the human marker (HF183) and the canine marker (BacCan) were investigated. The MB-1 sample resulted in a trace amount of the human marker and 2.27E+03 for the canine marker. The N5-1 sample returned quantifiable results for both markers with 3.56E+03 for the human marker and 4.94E+03 for the canine marker.

4.5.2.4 Tropical Storm Ida: September 2021

On September 1-2, 2021, T.S. Ida impacted the Kensico watershed by depositing approximately 5.8 inches of precipitation. This event was preceded by 4.36 inches of rain brought by T.S. Henri 10 days earlier. DEP visually inspected the area around Delaware Shaft 18 and the stormwater BMPs within the Kensico watershed both during and after T.S. Ida. A silt fence failure was noted along the shoreline proximal to Shaft 18 and was addressed quickly to minimize the amount of soil runoff into the reservoir adjacent to the intake chamber. This was important even though Kensico Reservoir was in float mode during the storm event since water was still able to be withdrawn from Kensico to meet demand for the duration of the Kensico Shoreline Stabilization project. Around the watershed, the N5 sub-basin experienced significant erosion that resulted in a localized increase in turbidity and required an emergency spillway repair. Initial turbidity increases at DEL18DT, for the continuous monitoring and grab samples, were probably attributed to the silt fence failure at Shaft 18, rather than N5, due to travel time. Fecal coliform results at DEL18DT exceeded 20 fecal coliforms $100mL^{-1}$ for the first four samples collected after the storm event began, following an expected exponential decay. The six-month daily average for the percent of samples exceeding 20 fecal coliforms $100mL^{-1}$ at DEL18DT was just over 2% percent following T.S. Ida, which is well below the SWTR 10% limit for meeting fecal coliform water quality standards. Additional information regarding T.S. Ida is provided in the after-action report "Tropical Storm Ida – Response to Elevated Turbidity and Fecal Coliform Counts" and is available upon request.

4.5.2.5 Storm Event: October 2021

On October 25-26, 2021, a storm event with approximately 4.43 inches of precipitation (as measured at Westchester County Airport weather station KHPN) triggered storm event monitoring at Kensico streams. The storm event sampling continued until the morning of October 27 and covered two major peaks in flow, the first starting in the morning on October 26 and the second during the evening of the same day. Flows at sites N5-1 and Malcolm Brook (MB-1) reached their discharge maxima before noon on October 26, with discharges reaching 35.59 cfs at N5-1 and 9.15 cfs at MB-1, after which flow quickly declined at both sites. This was followed by additional precipitation in the afternoon and another increase in flow with discharges reaching 16.62 cfs at N5-1 and 6.20 cfs at MB-1, after which flow tapered off over the next two days. Seventeen automated samples were collected and analyzed from the Kensico stream storm sites (MB-1 and N5-1) during the increases and decreases in flow. Fecal coliforms in the MB-1 storm samples were highest (17,000 fecal coliforms $100mL^{-1}$) in the first sample early on October 26, during the initial rise in stream discharge. Turbidity in Malcolm Brook reached its maximum (40 NTU) at the peak flow. Fecal coliforms and turbidity showed a different pattern at N5-1 with turbidity reaching its maximum (65 NTU) in the first sample, and fecal coliforms reaching its maximum (52,000 fecal coliforms $100mL^{-1}$) in the composite sample (representing five samples) collected closest to the peak flow. Specific conductivity results behaved similarly at both sites, with the highest values (428 $\mu S\ cm^{-1}$ at MB-1 and 234 $\mu S\ cm^{-1}$ at N5-1) in the first storm samples at each site. Conductivity results then decreased until after midday on October 26, followed by increasing conductivity results during the last 3-5 samples.

Microbial source tracking with Bacteroidales was used to analyze four samples from each site, MB-1 and N5-1. The human marker (HF183) was tested and was not detected in three of the four MB-1 samples. The fourth MB-1 sample was positive for a trace amount of the human marker, which is consistent with past results. Conversely, all four N5-1 samples were positive for the human marker in quantifiable amounts. Concentrations ranged from 2.16E+03 to 1.01E+04, suggesting input from a human source during the storm.

Fecal coliform samples taken at DEL18DT ranged from E7 fecal coliforms $100mL^{-1}$ on October 27 to a high of 33 fecal coliforms $100mL^{-1}$ on October 28. Turbidity levels range from

0.7 NTU on October 26 and October 27 to 1.0 NTU on November 1. Specific conductivity ranged from 65-69 µS cm^{-1} between October 26 and November 2.

5. Pathogen Monitoring and Research

5.1 Introduction

Samples collected for protozoan analysis in 2021 were analyzed by Method 1623.1 with EasyStain and heat dissociation. During this year, 423 samples were collected and analyzed for protozoan enumeration, plus 52 additional samples were collected and analyzed by a cell culture immunofluorescent assay (CC-IFA) to monitor for any infectious *Cryptosporidium* at Hillview Reservoir. A breakdown of the 2021 sampling effort is provided in Table 5.1.

Table 5.1 Distribution of protozoan sampling, 2021.

Location	Number of Samples	Percent of Total
Kensico and Croton Keypoints	145	34.3%
Streams	112	26.5%
Post UV and Hillview	104	24.6%
Upstream Reservoir Outflows	49	11.6%
Wastewater Treatment Plants	13	3.1%

In addition to COVID-19 related monitoring reductions, the Catskill Aqueduct was shut down at various times during 2021 in support of the Catskill Aqueduct Repair and Rehabilitation project, resulting in the inability to collect several protozoan samples at CATALUM. Kensico outflow results are posted weekly on DEP's website (https://data.cityofnewyork.us/Environment/DEP-Cryptosporidium-And-Giardia-Data-Set/x2s6-6d2j) and reported annually in this report.

5.2 Source Water Results

Catskill Aqueduct Inflow and Delaware Aqueduct Inflow and Outflow

All 36 CATALUM samples were negative for *Cryptosporidium* (Table 5.2 and Figure 5.1), while *Giardia* was detected in 17 out of 36 samples (47.2%). Both protozoans were detected at a higher frequency at DEL17 compared to CATALUM in 2021. Six DEL17 samples (11.5%) were positive for *Cryptosporidium* and 75.0% of the samples were positive for *Giardia*.

Table 5.2 Summary of *Cryptosporidium* and *Giardia* monitoring data at Kensico and New Croton keypoints in 2021.

	Keypoint Location	Number of Positive Samples	Mean[2]	Maximum
Cryptosporidium (oocysts $50L^{-1}$)	CATALUM (n=36)	0	0.00	0
	DEL17 (n=52)	6	0.13	2
	DEL18DT (n=52)	4	0.08	1
	CROGH[1] (n=5)	0	0.00	0
Giardia (cysts $50L^{-1}$)	CATALUM (n=36)	17	0.69	4
	DEL17 (n=52)	39	1.98	7
	DEL18DT (n=52)	35	1.35	7
	CROGH[1] (n=5)	1	0.60	3

[1]May include alternate sites sampled to best represent outflow during “off-line” status -No alternate sites sampled in 2021**.**

[2]Sample volumes not exactly equal to 50L are calculated to per L concentrations and then normalized to 50L for determination of means. Zero values are substituted for non-detect values when calculating means.

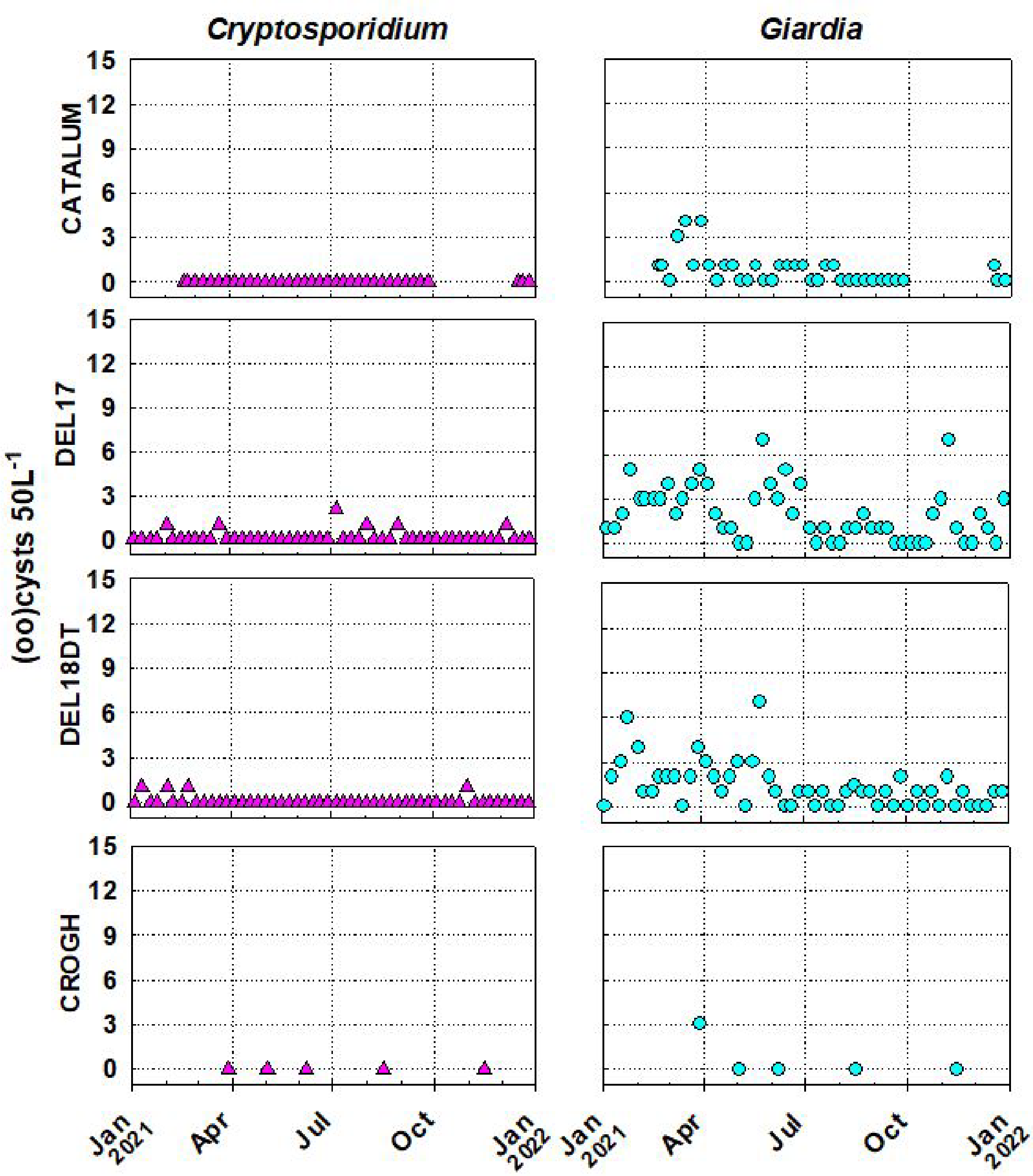


Figure 5.1 Weekly routine keypoint protozoan monitoring results for 2021.

Four of the 52 (7.7%) samples collected at the outflow of Kensico Reservoir (DEL18DT) were positive for *Cryptosporidium* this year and the mean annual oocyst concentration was 0.08 oocysts L^{-1}. *Giardia* detection in samples from the outflow was 67.3% positive for cysts, with a mean concentration of 1.35 cysts L^{-1}.

Croton System

The New Croton Reservoir outflow was sampled quarterly for protozoans in 2021, with one additional sample in the second quarter due to over-scheduling. All five of these samples were negative for *Cryptosporidium* (Table 5.2 and Figure 5.1). *Giardia* was detected in one out of five samples, with a mean annual concentration of 0.60 cysts L^{-1}.

5.2.1 2021 Source Water Results Compared to Historical Data

Kensico Reservoir

Cryptosporidium

Detections - In 2021, six of the 88 Kensico inflow samples (CATALUM and DEL17 combined) were positive for *Cryptosporidium* (all occurred at DEL17), for a combined inflow detection rate of 6.8%. The oocyst detection rate was a little less than half that from 2020 (15.5%), but similar to detections in 2019 (7.5%), and within the annual historical range from 0.9% to 20.5% when combining data from the two inflows.

By comparison, the percent of *Cryptosporidium* detections at the Kensico outflow was similar to the combined inflows in 2021 (7.7% - DEL18DT), and slightly higher than the outflow in 2020 (5.8%). However, the 2021 oocyst detection rate was half the historical detection rate from 2001-2020 (11.3%, n=1132). For an extended temporal comparison of *Cryptosporidium* data at these sites, see Figure 5.2.

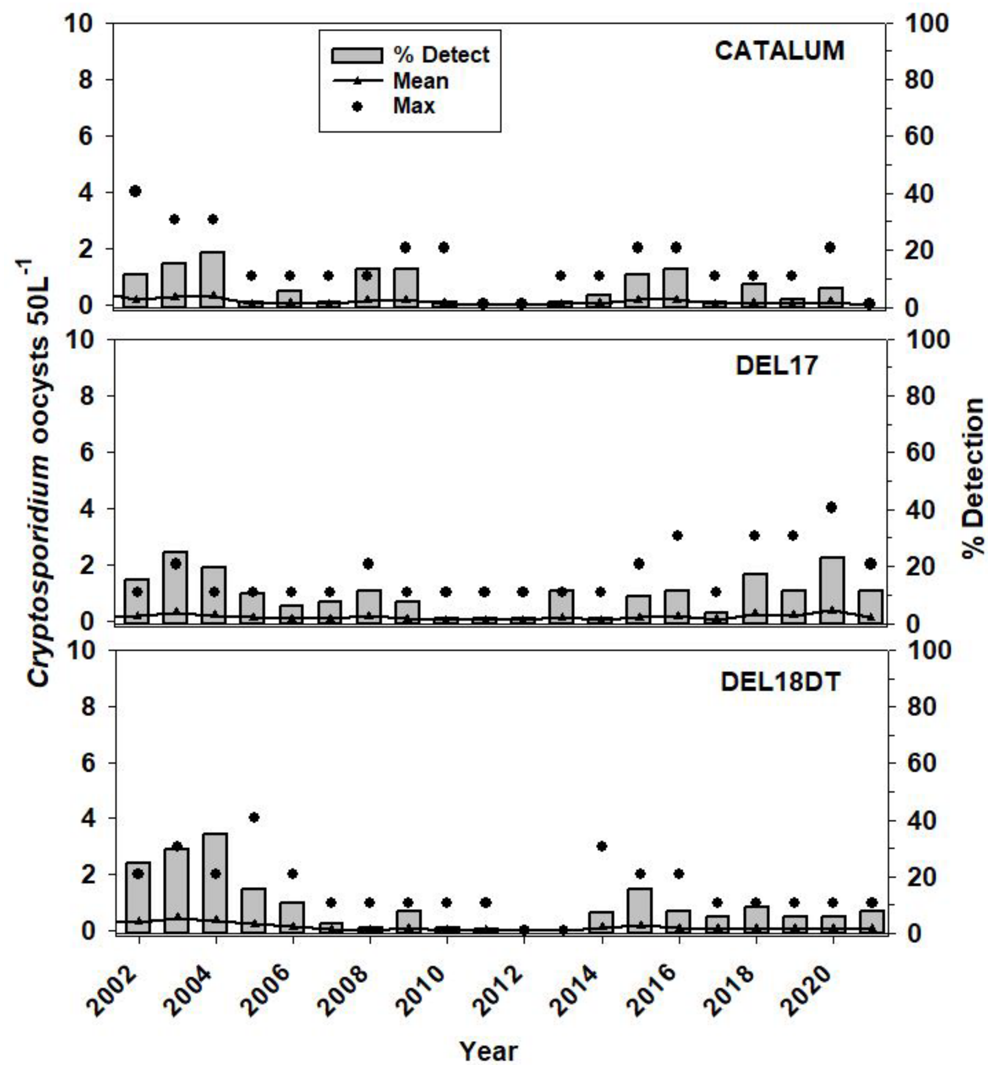


Figure 5.2 *Cryptosporidium* annual percent detection, mean concentration, and maximum result for the Kensico keypoint sites during each year from 2002 through 2021.

Concentrations - The annual mean concentration of oocysts at both CATALUM and DEL17 has been < 1 oocyst $50L^{-1}$ for the period of record since 2002 (0 – 0.35 oocysts $50L^{-1}$; n= 987 CATALUM and 1019 DEL17). As there were no detections of *Cryptosporidium* at CATALUM in 2021, and the annual mean concentration for DEL17 was 0.13 oocysts $50L^{-1}$, 2021 results were within the historical concentration range.

The DEL18DT mean oocyst concentration for 2021 (0.08 oocysts $50L^{-1}$) was very close to means observed in 2018 and 2019 (0.09 and 0.06 oocysts, respectively) and lower than the historical mean of 0.14 oocysts (2001-2020, n=1132).

Giardia

Detections - The *Giardia* detection rate for pooled results at the two inflows (63.6%) was similar to the detection rate at DEL18DT (67.3%) in 2021. The rate at DEL17 was 75.0%, which was higher than CATALUM at 47.2% (Figure 5.3). Again, it must be noted that the Catskill Aqueduct to Kensico Reservoir was shut down for several weeks in 2021, reducing the sample size from 52 to 36 samples. The *Giardia* detection rate at the Catskill inflow was close to the historical rate of detection for this site (41.6%, 2001-2020 n=986). DEL17 had a similar *Giardia* detection rate compared to 2020 (73.1%), however, it was higher than the historical detection rate of 63.4% (2001-2020, n=1018).

The 2021 *Giardia* detection rate at DEL18DT (67.3%) was the same as 2020, and similar to 2019 and 2018 (71.2% and 69.8%, respectively), but higher than in any of the six years prior to 2018 (range for 2012-2017 36.5 – 57.7%). The 2021 detection rate was close to the mean historical detection rate for DEL18 (63.0%, 2001-2020 n=1132).

Concentrations - The annual mean *Giardia* concentration at CATALUM in 2021 (0.69 cysts) was lower than 2020 (1.87 cysts) or any of the means from the previous five years (2020-2016) ranging from 0.83 – 1.87 cysts (Figure 5.3). The 2021 mean was within the range of means over the course of all samples taken at the Catskill inflow (2001-2020, 0.17 – 1.87 cysts) but lower than the historical average (2001-2020=0.96 cysts, n=986). This could be a consequence of the lower number of samples in 2021 resulting from aqueduct shutdowns. The annual mean cyst concentration at DEL17 was 1.98 cysts, approximately half of the mean from 2020 (3.94 cysts), which was much lower than in 2019 (6.96 cysts, the highest recorded annual mean). Unlike the two previous years, 2021 was closer to the historical mean of 2.23 cysts (2001-2020 n=1018). Maximum sample concentrations were also generally lower in 2021 (maximum = 7 cysts), compared to 2019 and 2020 (16 and 19 cysts, respectively).

The annual mean *Giardia* concentration at DEL18DT in 2021 (1.35 cysts) was similar to 2020 (1.96 cysts), and well within the range of annual means from previous years (2001-2020, means 0.71-3.70 cysts). In summary, the mean *Giardia* concentration at the outflow of Kensico Reservoir in 2021 was between the means at the two inflows (CATALUM=0.69; DEL17=1.98 cysts).

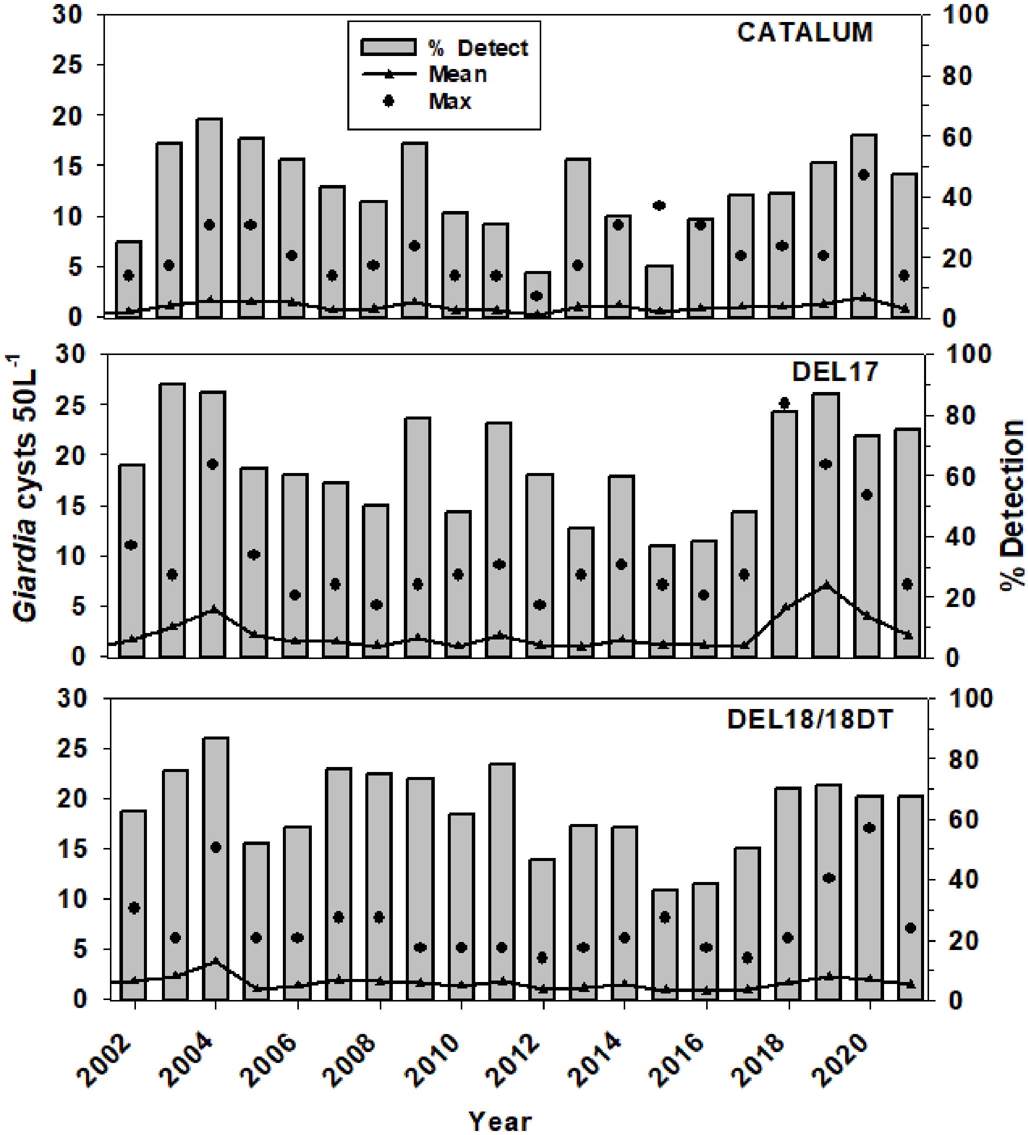


Figure 5.3 *Giardia* annual percent detection, mean concentration, and maximum result for the Kensico keypoint sites during each year from 2002 to 2021.

Croton Source Water

Cryptosporidium

None of the five samples at the New Croton Reservoir outflow (CROGH) were positive for *Cryptosporidium* in 2021 (Table 5.2). This reduced detection of oocysts at CROGH since 2012 may be an artifact of the reduction in monitoring frequency from weekly to monthly at New Croton in 2012, and from monthly to quarterly in 2017 due to fulfilling requirements of the Croton Consent Decree (Figure 5.4).

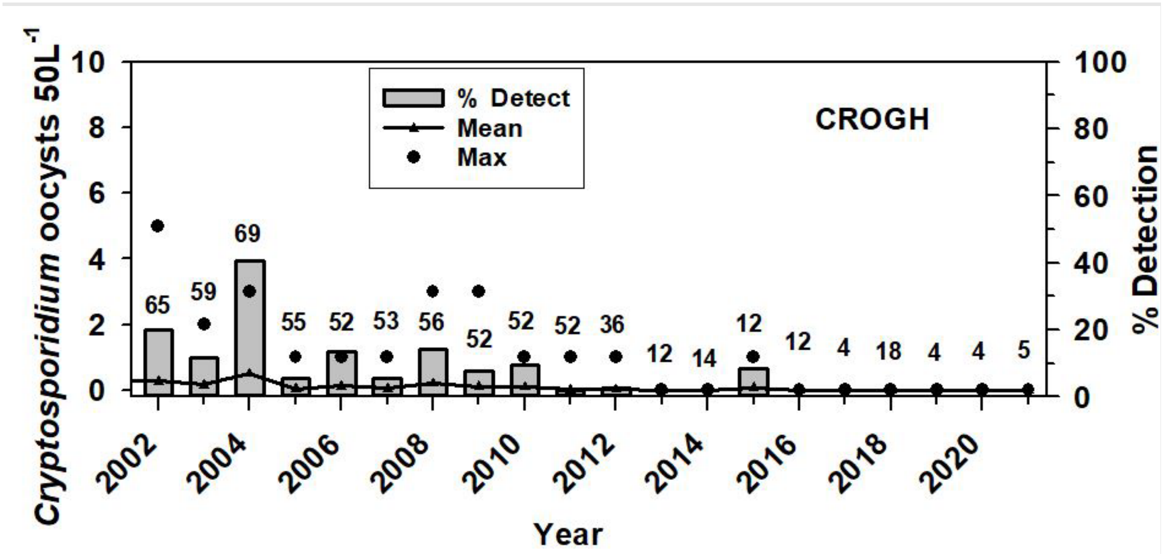


Figure 5.4 *Cryptosporidium* annual percent detection, mean concentration, and maximum result for the New Croton keypoint sites, 2002 to 2021. Numbers above each bar indicate sample size.

Giardia

The rate of *Giardia* detection and mean concentration at the New Croton Reservoir outflow was lower in 2021 (20.0% and 0.60 cysts) than in in 2020 (75.0% and 4.00 cysts, respectively) and 2019 (50.0% and 2.74 cysts, respectively) (Figure 5.5). It is difficult to interpret the comparison of 2021 and historical summary statistics due to analytical method changes and to the reduction in sampling frequency over the years. However, for some perspective, the overall mean *Giardia* detection rate at the outflow from 2001-2020 was 50.1% (347 detections out of 693 samples) with a mean concentration of 1.28 cysts.

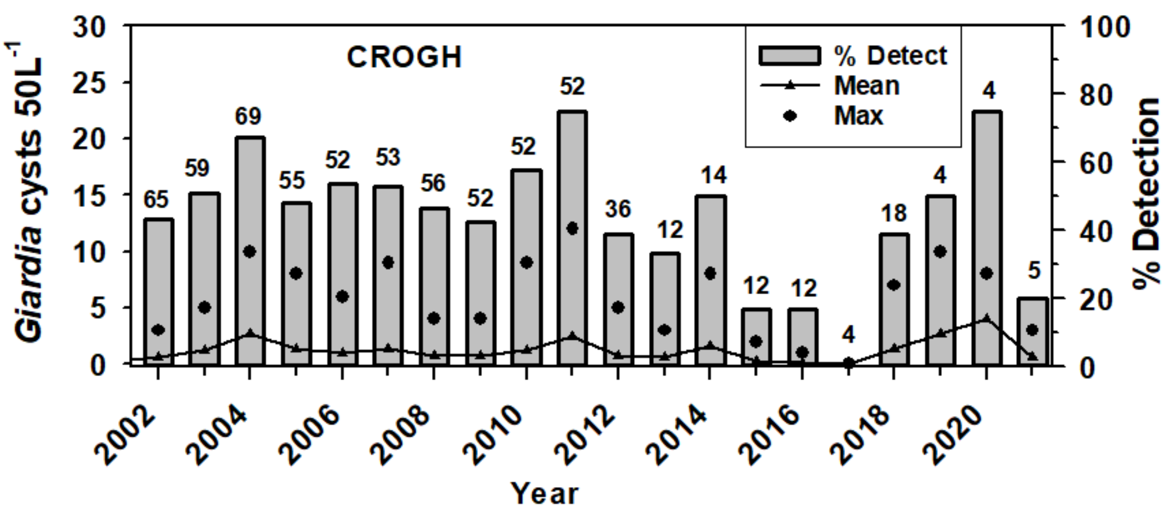


Figure 5.5 *Giardia* annual percent detection, mean concentration, and maximum result for the New Croton keypoint sites, 2002 to 2021.Numbers above each bar indicate sample size.

Seasonality

Seasonal variations in *Giardia* concentrations may be discerned for samples collected in 2021 at the Kensico inflows and outflow, however, the historically noted variation in *Giardia* becomes much more obvious by applying a locally weighted regression (LOWESS) smoothed line (Figure 5.6). These seasonally elevated *Giardia* concentrations are most obvious at DEL17 during the colder (early and late) months of 2019 and 2020. LOWESS analysis has not been performed for the New Croton Reservoir outflow since quarterly sampling was introduced.

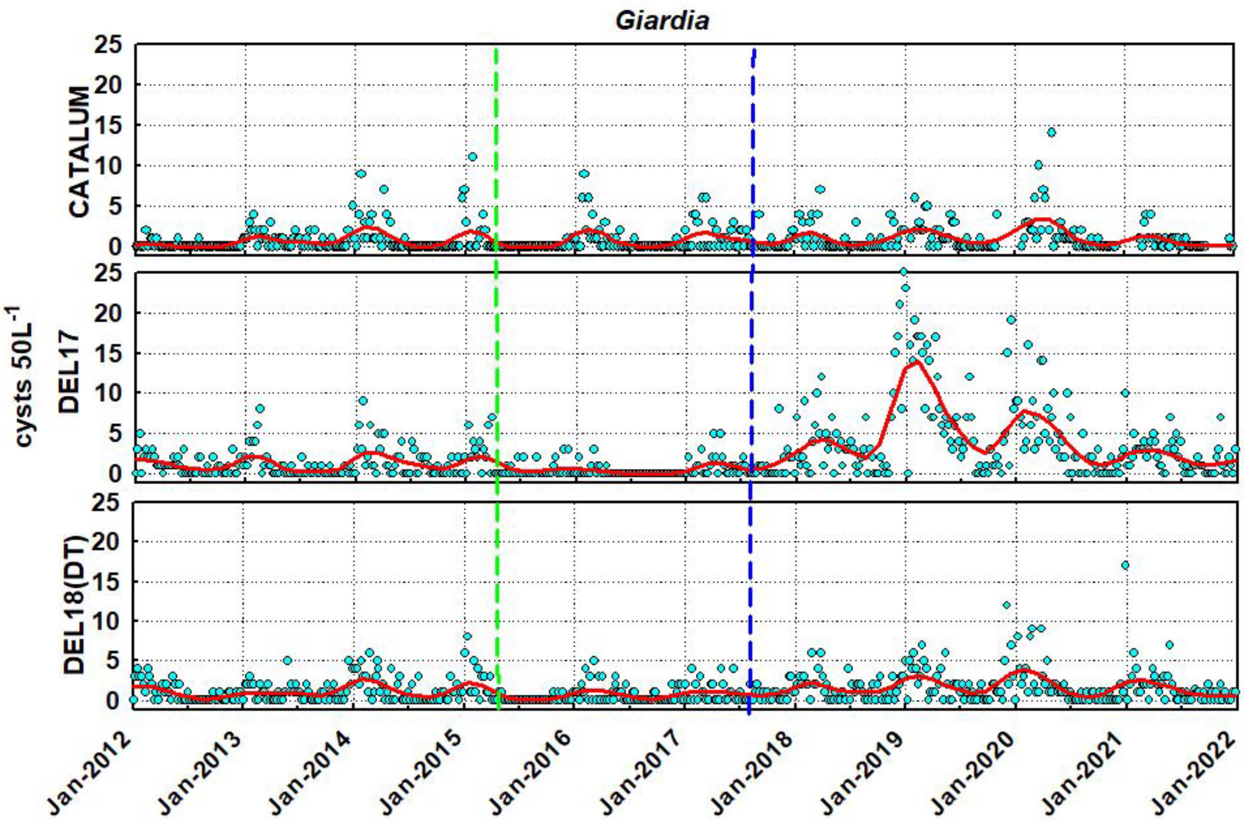


Figure 5.6 Weekly routine source water keypoint results for *Giardia* (circles), and LOWESS 5% smoothed regression (red curved line), January 1, 2012 to December 31, 2021. The green dashed line indicates the change from Method 1623HV to Method 1623.1 with EasyStain.

5.2.2 2021 Source Water Compared to Regulatory Levels

DEP completed its monitoring requirements for the Long Term 2 Enhanced Surface Water Treatment Rule (LT2, USEPA 2006a) in 2018; however, the calculation procedure described in the LT2 is still performed annually by DEP to measure results against the thresholds.

Unfiltered Supply

The Catskill/Delaware System is NYC's unfiltered water supply. For the two-year period of 2020 and 2021, there were a total of 104 samples collected at the Delaware outflow of Kensico Reservoir. The *Cryptosporidium* mean of monthly means for this 24-month period was 0.0014 oocysts L^{-1} for the Delaware outflow, well below the threshold level of 0.01 oocysts L^{-1} for unfiltered systems indicated in the LT2 (Figure 5.7). This calculation is consistent with historical LT2 calculations for NYC source water, which have always remained below the threshold levels. In general, the monthly means for the Delaware outflow began declining in approximately 2004-2005 and continued to decline through 2013. During the 2014-2015 period, a slight potential increase was noted in the calculated mean, which coincided with the change to Method 1623.1/EasyStain for protozoan analysis.

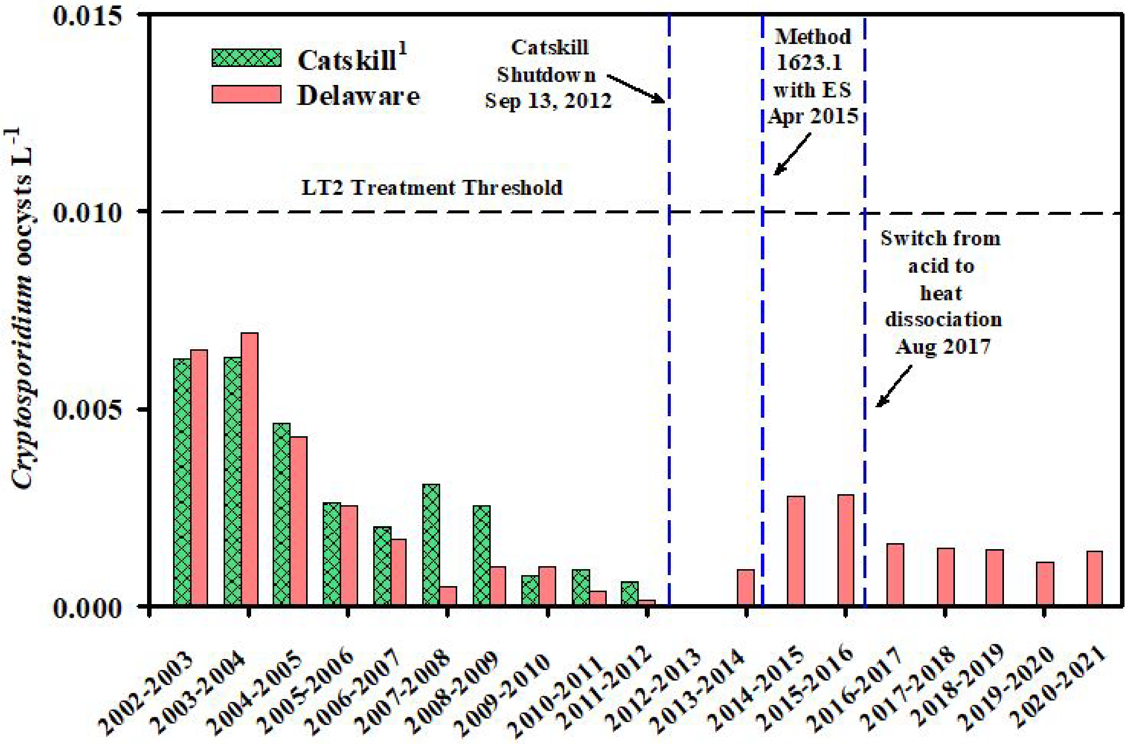


Figure 5.7 *Cryptosporidium* means using LT2 calculation method since initiation of Method 1623HV (1623.1 with EasyStain since April 2015) at the Delaware Aqueduct 2002-2021 and the Catskill Aqueduct 2002-2012.[1] Monitoring was discontinued at the Catskill Aqueduct effluent from Kensico when it was shut down in 2012.

5.2.3 2021 Source Water Matrix Spike and Quality Control Results

Quality control (QC) testing performed during protozoan analyses includes both matrix spike (MS) samples and ongoing precision and recovery (OPR) samples. To determine MS recoveries, sample matrices are spiked with known amounts of oocysts and cysts and then analyzed according to the same method used for routine samples. During 2021, MS recovery of *Cryptosporidium* from the three Kensico keypoint sites ranged from 22-63%, while *Giardia* recovery was 20-74% (Table 5.3). The highest and lowest MS recovery values for both *Giardia* and *Cryptosporidium* occurred at DEL17, and the lowest recoveries were both detected in December.

Table 5.3 Keypoint Matrix Spike Results, 2021.

Date	*Cryptosporidium* % Recovery	*Giardia* % Recovery
	CATALUM	
3/1/2021	57	57
7/19/2021	61	59
	DEL17	
3/22/2021	63	51
8/2/2021	61	74
12/13/2021	22	20
	DEL18DT	
4/19/2021	53	58
8/30/2021	59	67
	CRO1T	
	None	

Weekly OPR testing involves the spiking of reagent-grade water in the laboratory with known amounts of oocysts and cysts. These QC samples are important for testing the method reagents and the laboratory process without interference from the sample matrix. In 2021, 53 OPR samples were analyzed, one of which was in anticipation of greater than 20 samples being collected in one week. Acceptable OPR results (33-100% recovery for *Cryptosporidium* and 22-100% recovery for *Giardia*) were always obtained before proceeding with the weekly samples. Ranges of recovery for all protozoan OPR samples in 2021 were 32-90% for *Cryptosporidium* and 27-77% for *Giardia*.

5.3 Upstate Reservoir Outflows

The Catskill and Delaware aqueducts deliver water to Kensico Reservoir from the West of Hudson (WOH) watershed. The WOH watershed consists of six reservoirs in two systems: Ashokan and Schoharie in the Catskill System, and Cannonsville, Neversink, Pepacton, and Rondout in the Delaware System. Five of the six WOH reservoir outflows were monitored monthly, while the outflow of the Ashokan Reservoir was monitored weekly at CATALUM further downstream on the Catskill Aqueduct before it enters Kensico Reservoir. Data for CATALUM are also reported in the Kensico section of this report. When a reservoir was off-line, monthly reservoir sampling was not required since water from that basin was not being delivered to a downstream reservoir. Monitoring under this objective was reduced during the

COVID-19 pandemic without impacting DEP’s ability to effectively operate the water supply. DEP will be discontinuing routine monitoring under this objective in 2022. DEP may temporarily resume certain pathogen monitoring during periods of high turbidity, runoff events, storms, or any other upset conditions.

There were 85 samples collected at upstate reservoir outflows, which included 77 samples from WOH reservoir outflows and eight samples from Cross River and Croton Falls reservoir outflows. The autumn shutdown of the Catskill Aqueduct resulted in advanced sampling at Cross River and Croton Falls as a precursor to utilizing these pump stations. While the pump stations did not actually supplement the water supply in 2021, four protozoan samples were taken from each outflow site to satisfy sampling requirements prior to the pumping operations.

Cryptosporidium

In 2021, there were 77 samples collected at WOH reservoir outflows and two samples (2.6%) were positive for *Cryptosporidium*, one at Schoharie and one at Rondout (Table 5.4). This detection rate is lower than during the past three years (8.2% - 9.8%), but interpretation of the data was complicated by decreases in monitoring frequencies due to COVID-19. Ashokan, Cannonsville, Neversink, and Pepacton had no *Cryptosporidium* detections in 2021.

Table 5.4 Summary of 2021 protozoan results for upstate reservoir outflows.

Site	n	*Cryptosporidium* Mean[1] ($50L^{-1}$)	% Detects	Max (Liters sampled)	Max (L^{-1})	*Giardia* Mean[1] ($50L^{-1}$)	% Detects	Max (Liters sampled)	Max (L^{-1})
Schoharie	4	1.14	25.0	2 (22.0)	0.09	31.31	100.0	41 (22.0)	1.86
Ashokan (CATALUM)	36	0.00	0.0	0 (50.0)	0.00	0.69	47.2	4 (50.0)	0.08
Cannonsville	10	0.00	0.0	0 (50.0)	0.00	3.69	80.0	6 (50.5)	0.12
Pepacton	11	0.00	0.0	0 (50.0)	0.00	1.08	72.7	3 (50.0)	0.06
Neversink	4	0.00	0.0	0 (50.0)	0.00	4.91	100.0	7 (50.0)	0.14
Rondout	12	0.08	8.3	1 (50.3)	0.02	2.80	91.7	7 (52.8)	0.13

[1]Sample volumes not exactly equal to 50L are calculated to per L concentrations and then normalized to 50L for determination of means. Zero values are substituted for non-detect values when calculating means.

Giardia

There were 52 *Giardia* detections (67.5%) among the 77 samples collected at the WOH reservoir outflow sites (Table 5.4). This is slightly lower than the detection rates for 2020 and 2019 (77.5 and 78.0%, respectively) however, higher than 2015 - 2018. Like the *Cryptosporidium* data, interpretation was complicated by variations in monitoring frequencies over the years.

Concentrations of *Giardia* in the upstate reservoirs were lower at most sites than those found in prior years, apart from Schoharie. Schoharie had the highest annual mean *Giardia* concentration among the upstate outflows for the sixth year in a row in 2021 (31.31 cysts). While this mean was higher than the mean observed in 2020 (12.06 cysts), and higher than the historical mean (11.36 cysts, 2002-2020, n=203), it was quite similar to the means from 2019 and 2018. The annual mean concentration at Rondout was much lower in 2021 (2.80 cysts) compared to the three prior years (approximately 8 cysts each) and is now lower than the historical mean of 3.99 cysts (2002-2020, n=285). Annual mean *Giardia* concentrations at the three contributing upstream reservoirs (Cannonsville, Pepacton, and Neversink) were also lower in 2021. The Cannonsville mean concentration was 3.69 cysts in 2021, Pepacton was 1.08 cysts, and Neversink was down to 4.91 cysts, from 11.69 cysts in 2020. Ashokan (monitored at CATALUM) was lower in 2021 (0.69 cysts) compared to 2020 and 2019 (1.87 and 1.24 cysts, respectively) and slightly lower than the historical mean (2002-2020=0.96 cysts, n=986).

Additional Sampling

As part of the 2017 FAD required monitoring prior to pumping, weekly samples were collected at the Cross River and Croton Falls pump stations for four weeks between October 12 and November 1, 2021 (four samples each). None of the eight samples were positive for *Cryptosporidium*. One of the four Cross River samples was positive for *Giardia* (9 cysts) for a mean concentration of 2.25 cysts at this site (Zero values are substituted for non-detect values when calculating means). No *Giardia* cysts were detected at the Croton Falls outflow.

5.4 Watershed Streams and WWTPs

Routine monitoring for protozoa was conducted at 14 stream sites throughout the watershed in 2021. A total of 112 watershed stream samples were collected and analyzed, with 16 from the WOH watershed and 96 from the Kensico Reservoir (EOH) watershed. An extra set of Kensico stream samples was collected in September as a replacement for the original routine run due to a quality issue with the negative staining control; therefore, only the replacement set was counted in the total.

Stream sampling frequency varied in 2021. WOH stream monitoring resumed in mid-September and the eight perennial tributaries to Kensico Reservoir (EOH) were monitored monthly from January through December. Results discussed in this section are from 47-53 liter samples unless otherwise noted, with concentrations normalized to 50L to facilitate comparison of sample results.

In 2021, 13 samples were collected at 10 WWTPs. A discussion of WWTP results is provided at the end of the stream results section for each corresponding region.

West of Hudson Streams

Stream sampling resumed WOH except for the upstream PROXG sites. WOH Catskill and Delaware stream site locations are shown in Appendix E Figure 4 and Appendix E Figure 5, respectively.

Cryptosporidium oocysts were detected in nine out of the 16 routine WOH stream samples (56.3%) (Table 5.5), slightly lower than the overall WOH stream detection in 2020 (70.0% of the 10 samples). Four of the WOH stream sites (CBS, CDG1, S4, and S5i) were sampled twice in 2021 and *Cryptosporidium* results at these sites were all low (2 or less oocysts) with an approximate mean of 1 oocyst each. The remaining two sites, PROXG and S7i, were sampled four times each, with annual mean concentrations of 5.24 and 11.27 oocysts, respectively. Each site had one result which was above the historical 95th percentile for that site (both samples taken in late October). These samples were taken after a period of almost 1.79 inches of rain (as measured at Albany International Airport weather station - KALB).

Table 5.5 Summary of WOH stream protozoan results in 2021.

Site	n	*Cryptosporidium* Mean[1] ($50L^{-1}$)	% Detects	Max (Liters sampled)	Max (L^{-1})	*Giardia* Mean ($50L^{-1}$)	% Detects	Max (Liters sampled)	Max (L^{-1})
CBS	2	1.00	50.0%	2 (50.0L)	0.04	12.00	100.0%	17 (50.0L)	0.34
CDG1	2	1.00	50.0%	2 (50.0L)	0.02	50.50	100.0%	92 (50.0L)	1.84
PROXG	4	5.24	75.0%	8 (21.0L)	0.38	125.97	100.0%	165 (50.0L)	5.02
S4	2	1.00	100.0%	1 (50.0L)	1.00	42.50	100.0%	74 (50.0L)	1.48
S5	2	0.99	50.0%	2 (50.5L)	0.04	52.61	100.0%	50 (50.5L)	1.11
S7i	4	11.27	25.0%	11 (12.2L)	0.90	135.45	100.0%	130 (12.2L)	10.66

[1]Sample means are determined after normalizing volumes to 50L. Zero values are substituted for non-detect values when calculating means.

Giardia cysts were detected in all 16 routine WOH stream samples collected in 2021. While some *Giardia* results were elevated, even the maximum concentration found in 2021 (130 cysts in a 12.2L sample at S7i) was within the historical range. Discovering *Giardia* more frequently and at higher concentrations than *Cryptosporidium* in the NYC watershed is common and is most evident at WOH streams where the difference between mean cyst and oocyst concentrations is often one to two orders of magnitude (Table 5.5).

Surveillance of 84 monitoring locations throughout the watershed began in 2003 and was intended to isolate geographic sources of pathogens. By 2008, the number of WOH sites was reduced to eight, which included targeted upstream sampling and eventually identified semi-aquatic mammals as the likely source. Because the results have not informed significant changes to our watershed protection or operational strategies, this monitoring will be phased out in 2022.

West of Hudson Wastewater Treatment Plants (WWTPs)

Protozoan monitoring at wastewater treatment plants (WWTPs) resumed on September 7, 2021, more than halfway through the third quarter of 2021. As such, not all WWTPs in the WOH watershed were sampled before the end of the third quarter. In addition, the Andes and Fleischmanns plants were not sampled in the fourth quarter due to a scheduling oversight. None of the nine WWTP samples collected in 2021 were positive for *Cryptosporidium* or *Giardia*.

Long-term (oo)cyst Monitoring at WWTPs was initiated in 2002 to verify the effectiveness of DEP's Wastewater Treatment Plant Upgrade Program over the long term. These data have been useful in highlighting the effectiveness of our wastewater treatment plant upgrade programs and the selected technologies, and no additional routine monitoring at these facilities is considered necessary after 2021. DEP will continue to conduct special investigations at watershed wastewater treatment plants on an as-needed basis.

East of Hudson Streams

The Kensico perennial streams were monitored for protozoans monthly in 2021, for a total of 96 samples. This is unlike 2020 when COVID monitoring reductions resulted in no samples from April through August.

Cryptosporidium

Cryptosporidium oocysts were detected in 24 out 96 (25.0%) of routine samples at Kensico stream sites in 2021 (Table 5.6), very similar to the rates of detection in 2019 and 2020 (24.0% and 22.0%, respectively). Mean concentrations at individual streams were similar, or only slightly higher, in 2021 compared to 2020, apart from BG9 and E9 which were lower than 2020 (Figure 5.8). All eight streams had mean concentrations <1 oocyst in 2021, with N5-1 exhibiting the highest mean concentration (0.99 oocysts). N12 had the highest individual result (25 oocysts). E9, MB-1, and N5-1 each had a slightly elevated oocyst maximum result in 2021 (approximately 6-9 oocysts $50L^{-1}$.

Table 5.6 Summary of routine Kensico perennial stream protozoan results for 2021.

		Cryptosporidium				*Giardia*			
Site	**n**	**Mean[1] ($50L^{-1}$)**	**% Detects**	**Max[2] ($50L^{-1}$)**	**Max (L^{-1})**	**Mean ($50L^{-1}$)**	**% Detects**	**Max[2] ($50L^{-1}$)**	**Max (L^{-1})**
BG9	12	0.67	41.7%	3	0.06	5.65	66.7%	26 (48.6L)	0.53
E10	12	0.59	25.0%	2	0.04	1.59	25.0%	5 (24.8L)	0.20
E11	12	0.25	16.7%	2 (50.1L)	0.04	5.82	58.3%	17 (23.0L)	0.74
E9	12	0.50	8.3%	6	0.12	10.07	58.3%	95	1.90
MB-1	12	0.96	25.0%	3 (21.8L)	0.06	3.05	58.3%	12	0.24
N12	12	0.92	33.3%	25	0.10	1.75	33.3%	16	0.32
N5-1	12	0.99	25.0%	9	0.18	1.73	50.0%	5 (30.1L)	0.17
WHIP	12	0.42	25.0%	3	0.06	0.92	33.3%	4	0.08

[1]Sample means are determined after normalizing volumes to 50L. Zero values are substituted for non-detect values when calculating means.

[2]Maximum results are listed as per the target volume of 50L unless another volume is given in parentheses next to the result.

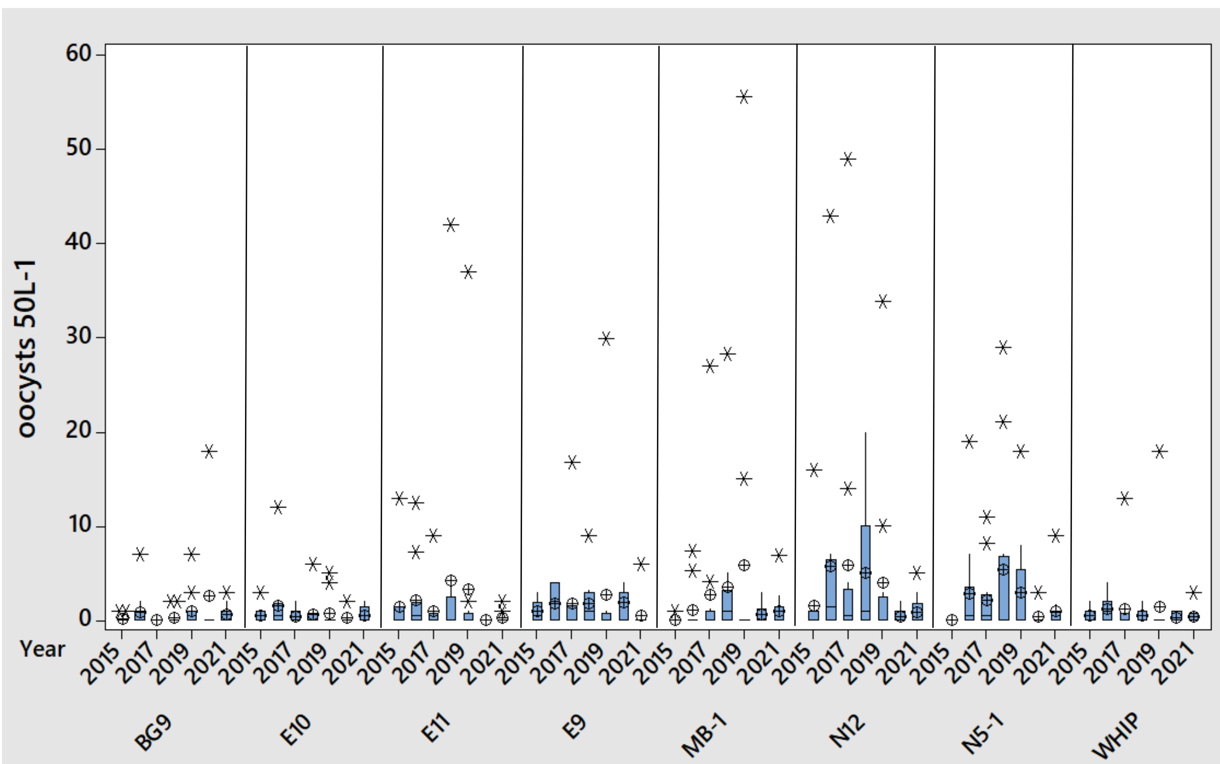


Figure 5.8 *Cryptosporidium* concentrations by year for routine samples at the eight Kensico streams from 2015 through 2021. Mean concentrations are indicated by the ⊕ symbol There were 12 routine protozoan samples per year at each site, with the exceptions of 10 samples at E9 in 2015, and seven samples at all sites in 2020.

Giardia

The *Giardia* detection rate for all routine samples at Kensico streams in 2021 was 47.9%, lower than in 2020 (80.4%), although there were almost twice as many samples in 2021 (n=96). Individually, the Kensico streams had detection rates ranging from 25.0% (at E10) to 66.7% (at BG9) (Table 5.6). *Giardia* results from 2015 to 2021 are provided in Figure 5.9. In 2021, annual means for each site were similar, or lower, to those in observed in 2020, except for E11 where a slight increase (from 3.24 to 5.82 cysts) was apparent. As in past years, the highest annual mean (10.08 cysts) and maximum (95 cysts) occurred at E9, which may be a consequence of being downstream of a wetland.

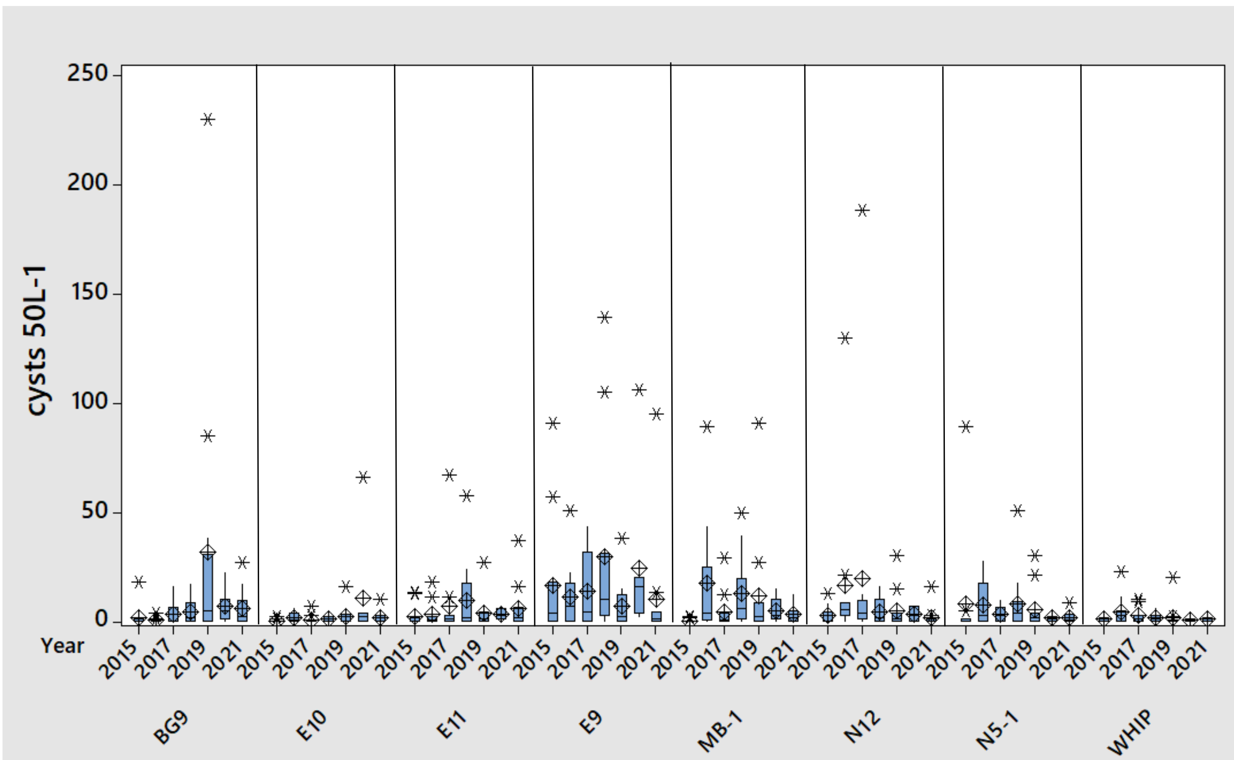


Figure 5.9 *Giardia* concentrations by year for routine samples at the eight Kensico streams from 2015 through 2021. Mean concentrations are indicated by the ⊕ symbol. There were 12 routine protozoan samples per year at each site, with the exceptions of 10 samples at E9 in 2015, and seven samples at all sites in 2020.

East of Hudson Wastewater Treatment Plants

Two EOH treatment plants, Carmel and Mahopac, were sampled in the third and fourth quarters of 2021. These samples were both negative for *Cryptosporidium* and *Giardia*.

5.5 Catskill-Delaware Ultraviolet Light Disinfection Facility and Hillview Reservoir Monitoring

Catskill-Delaware Ultraviolet Light Disinfection Facility

Routine weekly monitoring of the outflow of the Catskill-Delaware Ultraviolet Light Disinfection Facility (CDUV) began in January 2018, at site CCCLAB, and continued through 2021. This monitoring was initiated to determine if (oo)cysts were detectable with the USEPA method after UV treatment. Since they were detectable, it has demonstrated that this method for recovering these protozoans from water provides an overestimation of public health risk. Specifically, cysts and oocysts are recoverable and countable with this method, even though they have been deactivated by UV light and pose no risk to public health.

Of the 52 samples collected and analyzed in 2021, four (7.7%) were positive for *Cryptosporidium* (Table 5.7), which is the same detection rate as in 2020, but less than the detection rates in 2019 and 2018 (15.1 and 13.2%, respectively). The annual mean concentration for *Cryptosporidium* in 2021 was 0.08 oocysts, like that observed in 2020 (0.13 oocysts) and lower than the two previous years (2018-2019, 0.15 and 0.26 oocysts, respectively). Maxima have also changed very little over the past four years at this site, ranging from 1 oocyst in 2021 up to 4 oocysts (2019). *Giardia* was detected in 25 out of 52 samples (48.1%) in 2021.This very similar to the 22 out of 52 samples (42.3%) at CCCLAB in 2020. The annual mean concentration in 2021 (0.87 cysts) is within the range of mean cysts over the past three years (0.68-1.64 cysts). The maximum *Giardia* result at CCCLAB in 2021 was 5 cysts on March 29 which was lower than the past two years (8 and 12 cysts, respectively), and slightly higher than what was observed in 2018 (3 cysts).

Table 5.7 CDUV Plant protozoan monitoring results summary for 2021.

	***Cryptosporidium* oocysts**	***Giardia* cysts**
n	52	52
Number of Detects	4	25
% Detects	7.7%	48.1%
Mean ($50L^{-1}$)	0.08	0.87
Maximum ($50L^{-1}$)	1	5

Hillview

Giardia and *Cryptosporidium* have been monitored weekly at Hillview Reservoir Site 3 since August 2011 as part of the Hillview Administrative Order. In 2021, 52 weekly samples were collected, and results are presented in Figure 5.10 and Figure 5.11. In addition, 52 samples (100L) were analyzed by CC-IFA (Alderisio et al. 2019) at Hillview for *Cryptosporidium* infectivity, and all samples were negative.

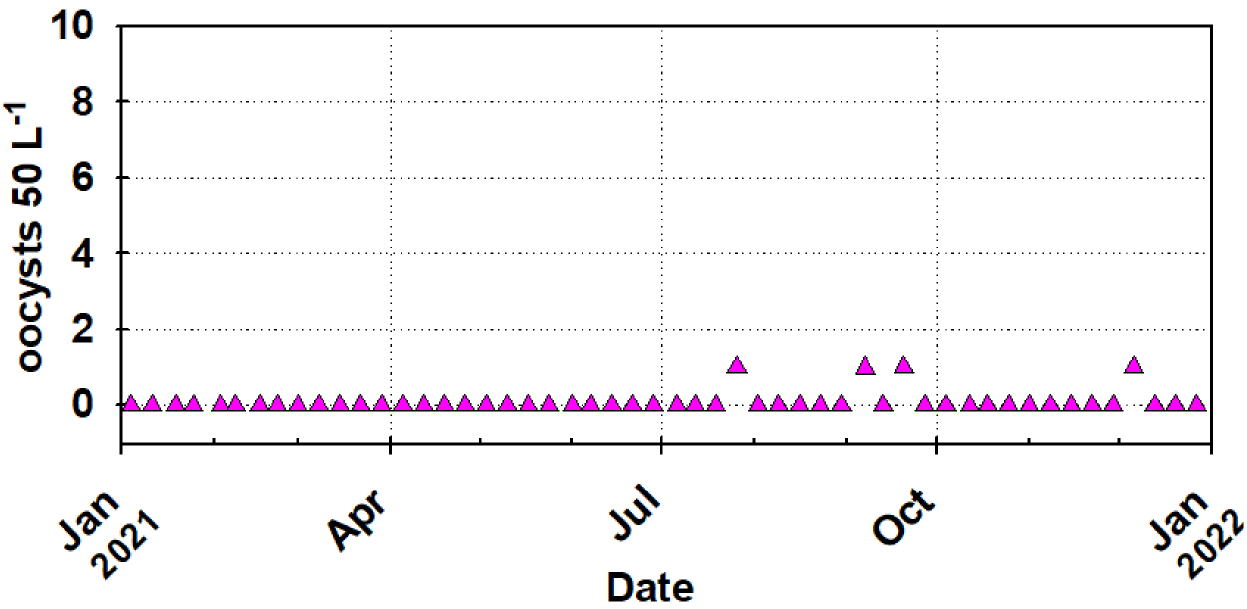


Figure 5.10 *Cryptosporidium* oocyst concentrations for weekly samples at Hillview Site 3 in 2021.

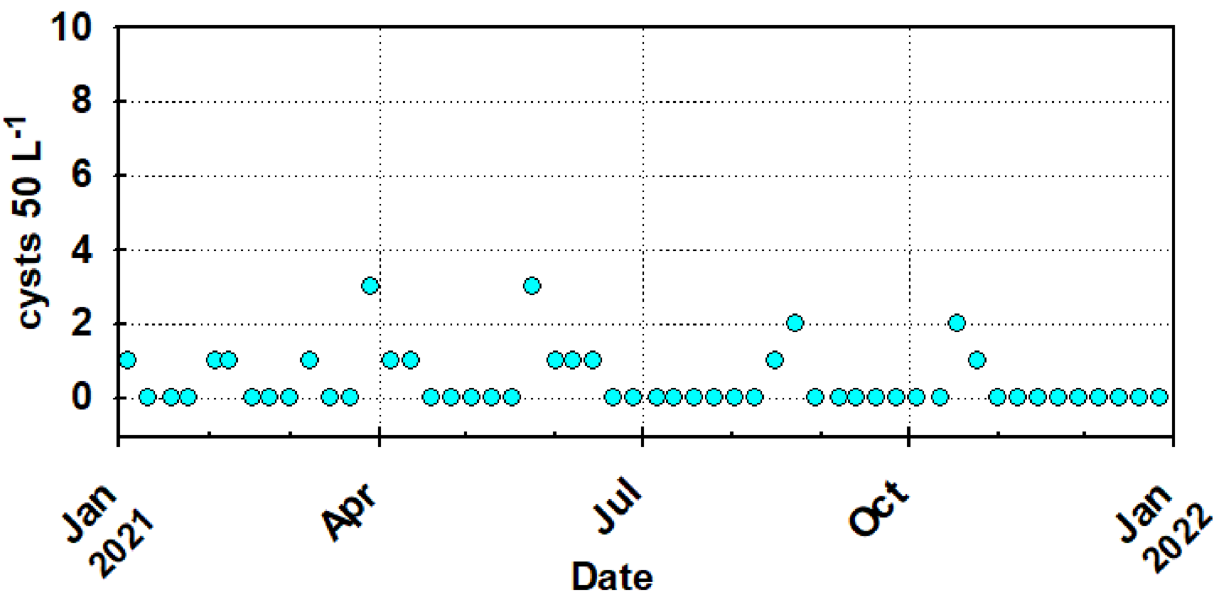


Figure 5.11 *Giardia* cyst concentrations for weekly samples at Hillview Site 3 in 2021.

Cryptosporidium was detected in 7.7% of Hillview samples in 2021 and the annual mean concentration was 0.08 oocysts (Table 5.8). The detection rate and mean were slightly lower in 2019 (3.8% and 0.04), but 2021 results were still well within the range for historical data (detections rates from 0 – 11.1% and means from 0 - 0.11 oocysts). The 2021 detection rate and mean concentration were also very close to the historical rate and mean for this site (5.0% and

0.05 oocysts for 2011-2020, n=498). The *Giardia* detection rate in 2021 (28.8%) was quite close when compared with 2020 (32.7%), and those rates observed from 2012-2014 (ranging from 31.5 to 35.2%). The annual mean *Giardia* concentration in 2021 (0.40 cysts) was lower than in 2020 (0.71) and 2019 (0.90 cysts), but right within the range of annual means observed from 2011 to 2018 (0.13-0.67 cysts) and very close to the historical mean for all years (2011-2020 mean=0.45 cysts, n=498).

Table 5.8 Hillview Site 3 protozoan detections from 2011 to 2021.

	Cryptosporidium		***Giardia***	
Year	**Detects**	**% Detect**	**Detects**	**% Detect**
2011[1]	0	0.0%	4	18.2%
2012	0	0.0%	17	31.5%
2013	2	3.8%	18	34.6%
2014	2	3.7%	19	35.2%
2015	6	11.1%	5	9.3%
2016	4	7.5%	6	11.3%
2017	2	3.8%	9	17.3%
2018	5	9.4%	9	17.0%
2019	2	3.8%	22	42.3%
2020	2	3.8%	17	32.7%
2021	4	7.7%	15	28.8%

[1]Routine sampling began in August 2011.
Dashed lines indicate method changes; Method 1623.1 with EasyStain – April 6, 2015, heat dissociation at Hillview – March 14, 2016.

6. Modeling and Analysis

6.1 Overview

DEP completed our first set of nutrient export simulations for West of Hudson (WOH) reservoirs. Model performance was good for total nitrogen, nitrate, total phosphorous, and dissolved nitrogen. Nutrient response increased with degree of agriculture in the watershed, except for Neversink Reservoir. DEP also developed models of UV_{254} in Cannonsville (r^2 =0.95) and Neversink (r^2=0.75) inflows as a surrogate for disinfection byproduct formation potential. Soil temperature, concentration of total phosphorus in stream flow, and stream flow rate were the best predictors of UV_{254}. DEP also extended the time-period of validation for simulations of turbidity and water temperature for Schoharie and Ashokan reservoirs. The performance of the water temperature and turbidity models were acceptable for operations.

The 109 OST runs that used W2 water quality simulations were completed from December 24, 2020, through April 14,2021, to support operational decisions surrounding turbidity issues generated by the Christmas 2020 storm. These runs examined potential impacts of diversion from Pepacton, Cannonsville, and Neversink (PCN) reservoirs on Rondout and Kensico turbidity. Several other operations were examined using the Operational Support Tool (OST), such as Delaware Aqueduct Shaft 4 operations and Ashokan Dividing Weir gate settings.

DEP also made several enhancements to OST water quality models, and how DEP visualizes model inputs used in initialization. A Power BI application was created to examine different sources of water quality data used to initialize OST W2 water quality simulations. DEP also expanded the flexibility of assigning water temperature and turbidity values to PCN reservoirs that do not currently have water quality models in OST. To shorten the runtime needed to assess alternative operations, a mode of OST was set up allowing us to run OST using only the W2 model in Kensico.

The National Weather Service (NWS) enhanced their Global Ensemble Forecast System (GEFS) meteorological forecasts and associate HEFS forecast of inflow to the reservoirs. DEP incorporated the new Hydrologic Ensemble Forecast System (HEFS) forecast into OST. Moreover, DEP helped NWS develop their own inflow forecast post-processor (ENSpost) that enhances accuracy of HEFS inflow ensembles and then added this forecast as another option in OST.

On another front, DEP constructed a new version of our VoPro model, updated OST rules to support the operation of pump stations and developed a phone application to report information from OST runs critical to operations during the Rondout-West Branch Tunnel (RWBT) outage. The Croton VoPro tool functions using the same forecasts, equations, etc. as our OST model and is much like a version of VoPro on which DEP has previously reported. This new VoPro is different from our original VoPro by focusing on operation of reservoirs in the Croton system. VoPro provides instantaneous feedback and assessment of short-term operations.

Our climate change indicators work continues with an increase of airport weather stations examined and an automated generation of climate change indicator maps. The expanded list of weather stations will allow us to compare trends over space and add confidence in observed trends.

In 2021, DEP constructed an automated process for downloading NWS GEFS ensemble meteorological forecasts and running the forecasts through DEP hydrological models. Once the forecasts have been tested, DEP will add them as another option in OST and VoPro computer models.

The modeling group published three papers in peer-reviewed journals in 2021 and gave four presentations at professional conferences. Moreover, the CUNY sub-contract with the University of Massachusetts resulted in a master's thesis by one of Dr. David Reckhow's students.

6.2 Modeling and Analysis of Nutrient Export from West of Hudson Watersheds

DEP during 2021 continued to put significant effort into the application and testing of the hillslope (HS) version of the Soil and Water Assessment Tool (SWAT) to the WOH watersheds. The first step in these model applications involved the simulation of streamflow. Good streamflow simulations for the historical period of 2001-2018 were obtained for all watersheds. Now, the application of SWAT-HS is being extended to make water quality simulations in all six WOH watersheds. This effort will support the evaluation of watershed protection programs and the impact of climate change on the entire WOH system.

Watershed protection programs have resulted in significant reductions in nutrient export from the WOH watersheds over the past 25 years. This is particularly true for the Cannonsville watershed, where there is relatively more agricultural land use. Nutrient loading from WOH watersheds have been relatively stable in recent years indicating a new baseline reference. An initial attempt for estimating baseline reference nutrient loads using available data and the SWAT-HS model for 2009-2018 is presented. Nutrient loading estimates are presented in kg km^{-2} yr^{-1} for the 10-year period to allow comparison among watersheds.

6.2.1 Methodology

The SWAT-HS model (Hoang et al. 2017) was used to estimate nutrient loading from major reservoir inflow locations (Figure 6.1) of six WOH watersheds. Water quality parameters considered were total dissolved phosphorus, total phosphorus, nitrate, and total nitrogen. Model simulations were compared with measured data from the DEP monitoring program collected at biweekly to monthly frequency to test the validity of the predictions. Measured concentrations during a month were assumed as representative of monthly average for monthly load estimation. Nonpoint sources of nutrients simulated in the model include fertilizer and manure applied to croplands, manure deposited by cattle in pastures, and atmospheric deposition of nitrogen.

The crop rotation schedule used as model input is four years of corn followed by six years of hay. Fertilizer inputs include application of starter inorganic fertilizer (18% nitrogen and 18% phosphorus) on the day of planting at the rate of 100 kg ha^{-1}. Manure application is at the beginning (April-May) and at the end (September-October) of the growing season. Each application is 2,670 kg ha^{-1} of dairy manure, which is ~374 kg ha^{-1} dry weight. Manure input (dry weight) in pastures included dairy manure spreading at the rate of 2.4 to 3.3 kg ha^{-1} $day^{-1}$and beef manure application through grazing at the rate of 0.7 to 3.3 kg ha^{-1} day^{-1}. Methods for estimating fertilizer and manure input can be found in Hoang et al. (2019). The average annual rates of atmospheric deposition for NH_4 and NO_3 in precipitation (0.19 and 1.0 mg L^{-1}, respectively) and dry deposition (0.46 kg NH_4 ha^{-1} and 0.18 kg NO_3 ha^{-1}) were obtained from Clean Air Status and Trends Network data for Claryville, NY (CASTNET, 2018). These values were used for the Neversink watershed and adjusted for the other watersheds during the calibration process.

Precipitation and air temperature data required to drive the model were obtained from the Parameter-elevation Relationships on Independent Slopes Model (PRISM) climate data (Daly et al., 2008). The Mountain Microclimate Simulation Model (MT-CLIM) (Hungerford et al., 1989) was used to estimate relative humidity and solar radiation from air temperature data. Using the SWAT-CUP calibration program, model parameters related to nutrients were calibrated to observed loads using a single iteration consisting of 600 simulations. Simulations using best parameter sets based on multiple objective functions were used for comparison with observed loads. The chosen objective functions were Nash-Sutcliffe Efficiency (NSE), Modified Nash-Sutcliffe Efficiency (MNSE), Regression coefficient (R^2), Modified Regression coefficient (bR^2), Sum of the Squares of Residuals (SSQR), Percent Bias (PBIAS), and Kling-Gupta Efficiency (KGE) (Abbaspour 2014). For the Ashokan watershed, nutrient loads from the Shandaken Tunnel were subtracted from observed loads at Coldbrook to estimate contributions from the watershed alone. Streamflow parameters within a previously identified range were allowed to vary during nutrient calibration.

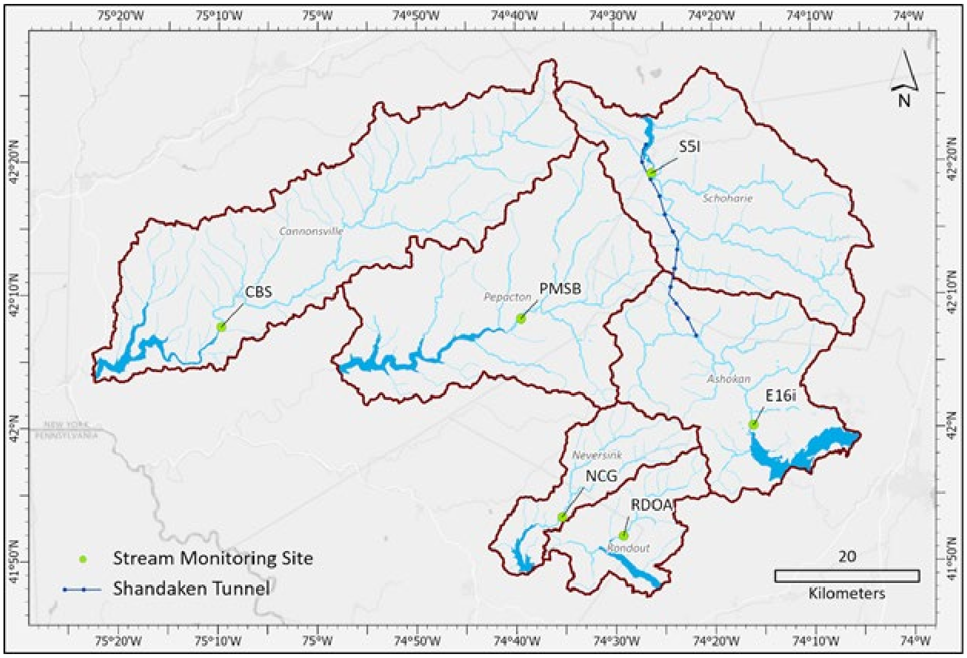


Figure 6.1 West of Hudson watersheds showing major inflow stream locations.

6.2.2 Watershed Modeling Results

Figure 6.2-Figure 6.7 shows time series of modeled and observed monthly nutrient loads for the six WOH stream sites. Predicted series include three to seven simulated monthly values depending on the number of unique parameter sets obtained from the seven objective functions used. In all cases, the predicted values were comparable to the range in the observed values and followed the general temporal pattern. The period of simulation used in this analysis covers a range of hydrologic conditions, making it representative for a baseline reference.

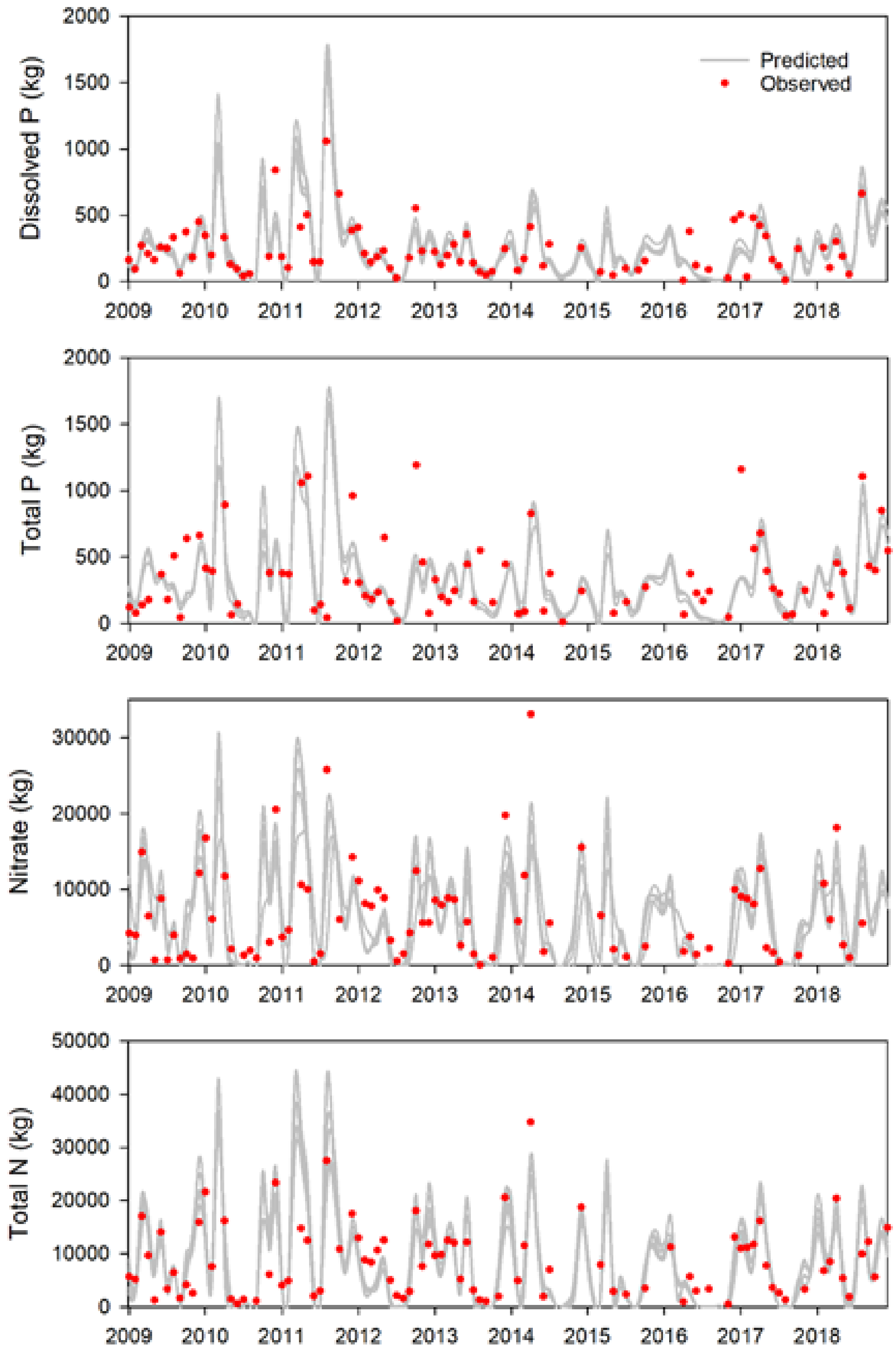


Figure 6.2 Predicted and observed monthly nutrient loads at E16i in Ashokan watershed.

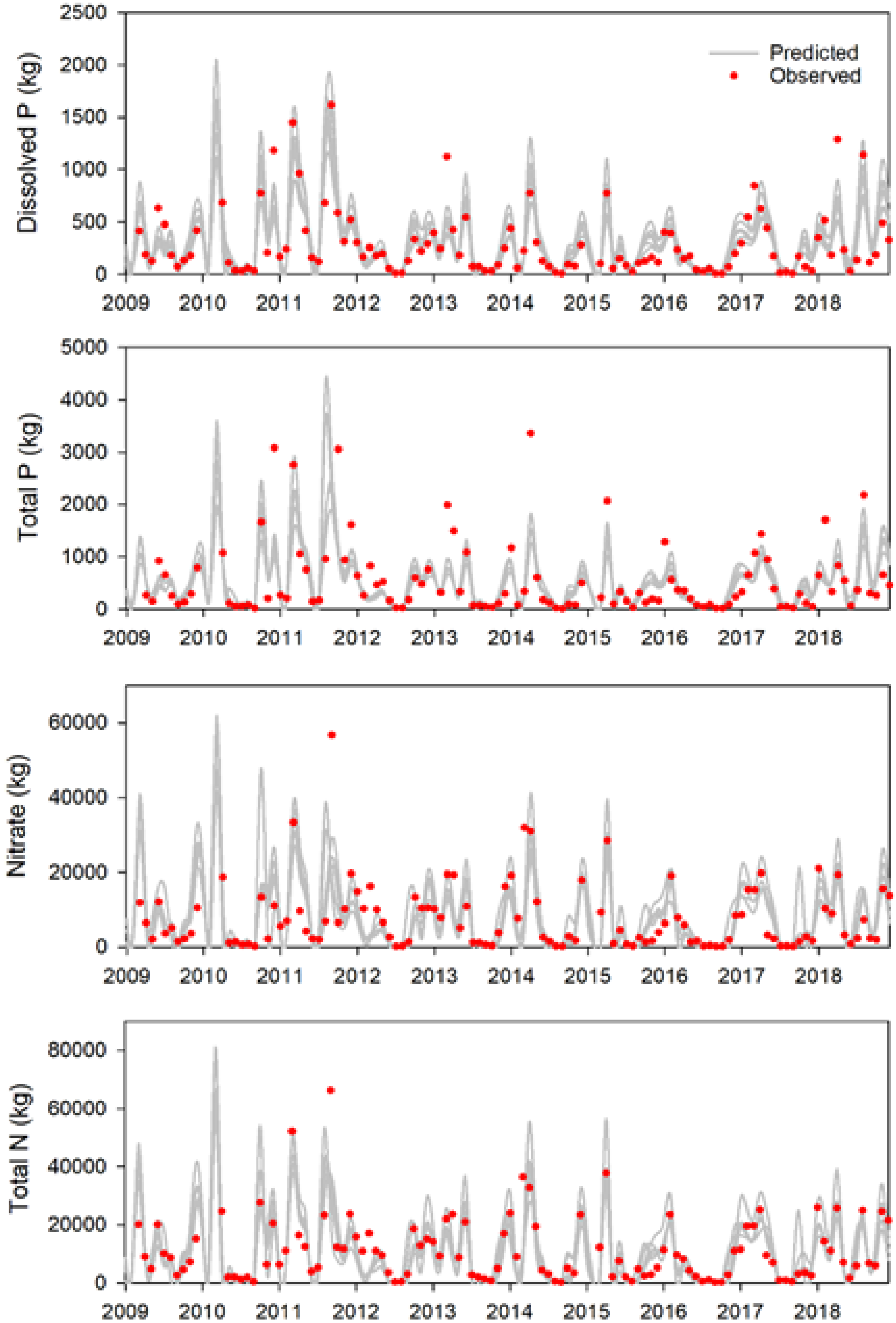


Figure 6.3 Predicted and observed monthly nutrient loads at S5i in Schoharie watershed.

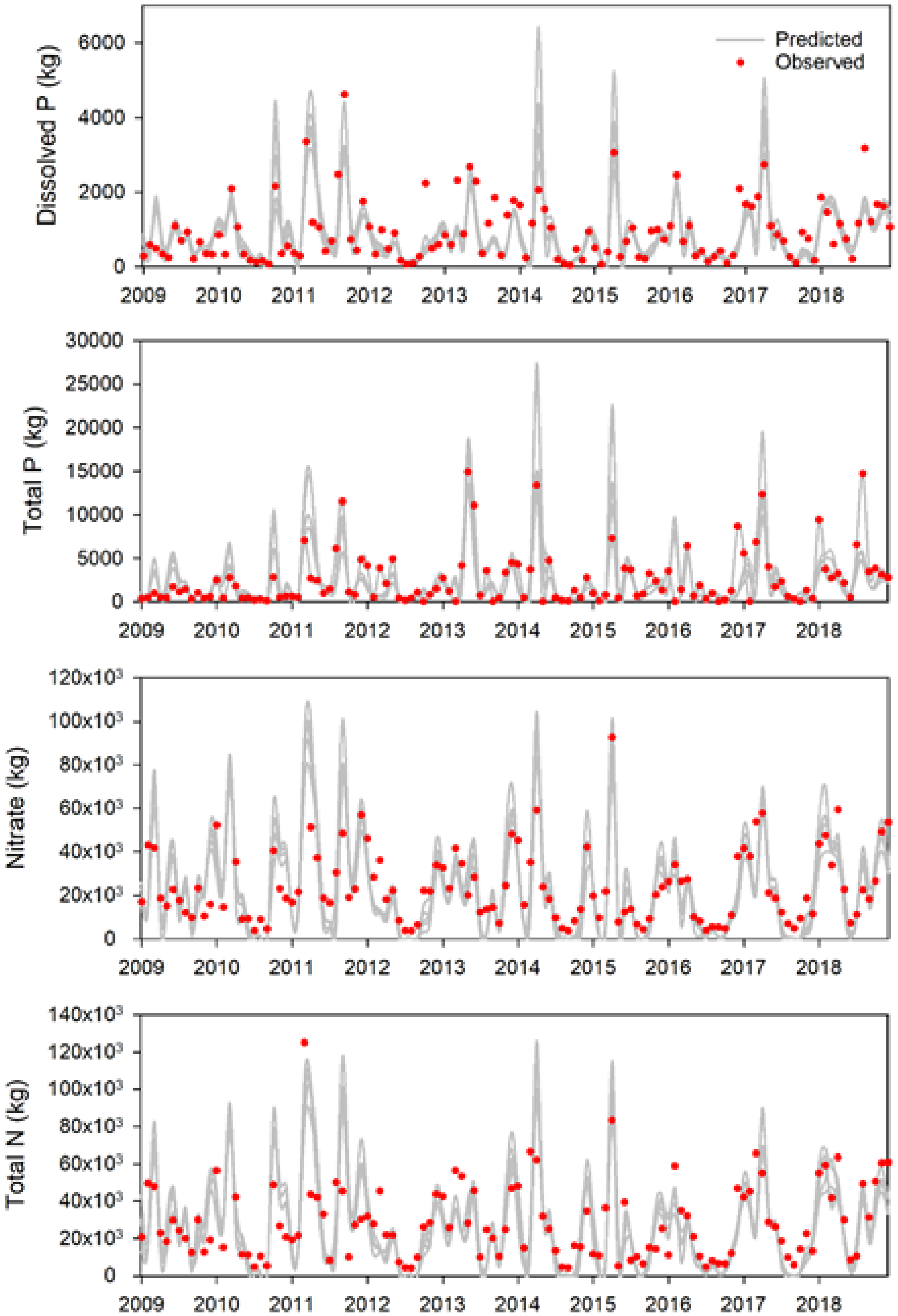


Figure 6.4 Predicted and observed monthly nutrient loads at CBS in Cannonsville watershed.

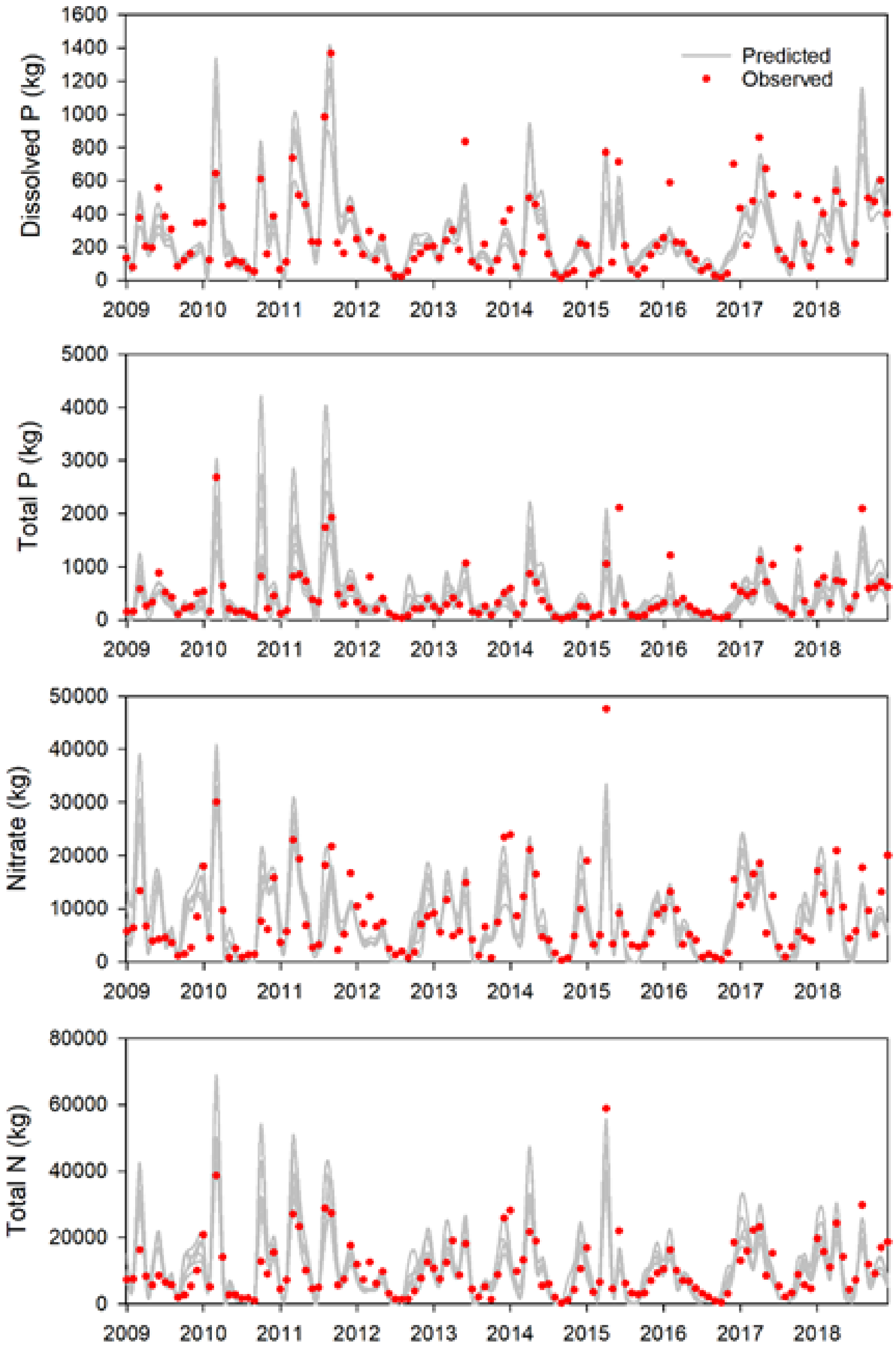


Figure 6.5 Predicted and observed monthly nutrient loads at PMSB in Pepacton watershed.

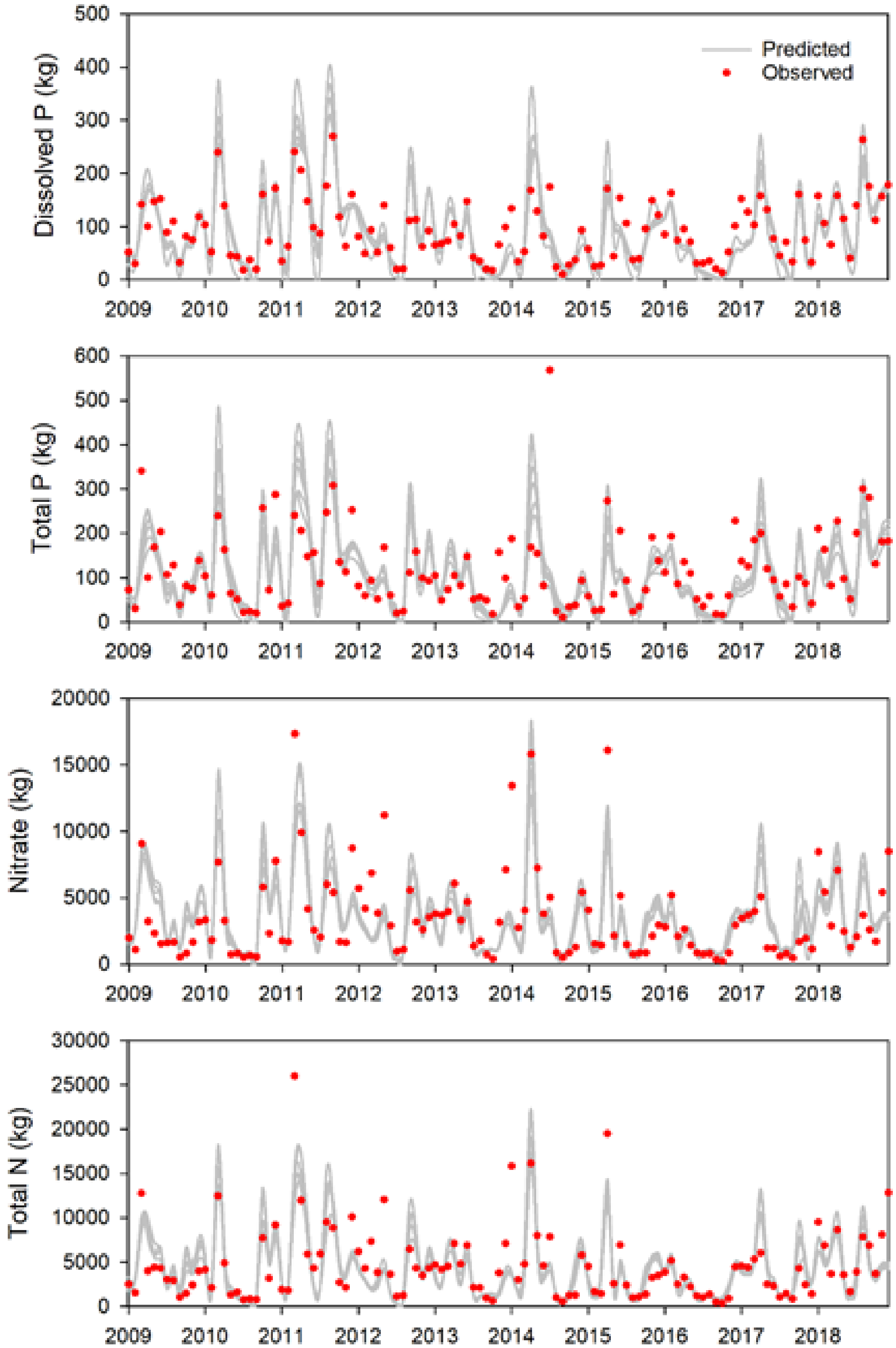


Figure 6.6 Predicted and observed monthly nutrient loads at NCG in Neversink watershed.

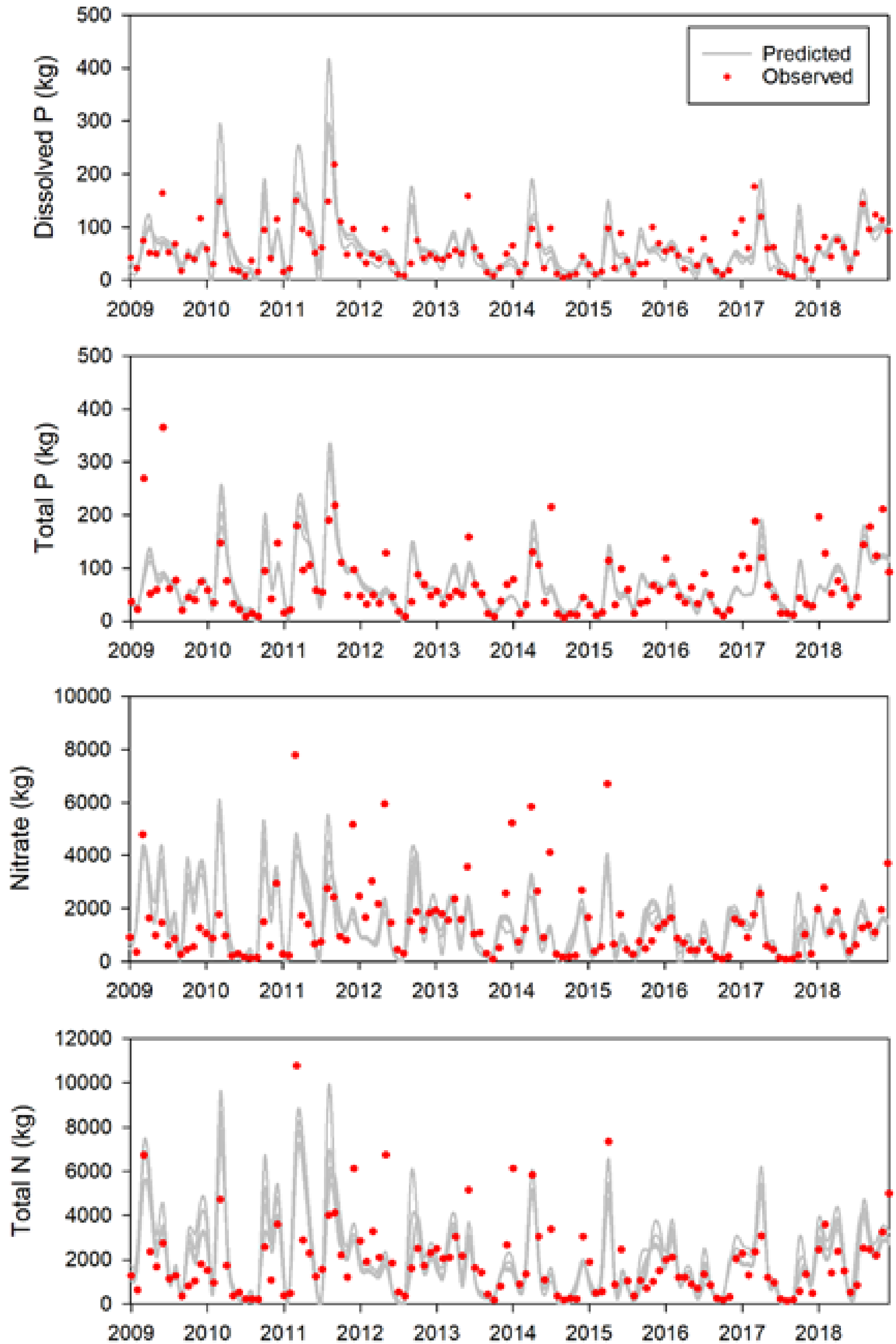


Figure 6.7 Predicted and observed monthly nutrient loads at RDOA in Rondout watershed.

Table 6.1 shows the best model performance using parameter sets based on four widely used objective functions that are comparable across sites. Three out of the four water quality variables showed satisfactory model performance for the Ashokan watershed at E16i based on R^2 and NSE values. Relatively poor performance of TP for this site may be because of lag in TP response from the Shandaken Tunnel at the Coldbrook site. The possibility of this lag effect is supported by the relatively low PBIAS value for TP which is independent of the timing of nutrient loading. For the Schoharie watershed at S5i, all four variables had satisfactory model performance, with dissolved phosphorus having the best and nitrate having the worst performance based on R^2 and NSE values. Models of the Cannonsville watershed at CBS and Pepacton watershed at PMSB gave satisfactory predictions of all four water quality variables based on all four performance metrics used. Among the six stream sites, models of the Neversink watershed at NCG and the Rondout watershed at RDOA had the worst performances. These results are indicative of lower response of nutrients to runoff events in these relatively undisturbed watersheds compared to other watersheds with more agricultural land use. Unlike R^2 and NSE, the KGE values are less sensitive to high values. The KGE values were consistently good across all watersheds and for all water quality variables. The PBIAS for all variables and for all watersheds were under 1%, which shows the ability of the model to predict nutrient loads closer to the observed loads.

Table 6.2 shows estimate of nutrients loads (kg km^{-2} yr^{-1}) for the 10-year period using measured data and the SWAT-HS model. Mean model estimates are based on the average of best simulation for each objective function and the model range is the range in nutrient loads when using the best simulation for each objective function. In some cases, the best simulation is the same for more than one objective function. Therefore, the range is based on three to seven model simulations. The mean of the simulations was close to the estimate using data in all cases. This was not surprising due to the low PBIAS values estimated for all parameters across all watersheds. The range in estimate provides a measure of model error due to parameter uncertainty. This expected range could serve as a baseline reference to which estimates for future periods may be compared. The two sites in the Catskill System had comparable nutrient loads except that S5i had a slightly higher TN and TP loads as well as a wider range in simulated loads for all four variables than E16i. The higher nutrient loads at S5i compared to E16i is explained by the presence of more agricultural land use. Mean nutrient loads were the highest for the Cannonsville watershed at CBS and the range in predicted loads did not overlap with any other watershed. Pepacton at PMSB had the second highest mean DP and TP loads per unit drainage area. The DP and TP loading at NCG in Neversink and RDOA in Rondout watershed were comparable. However, the nitrate and TN loading at NCG was closer to PMSB whereas the loading of nitrate and TN at RDOA was closer to S5i and E16i. Although Neversink and Rondout are relatively undisturbed watersheds with similar land use, the nitrogen export from Neversink is much higher than Rondout with no overlap in predicted ranges. Such variations may be due to differences in baseflow acid neutralizing capacity in these watersheds which can be influenced by topographic and drainage characteristics such as slope, flow paths, and water transit time.

Table 6.1 Model performance statistics for monthly nutrient load predictions.

	R^2	NSE	KGE	PBIAS (%)
Ashokan @ E16i				
DP	0.60	0.69	0.80	-0.1
TP	0.31	0.17	0.56	0.1
NO	0.56	0.50	0.74	0.1
TN	0.69	0.62	0.81	0.1
Schoharie @ S5i				
DP	0.74	0.72	0.80	0.0
TP	0.61	0.59	0.66	0.0
NO	0.52	0.50	0.71	0.1
TN	0.67	0.63	0.80	-0.1
Cannonsville @ CBS				
DP	0.63	0.57	0.74	0.2
TP	0.61	0.55	0.74	0.7
NO	0.66	0.60	0.79	0.1
TN	0.55	0.45	0.72	-0.1
Pepacton @ PMSB				
DP	0.75	0.75	0.84	0.0
TP	0.74	0.67	0.76	0.2
NO	0.58	0.55	0.76	-0.1
TN	0.66	0.63	0.80	0.0
Neversink @ NCG				
DP	0.72	0.57	0.79	0.0
TP	0.43	0.34	0.64	-0.1
NO	0.54	0.53	0.70	-0.4
TN	0.58	0.56	0.75	0.0
Rondout @ RDOA				
DP	0.53	0.45	0.72	-0.1
TP	0.39	0.35	0.59	0.1
NO	0.32	0.30	0.52	-0.1
TN	0.51	0.48	0.70	-0.7

Table 6.2 Comparison of SWAT-HS predicted nutrient loads with estimates from data. Model ranges are estimates based on continuous simulation without any missing period.

	Estimated from data **$kg/km^2/yr$**	**Estimated from model (mean)** **$kg/km^2/yr$**	**Estimated model range** **$kg/km^2/yr$**
Ashokan @ E16i			
DP	5.8	5.9	5.9-7.1
TP	8.5	8.3	8.0 – 8.6
NO3	160	157	139-169
TN	205	205	192-227
Schoharie @ S5i			
DP	5.7	6.2	5.1 - 8.1
TP	10.7	10.1	8.8 – 12.3
NO3	152	160	137 - 197
TN	221	215	194 - 265
Cannonsville @ CBS			
DP	12.3	11.9	10.8 - 13.1
TP	35.5	33.6	30.4 – 38.1
NO3	334	311	289 - 334
TN	389	358	337 - 390
Pepacton @ PMSB			
DP	8.1	7.7	6.3 - 8.4
TP	12.6	12.3	8.5 - 14.7
NO3	232	227	212 - 239
TN	293	306	257 - 357
Neversink @ NCG			
DP	6.5	6.4	6.1 - 6.5
TP	8.1	7.7	6.6 - 8.2
NO3	240	252	221 - 275
TN	319	307	274 - 325
Rondout @ RDOA			
DP	6.9	7.1	6.9 - 7.4
TP	8.3	8.4	8.3 - 8.5
NO3	169	171	164 - 181
TN	229	245	225-275

6.2.3 Highlights from Watershed Modeling and Analysis

- A first attempt to estimate nutrient loads at major reservoir inflow sites for six West of Hudson watersheds using the SWAT-HS model is presented.

- Simulated loads of DP, TP, NO3, and TN were compared to estimates using data from DEP water quality monitoring program.

- Model performance statistics indicate lower runoff response of nutrients in relatively undisturbed watersheds compared to watersheds with significant agricultural land use.

- Model predicted average annual nutrient loads were comparable to estimates using data for all water quality parameters and for all watersheds.

- Cannonsville watershed, which has the most area under agricultural land use, also has the highest nutrient export per unit drainage area. Nutrient export from other watersheds were proportional to area under agricultural land use except for Neversink.

- Nitrogen export from the Neversink watershed is much higher than Rondout watershed with similar land use, with no overlap in predicted ranges in estimated loads. Such differences are likely due to topographic and drainage characteristics that may influence baseflow acid neutralizing capacity. The cause for this difference needs further investigation.

- Estimated nutrient loads are for a period with a wide range in hydrologic conditions, making it representative for a baseline reference to which estimates for future periods may be compared for watershed assessment.

6.3 Empirical Models of UV_{254} to Assess Disinfection Byproducts (DBPs) Formation Potential

Chlorine, a widely used disinfectant in water supply systems, reacts with organic carbon to form several disinfection byproducts (DBPs), some of which are carcinogenic. The USEPA has set a maximum contaminant level (MCL) of 80 µg L^{-1} for total trihalomethanes (TTHMs) and 60 µg L^{-1} for the sum of five haloacetic acids as site-specific running annual averages (USEPA 2006). Since 2012, regulations have become more stringent, with stage 2 DBP rule compliance based on site-specific running averages of quarterly samples rather than averages across the entire system. Such regulations increase public health protection by reducing the risks associated with DBPs in drinking water. At the source waters, DBP levels are often assessed using DBP formation potential (DBPfp) to compare the propensity of water samples collected from different sites to form DBPs upon chlorination. Typically, DBPs and DBPfp are measured in the laboratory using gas chromatography, which can be time consuming with turnaround times less than ideal for operational decisions. The ultraviolet (UV) light absorbance by a water sample at 254 nm wavelength (UV_{254}) is an indicator of dissolved organic matter (DOM) content in water and offers a reasonable surrogate for DBPfp (Golea et al. 2017; Shakhawat 2022). This is true even in the case of water samples from NYC watershed streams (Figure 6.8). A method for continuous estimation of in-stream UV_{254} from easily available environmental variables for subsequent prediction and assessment of DBPfp in source waters is presented.

6.3.1 Methodology for Empirical Modeling

Measurements of UV_{254} from major inflow locations to Cannonsville and Neversink reservoirs were used for developing empirical models. There were 522 observations collected between July 5, 2016, and December 27, 2021, available for the Cannonsville stream site at Beerston (CBS) and 276 observations collected between October 24, 2016, and December 27, 2021, available for the Neversink stream site at Claryville (NCG).

Environmental variables that influence the production of dissolved organic matter in the watershed and its transport through streams into the reservoirs were identified from a set of possible variables. Variables considered were watershed conditions such as soil moisture levels, soil temperature, air temperature, relative humidity, precipitation, and instream variables such as streamflow, total nitrogen, total phosphorus, stream temperature, turbidity, and electrical conductivity. For streamflow, DEP used data from the USGS gages at Walton and Claryville. Water quality variables were available from the DEP water quality monitoring program. Data from the NY State Mesonet (https://www2.nysmesonet.org/) sites within the watershed were used for variables related to watershed conditions. Multiple regression models were developed after pairing predictor variables with UV_{254} measurements and identifying variables able to explain the observed variability in the data. Coefficients from the regression models were then used to develop a continuous time series of estimated UV_{254} values for the two stream sites for a wide range of hydrologic conditions.

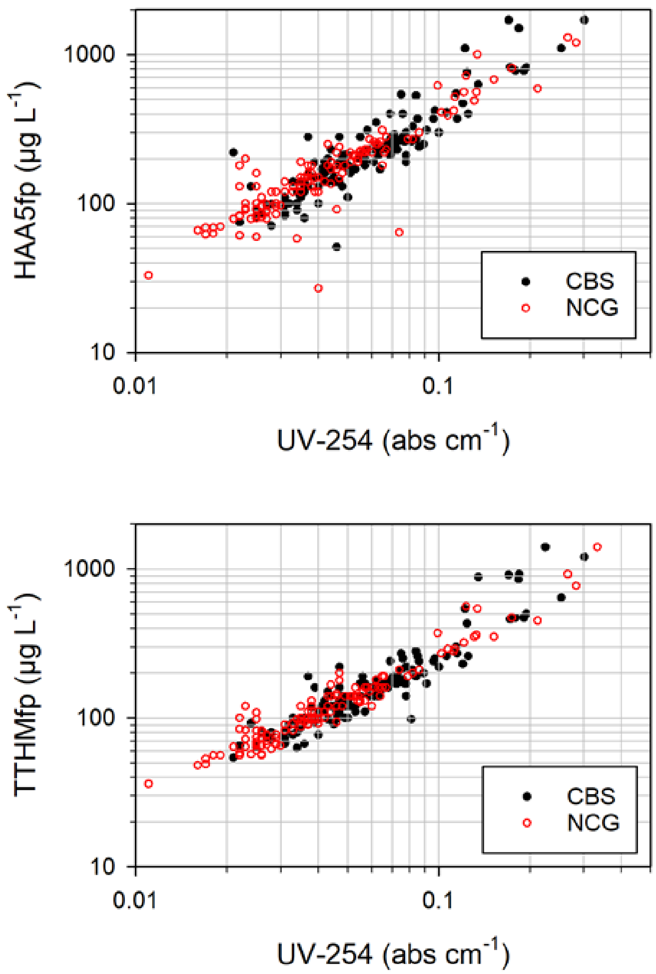


Figure 6.8 Relationship between UV_{254} and DBPfp in water samples from Cannonsville (CBS) and Neversink (NCG) stream sites.

6.3.2 Results of Empirical Modeling

A multiple regression model (Eq. 6.1) for the Cannonsville stream site included streamflow(Q), total phosphorus, and soil temperature at 50-centimeter depth as predictor variables. For the Neversink site a two-parameter model (Eq. 6.2) gave the best fit. Overall performance of the models was satisfactory with R^2 values of 0.95 for the CBS site and 0.75 for the NCG site (Figure 6.9 and Figure 6.10). Figure 6.10 shows a comparison of empirical model predictions with observations for 2021.

$$\ln (UV_{254} cm^{-1}) = 0.044\ SoilTemp_{s0} °C + 0.266 \ln (Total\ P.\ mg\ l^{-1}) + 0.300 \ln (Q.m3s^{-1}) - 3.198 \quad 6.1$$

$$\ln (UV_{254} cm^{-1}) = 0.027\ SoilTemp_{s0} °C + 0.597 \ln (Q.m3s^{-1}) - 4.432 \quad 6.2$$

Streamflow as a predictor in the model represents transport component of DOM from the watershed through the streams. Soil temperature as a predictor represents seasonality in DOM production and transport. Total phosphorus as a predictor variable in the CBS site model may be an indication of its co-transport with aromatic DOM such as humic and fulvic acids which are the principal precursors for regulated DBPs. Model performance is particularly good at the low ranges which also corresponds to low ranges in streamflow, where instantaneous measurements are a good representation of daily averages. At the higher ranges, instantaneous measurements may not give a true representation of the daily average value, which may have resulted in model underestimation of the measured values. This was true at both sites, although it was more pronounced at the NCG site where the number of samples collected was also less. Model fit may also improve with additional sampling, particularly at the higher ranges and at a higher frequency.

Figure 6.11 shows the seasonal variation in UV_{254} based on estimated multi-year (2002-2021) average daily values. Temporal pattern was similar for both sites during winter and early spring. But it diverged throughout the growing season before converging again in late autumn. Differences in temporal patterns during the growing season is explained by the presence of agricultural land use in the Cannonsville watershed. Agricultural practices such as tillage and manure application can contribute to runoff and erosional sources of dissolved organic carbon and therefore greater UV_{254} levels during the growing season.

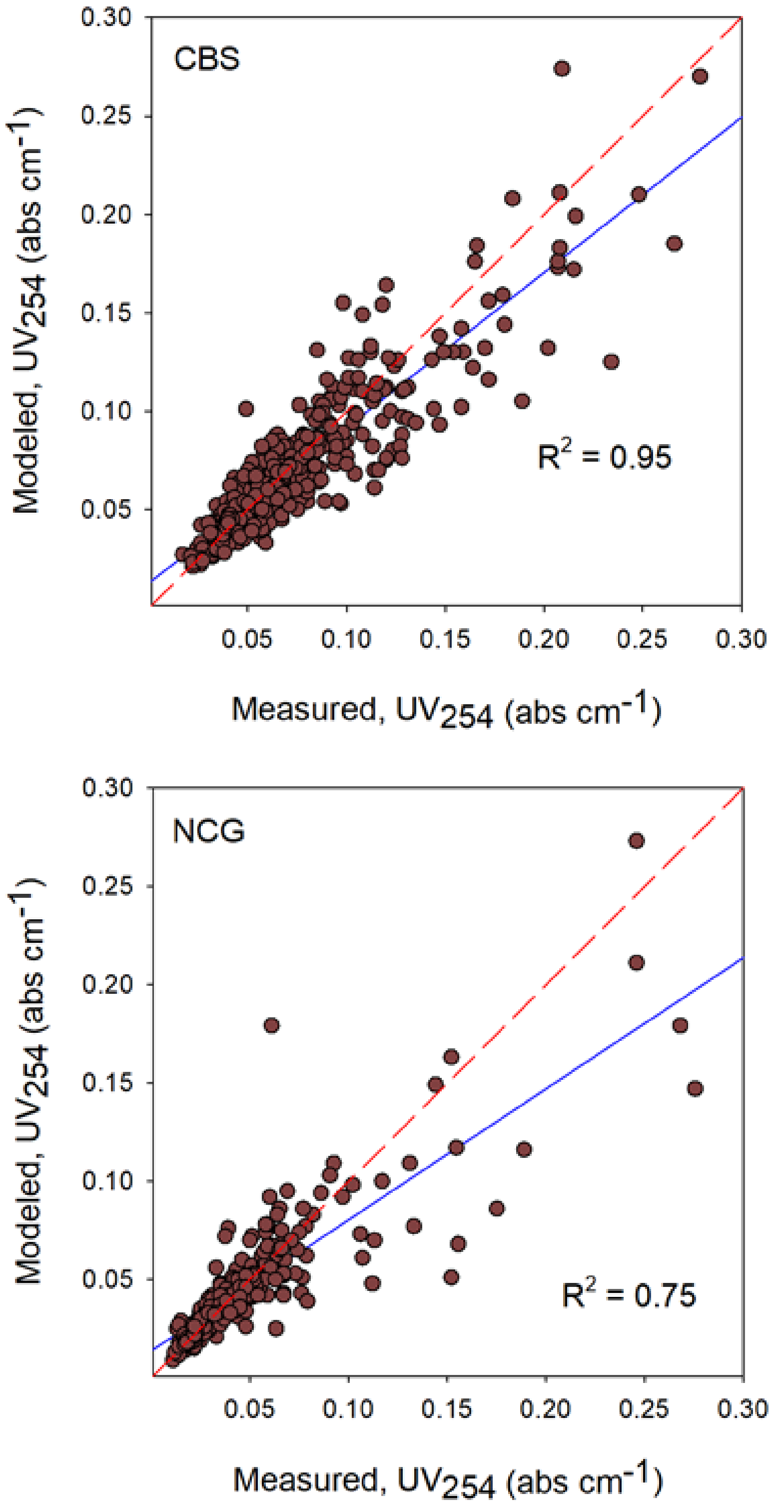


Figure 6.9 Model predicted vs measured UV_{254} along a 1:1 line.

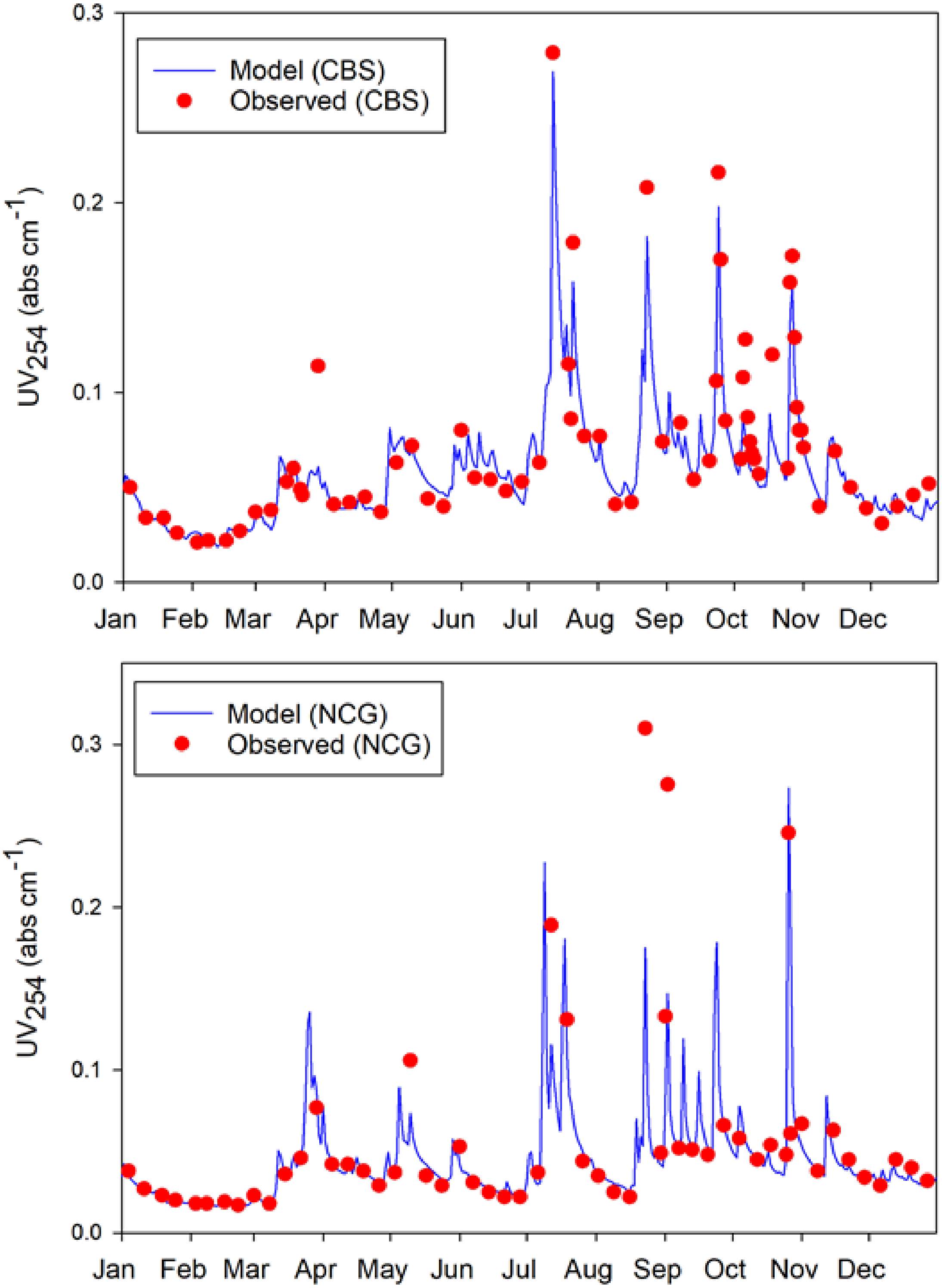


Figure 6.10 Comparison of model predicted and measured UV_{254} for 2021.

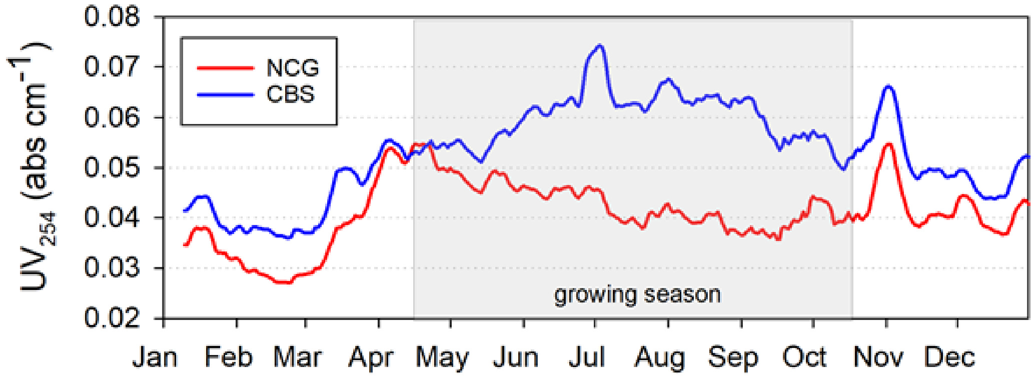


Figure 6.11 Seasonal variation in UV_{254} based on a 10-day running mean of 20-year (2002-2021) average daily predictions. Time series for CBS site shows the effect of growing season.

6.3.3 Highlights from Empirical Modeling of UV_{254}

- Empirical models of UV_{254} are developed for major inflow streams to Cannonsville and Neversink reservoirs.
- Model performance is generally good when compared to observations and may improve further with additional sampling particularly at the higher ranges.
- Terms in the empirical model represent transport, seasonality, and co-transport of aromatic DOM such as humic and fulvic acids.
- Long-term estimates of UV_{254} indicates distinct seasonal pattern for the two sites during the growing season.
- Synoptic estimates of UV_{254} from several source water stream sites allows comparison and assessment of DBPfp to support water supply operations decisions.
- Long-term historical time series of UV_{254} generated using empirical models can be used as input to test a mechanistic reservoir model of DBPfp.

6.4 Extended Validation of Turbidity Models for Schoharie and Ashokan Reservoirs

Schoharie Reservoir: Validation testing of the Schoharie W2 model was extended for the most recent interval (2009-2019) not covered in the original validation testing done during Catskill turbidity control studies and OST development (Gannett Fleming & Hazen and Sawyer 2009). Following 2008, the Schoharie watershed experienced major pluvial as well as drought conditions, with record precipitation and flooding during Hurricane Irene in 2011 and dry conditions in 2015-2016. These wide-ranging model-forcing functions offered an opportunity to retest and validate the model. Hence, this study was undertaken.

For the extended validation of the model, DEP updated previously developed empirical equations for estimating various model inputs and developed some new equations (Table 6.3). In addition, bathymetry was updated according to a survey conducted in 2014 (Nystrom 2018).

Table 6.3 List of new and updated empirical equations for estimating model inputs [Tn = turbidity (NTU) and Q = flow (m3 s-1)].

Variable	Equation
Air temperature (C)	$T_{air,Schoharie} = 0.92\, T_{air,Albany}$; $r^2 = 0.98$
Dewpoint (C)	$T_{dew,Schoharie} = 0.96\, T_{dew,Albany}$; $r^2 = 0.97$
Wind speed, x (m/s)	$W_{x,Schoharie} = 0.2125\, W_{x,Albany}$; $r^2 = 0.37$
Wind speed, y (m/s)	$W_{y,Schoharie} = 0.5417\, W_{y,Albany}$; $r^2 = 0.67$
Bear Kill inflow (m^3/s)	$\log(Q_{brk}) = -1.2471842644 + 1.1330699253 \log(Q_{Sch\,Cr})$; $r^2=0.85$
Manor Kill inflow (m^3/s)	$\log(Q_{mrk}) = -0.9611786474 + 0.956177777 \log(Q_{Sch\,Cr})$; $r^2=0.89$
Bear Kill Turbidity (NTU)	$\log(T_n) = 0.5487481 + 0.5738305 \log(Q_{brk}) + 0.1575958 (\log Q_{brk})^2$; $r^2=0.55$
Manor Kill Turbidity (NTU)	$\log(T_n) = 0.2831749 + 0.7677833 \log(Q_{mrk}) + 0.3974162 (\log Q_{mrk})^2$; $r^2=0.61$
Schoharie Cr. Turb.* (NTU)	$\log(T_n) = 0.47762 - 0.40105 \log(Q_{Sch\,Cr}) + 0.51676 (\log Q_{Sch\,Cr})^2$

*Median quantile relationship

Other updates included improving the empirical model for predicting inflow temperature of Schoharie Creek for winter months and extending the wave sub model for predicating wave energy as a driver of sediment resuspension in the reservoir for the conditions of 2009–2019.

Model performance was evaluated by visualizing in-reservoir vertical profiles, in-reservoir time series plots, and outflow time series plots. Here, four of such plots are presented. Figure 6.12 and Figure 6.13 compare observed and predicted temperatures in withdrawal and outflow for 2011-2019. The model simulated seasonal dynamics in withdrawal temperatures well, as indicated by low root mean square error (1.68 °C). Although, observations of outflow temperature (below Gilboa Dam) were not available as frequently, model generally performed good (RMSE = 1.83 °C). Model performance for selected depth profiles of turbidity and withdrawal turbidity is shown in Figure 6.14 and Figure 6.15, respectively. The model generally captured the vertical structure of turbidity in the reservoir; however, near-surface turbidities are over-predicted. Lack of validation of the wave sub model and the resulting uncertainty in the wave-driven resuspension is likely a contributing factor. The model mostly simulated well the peak withdrawal turbidities and subsequent attenuation observed during high runoff events (Figure 6.16). Additional sources of uncertainty are incomplete inflow turbidity data, and observations of withdrawal turbidity being influenced by backflow from Esopus Creek. Overall, these results are supportive of the continued acceptable performance of the model.

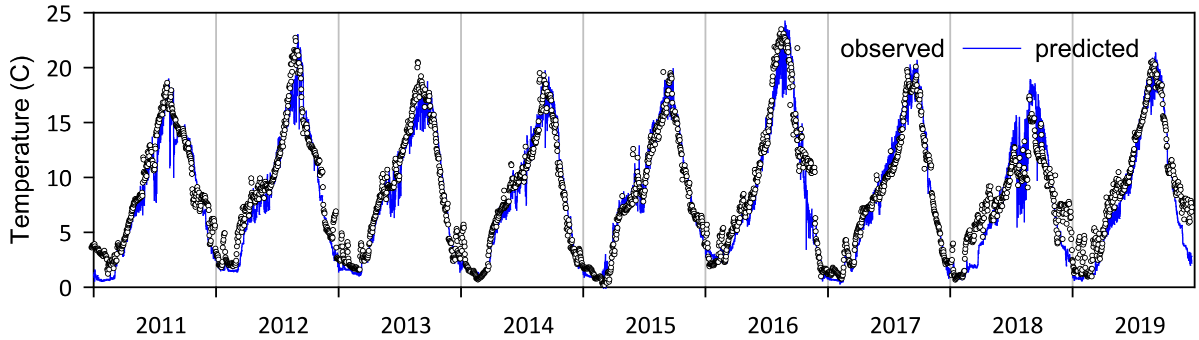


Figure 6.12 Performance of the model for Schoharie Reservoir presented as comparison of observed and predicted time series of withdrawal temperatures, 2011-2019. Observations (USGS) are recorded at site SRR2CM at the point of discharge into Esopus Creek. RMSE = 1.6

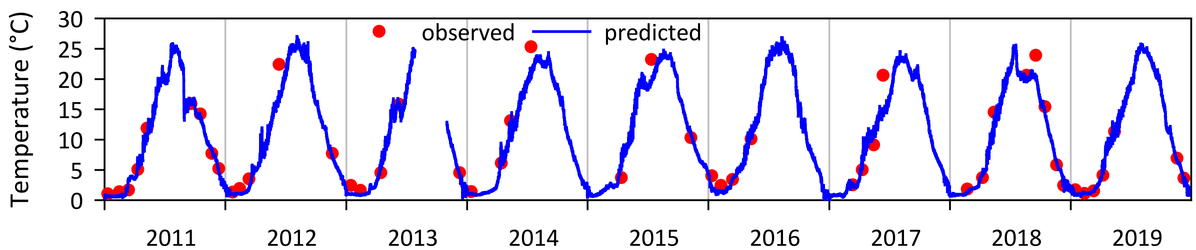


Figure 6.13 Performance of the model for Schoharie Reservoir presented as comparison of observed and predicted time series of outflow (release and spill) temperatures, 2011-2019. Observations are recorded at site SS below Gilboa Dam. RMSE = 1.83 °C.

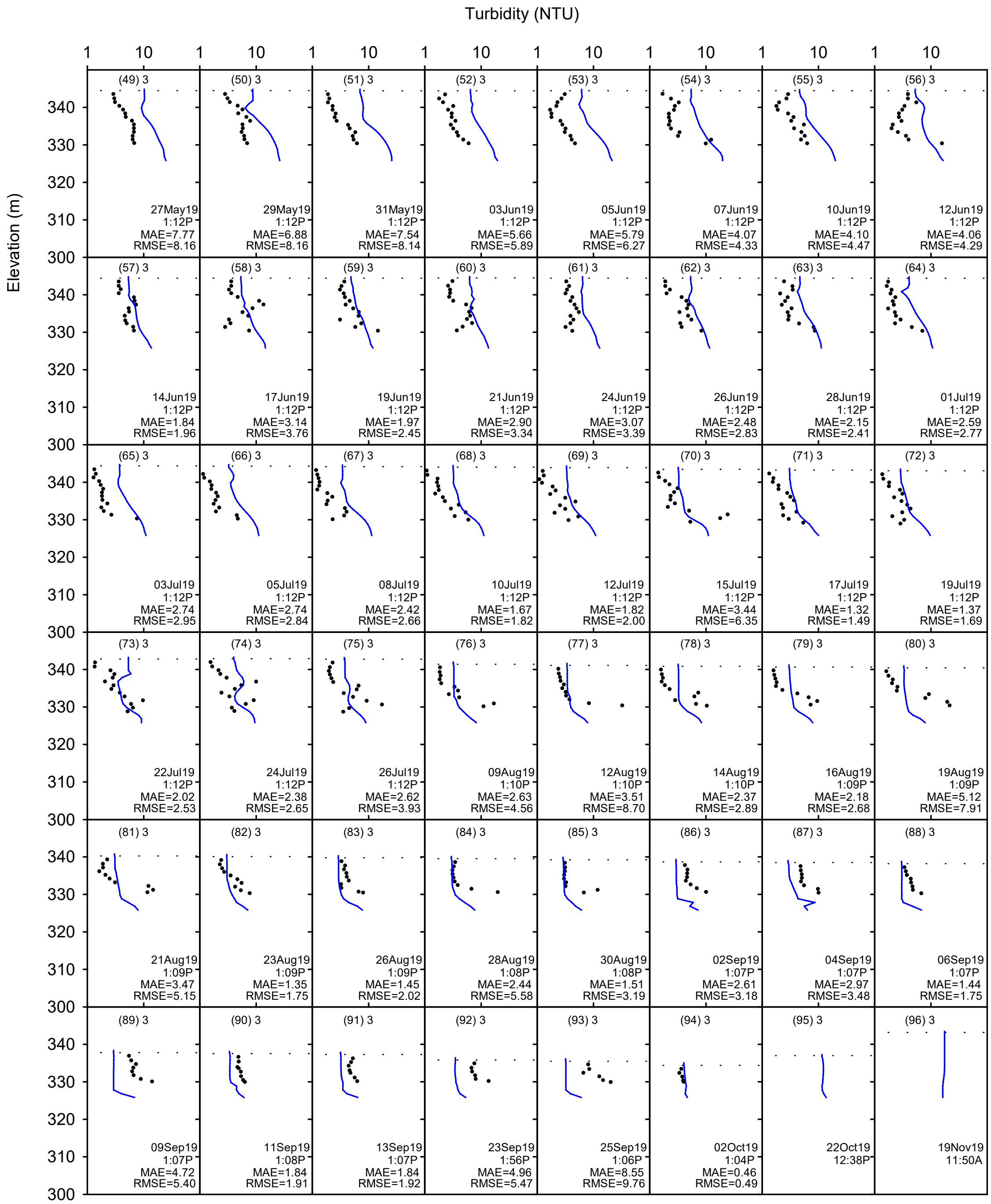


Figure 6.14 Performance of the model for Schoharie Reservoir presented as comparison of selected predicted and observed vertical depth profiles (May–October 2019) of turbidity at site 3SS. MAE and RMSE indicate mean absolute error (°C) and root mean square error (°C), respectively.

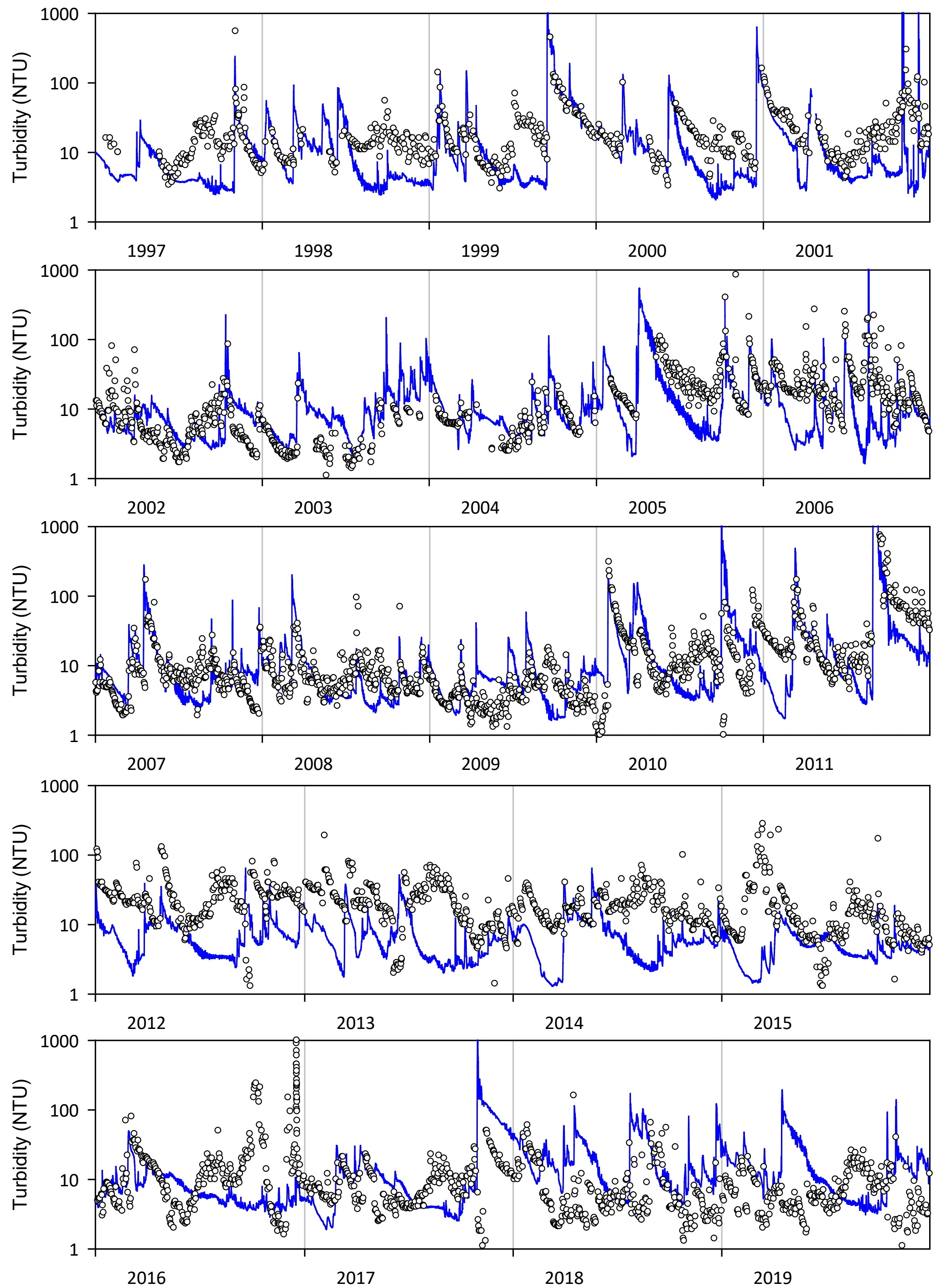


Figure 6.15 Performance of the model for Schoharie Reservoir presented as comparison of observed and predicted time series of withdrawal turbidities, 1997-2019. Observations are recorded at site SRR2CM at the point of discharge into Esopus Creek. MAE and RMSE were 17 NTU and 165 NTU for 1997-2010; and 29 NTU and 122 NTU for 2011-2019, respectively.

Ashokan Reservoir: Validation testing of the W2 model for Ashokan Reservoir was also extended for the most recent interval (2007-2019) not covered in the original validation testing done for OST development. Like the Schoharie watershed, the Ashokan watershed also experienced major pluvial as well as drought conditions in this interval. Additionally, several stream turbidity restoration projects in the watershed were undertaken that had material impact in reducing turbidity at the mouth of Esopus Creek. The results presented here confirm the model is valid and can be used to guide operational and planning decisions.

For the extended validation of the model, previously developed empirical equations for estimating various model inputs were updated and some new equations were developed (Table 6.4). In addition, bathymetry was updated according to a survey conducted in 2014 (Nystrom 2018).

Table 6.4 List of new and updated empirical equations for estimating model inputs [Tn = turbidity (NTU), and Q = flow (m^3 s^{-1})].

Variable	Equation
Bush Kill inflow (m3/s)	$Q_{Bsh} = 0.0934311\ Q_{Esp}$; r2=0.92
Bush Kill Turbidity (NTU)	$\log(T_n) = -0.4225712 + 0.6050797 \log(Q_{Bsh}) + 0.3278721 (\log Q_{Bsh})^2$; r2=0.41
Esopus Cr Turbidity* (NTU)	$\log(T_n) = 0.41278 - 0.25742 \log(Q_{Esp}) + 0.47809 (\log Q_{Esp})^2$

*Median quantile relationship

Daily values of Bush Kill turbidity as estimated from the regression (Table 6.4) were used as input to the model. A complete time series of Esopus Creek turbidity at Coldbrook was developed from continuous and routine laboratory measurements with gaps being filled with the estimated values from the median quantile regression (Table 6.4).

Model performance was evaluated by comparing observed and modeled in-reservoir vertical profiles, in-reservoir time series plots, and outflow time series plots. Here, two of such plots are presented in Figure 6.16 and Figure 6.17. The model simulated seasonal dynamics in withdrawal temperatures well, as indicated by low RMSE (1.3 °C). Abrupt change in withdrawal temperature is observed when there is change in the withdrawal basin or change in the elevation of the draw (Figure 6.16). The model generally captured peak withdrawal turbidities and subsequent attenuation observed during high runoff events (Figure 6.17; RMSE = 27.8 NTU). Relatively high RMSE is due to the underperformance of the model during and after Hurricane Irene in 2011. Significant uncertainty exists in estimates of turbidity loading to the Ashokan West Basin for this interval.

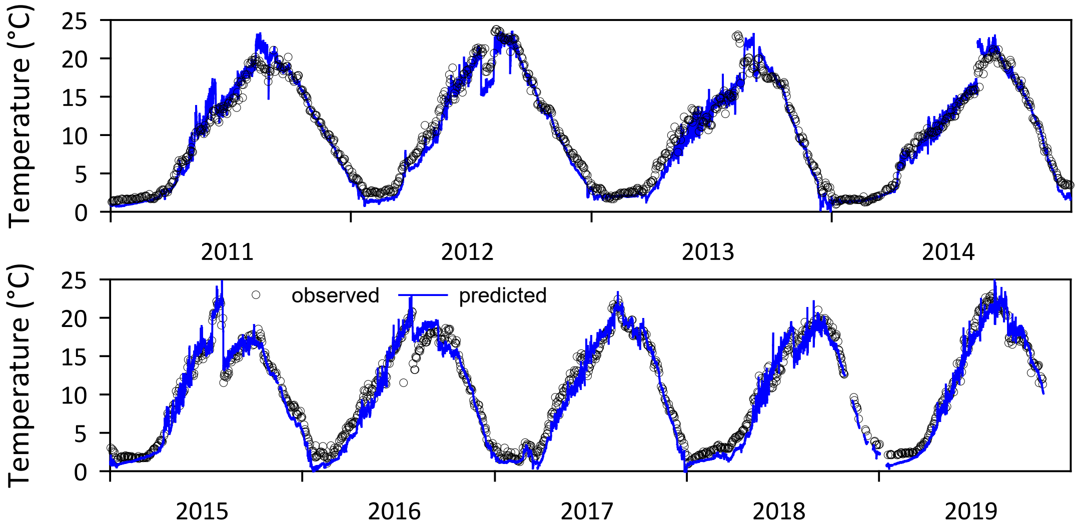


Figure 6.16 Performance of the model for Ashokan Reservoir presented as comparison of observed and predicted time series of withdrawal temperatures, 2011-2019. Observations are recorded at site EARCM. AAE = 1.0 °C; RMSE = 1.3 °C.

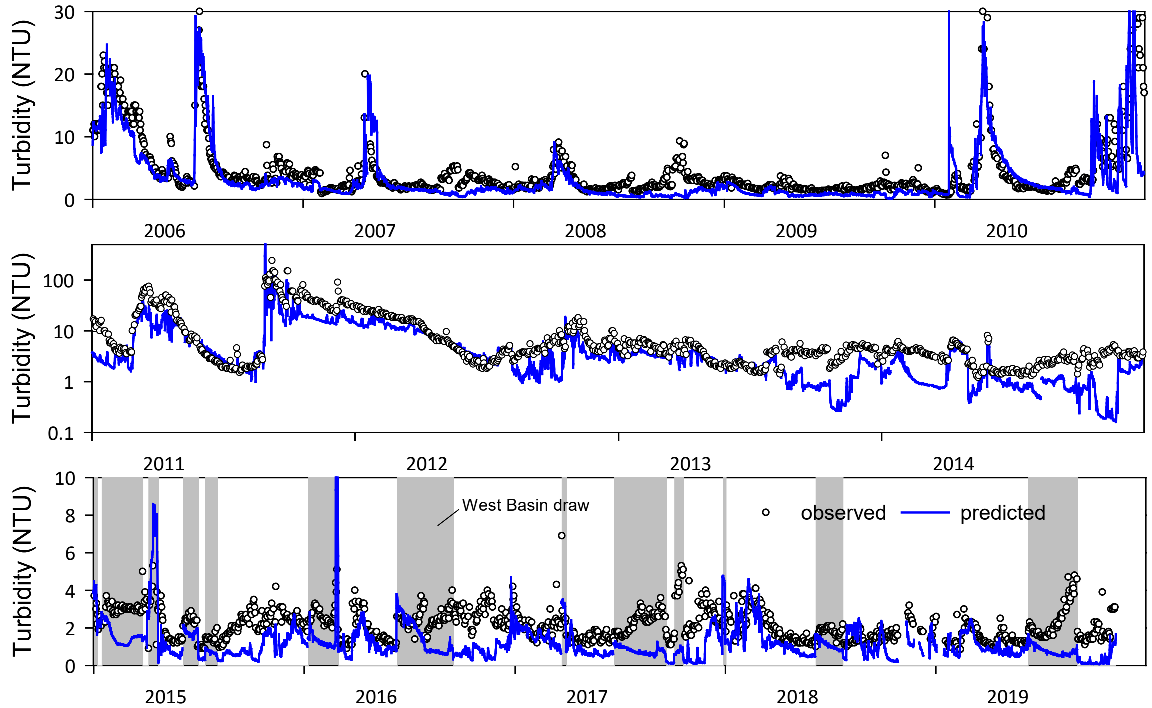


Figure 6.17 Performance of the model for Ashokan Reservoir presented as comparison of observed and predicted time series of withdrawal turbidity, 2006-2019. Shaded region represents time of Ashokan West Basin withdrawal. Observations are recorded at site EARCM. Error statistics for 2011-2019 are AAE = 3.7 NTU; RMSE = 27.8 NTU and for 2012-2019 (i.e., excluding Hurricane Irene) are AAE = 1.6 NTU; RMSE = 2.3 NTU.

6.5 Model Applications

During this reporting period, New York City's WOH watershed experienced a significant rain-on-snow event on December 24, 2020, referred to hereafter as the Christmas 2020 storm (CE2020). Nearly 1–6 inches of rainfall occurred watershed wide with heavier amounts localized in the upstream reaches of Schoharie Creek and Esopus Creek basins Figure 6.18). There was 1-2 feet of accumulated snow on the ground prior to the rain. Intense rain and melting snow caused rivers and creeks to rise above flood stage, resulting in transport of eroded sediment into and deterioration of water quality in the reservoirs.

A detailed view of the state of the system during and one month after CE2020 storm is presented in Figure 6.19. On December 25, 2020, daily average peak flow in Schoharie Creek was recorded as 606 m^3 s^{-1}, and 564 m^3 s^{-1} in Esopus Creek (Figure 6.19e – Figure 6.19f). These flow magnitudes have recurrence interval (RI) of ~ 30 and 15 years. The instantaneous peak flows were 1,181 m^3 s^{-1} (41700 CFS) and 1,107-m3 s^{-1} (39,100 CFS) in Schoharie and Esopus creeks, respectively. This type of event occurs infrequently and considering timing, geographical region, intensity, ground conditions, and water quality impacts on reservoirs, CE2020 was a rare event. The last event like CE2020 occurred in January 1996.

Instantaneous maximum turbidities of inflows to Cannonsville, Neversink, and Rondout reservoirs were 800-1,000 NTU (Figure 6.19g, Figure 6.19i, and Figure 6.19j). Pepacton Reservoir inflow is not continuously monitored. Esopus Creek (Coldbrook) and Schoharie Creek (Prattsville) turbidities measured at the upper limit of the range of detection (1,200-1,300 NTU; Figures Figure 6.19k, and Figure 6.19l); actual turbidities were likely substantially higher. Also, Esopus Creek continuous monitoring station was damaged in the storm.

Consistent with inflows, reservoir turbidities were also different. Maximum turbidities recorded near the intake locations in Cannonsville, Pepacton, Neversink, and Rondout reservoirs were 60, 15, 8, and 2.3 NTU; respectively (Figure 6.19m – Figure 6.19p). Higher turbidity (9.6 NTU) was observed in Rondout Reservoir at site 3 RR located below the confluence of the inflows (Figure 6.19p). The Ashokan West Basin was affected the most with 450 NTU turbidity at weir (Figure 6.19r). No data were available from Schoharie Reservoir, but aerial images suggested that it also had turbidity of magnitude generally like the Ashokan West Basin. Even though there is no significant tributary inflow, the Ashokan East Basin turbidity reached 75 NTU on January 4, 2021 (Figure 6.19r), primarily due to the transfer of water from the Ashokan West Basin through the dividing weir gates. This was necessary to contain the stormwater in the Ashokan West Basin and mitigate spill as well as to equalize the two basins. The gates were closed on January 5, 2021.

Subsequent attenuation of turbidity occurred at different rates (Figure 6.19m – Figure 6.19r). Cannonsville and Pepacton reservoirs saw an order of magnitude decline in turbidity in the 30 days after the storm (Figures 6.19m-6.19n). In contrast, turbidity in Neversink Reservoir remained 7–8 NTU (Figure 6.19o) during the same time due to relatively larger contribution from smaller (1–3 μm) size particles. Lacustrine portion of Rondout Reservoir was impacted moderately (peak turbidity 2.3 NTU; Figure 6.19p), and, therefore, recovered quickly. Recovery in the Ashokan West Basin was particularly slow. One month after the storm, turbidity was still 100 NTU (Figure 6.19r), whereas it had decreased from 75 NTU to < 10 NTU in the Ashokan East Basin. Contributing factors for the differing response in the reservoirs are initial heterogeneous distribution of turbidity plumes, initial size-distribution as well as concentration of turbidity-causing particles, and density of inflows and ambient waters.

Diversion turbidities (recorded when diversion was made) were very similar to the in-reservoir turbidities (Figure 6.19s-Figure 6.19x). After initial response of taking the Pepacton and Neversink offline (Cannonsville was already offline prior to the storm), first, Pepacton was brought back online, then Neversink, and then Cannonsville, so that a steady diversion from Rondout could be supported without much drawdown (Figure 6.19y-Figure 6.19ad). Schoharie and Ashokan were offline due to repair and rehabilitation activities. How OST helped guide the daily operations of the water supply during the January-April interval after CE2020 is discussed next.

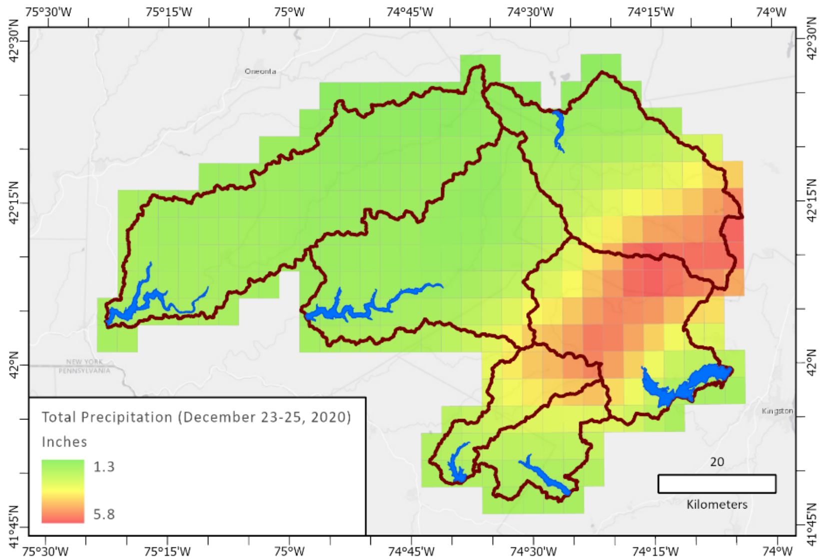


Figure 6.18 Precipitation (December 23-25, 2020) over West of Hudson watershed of NYC water supply (data source: PRISM 4-km grid).

6.5.1 Selected OST Runs

To guide operations after CE2020 storm, 109 OST runs were executed between December 24, 2021, and April 14, 2021, that had water quality simulations turned on and were conducted in position analysis mode. Table 6.5 lists selected runs with specific objectives. A subset of these is discussed in detail next.

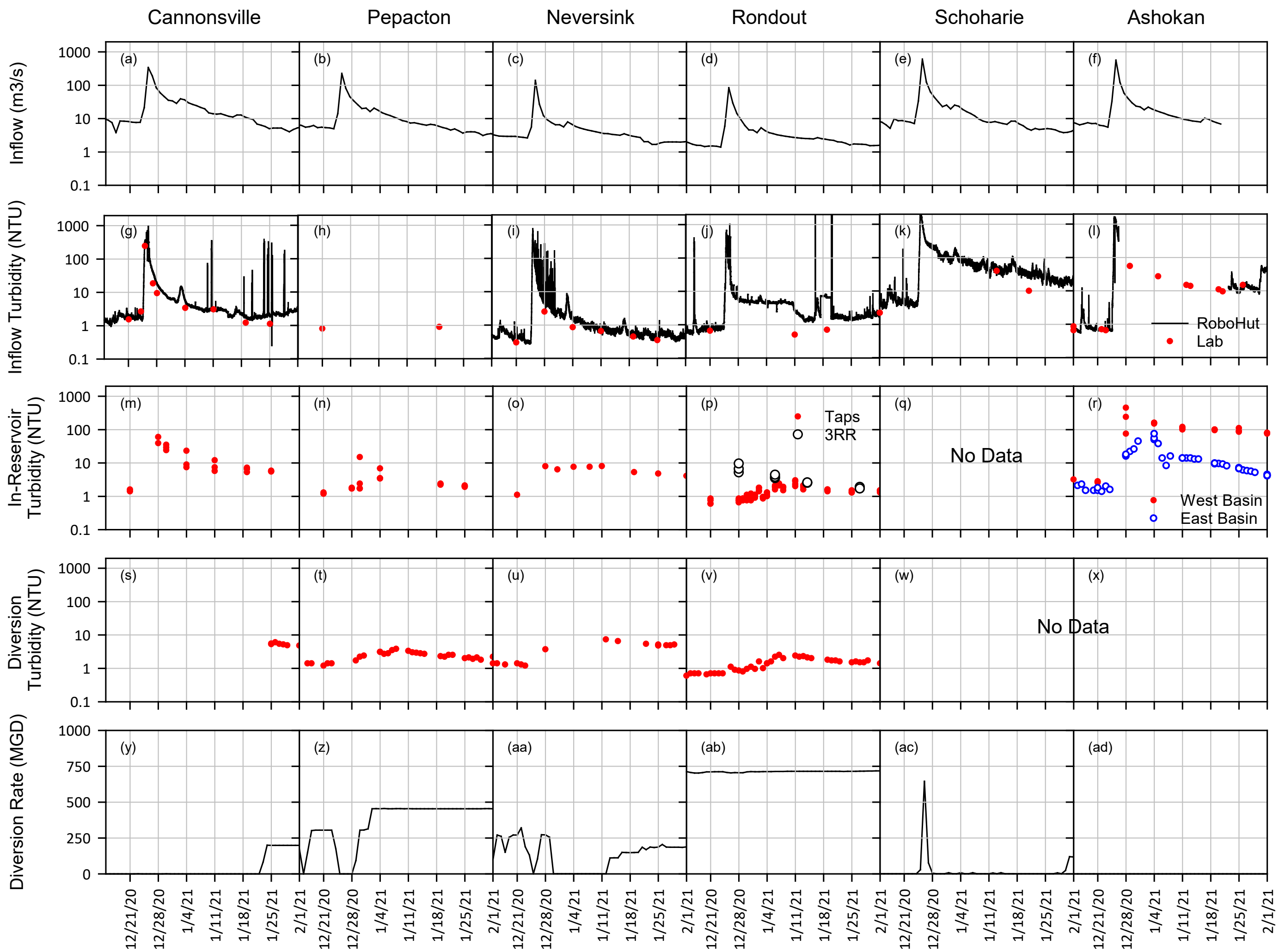


Figure 6.19 Inflows, state of water quality, and reservoir operations during and after rainstorm of December 24, 2020 (a-ad).

Table 6.5 List of selected OST-W2 runs conducted in the aftermath of Christmas Eve 2020 storm for guiding NYC water supply operations.

Date	No. of Scenarios	Objectives
01/06/2021	18	Determine optimal operation of Pepacton and Neversink reservoirs for up to weeks ahead while balancing water supply and water quality. Evaluate impact on Kensico diversion turbidity.
01/21/2021	3	Evaluate if Cannonsville Reservoir can be brought back online.
01/28/2021	8	Evaluate if Catskill Aqueduct (Ashokan Reservoir) can be brought back online. Determine optimal Delaware Aqueduct Shaft 4 diversion.
02/10/2021	12	Continue to assess if Catskill Aqueduct can be brought back online with minimum diversion required for the upstate communities. Determine optimal Delaware Aqueduct Shaft 4 diversion to minimize impact on Kensico Reservoir.
03/01/2021	1	Assess impact of releases from Ashokan West Basin on turbidity in Lower Esopus Creek.
03/02/2021	1	As Ashokan West Basin is approaching spill, evaluate the impact of opening the dividing weir gates on the Ashokan East Basin turbidity.
03/08/2021	2	With the Catskill Aqueduct on and the dividing weir gates open, determine if diversion from Ashokan East Basin can be sustained at rates above 60 MGD.
03/12/2021	3	Evaluate Ashokan Release Channel operations scenarios.
03/31/2021	1	Continue to assess Ashokan-Kensico turbidity under current operations.
04/11/2021	5	Continue to assess Ashokan-Kensico turbidity with operations geared toward increasing East Basin diversion.

6.5.1.1 January 6, 2021 Runs: PCN Reservoirs

Scenarios: Conduct OST-W2 runs with Cannonsville diversion off, Pepacton diversion 300, 350, and 450 MGD, Neversink diversion 100, 200, and 250 MGD, Pepacton turbidity 2.5-5.0 NTU, and Neversink turbidity 5-15 NTU. In addition, keep Schoharie and Ashokan offline for pre-scheduled repair and rehabilitation activities, New Croton Aqueduct (NCA) diversion 180 MGD through Catskill outage, and Rondout diversion 700 MGD. In all, 18 scenarios were setup to determine optimal operation of PCN reservoirs.

Results: OST-W2 simulations projected that Rondout Reservoir diversion turbidity was sensitive to both the diversion rate and turbidity levels incoming from PCN reservoirs. Rondout diversion turbidity would initially increase from 1.8 NTU to 2.6 NTU and then peak at 3.4 NTU in two weeks, while Kensico diversion turbidity would continue to increase and reach 1.1 NTU at the end of simulation (Figure 6.20).

Guided by these results, Cannonsville was kept offline until January 21,2021, Neversink was offline until January 11, 2021, then gradually ramped up to 200 MGD, while Pepacton was online diverting at 450 MGD supporting Rondout storage (Figure 6.19y-Figure 6.19aa). Rondout diversion was kept steady at 700 MGD.

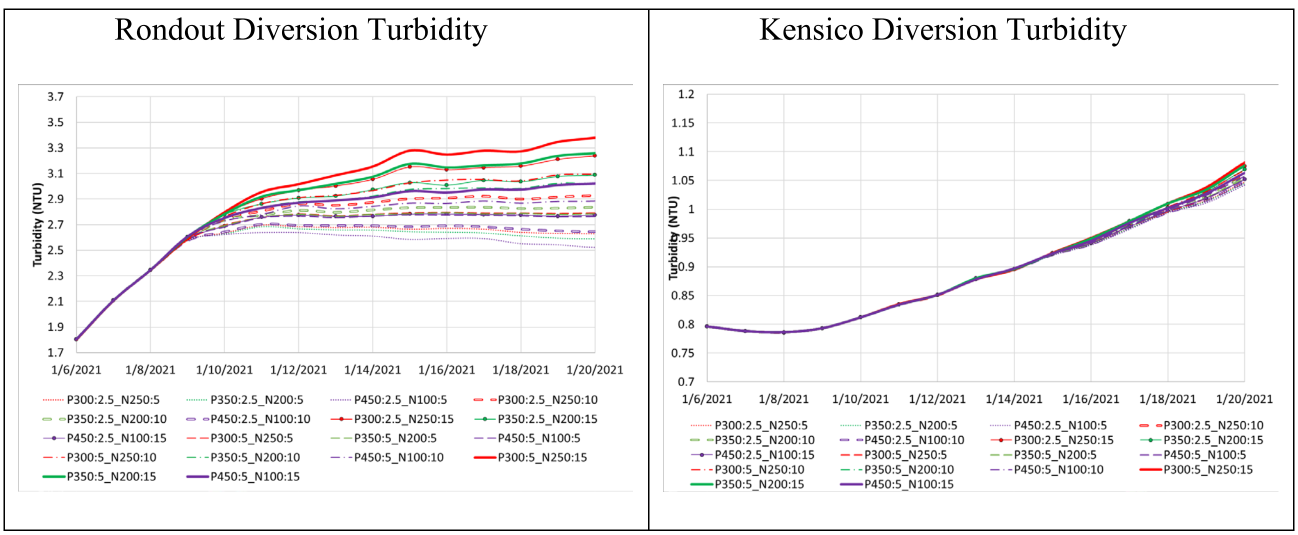


Figure 6.20 Projections of (a) Rondout and (b) Kensico diversion turbidity for a range of operating conditions of Pepacton and Neversink reservoirs.

6.5.1.2 January 21, 2021 Runs: Cannonsville Reservoir operation

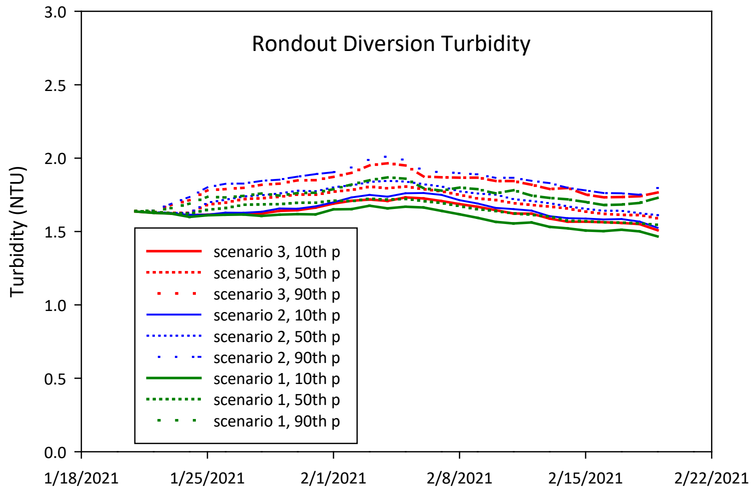
Scenarios: To forecast impact of Cannonsville coming back online, OST-W2 runs were conducted with the following specifications: Cannonsville diversion at 100, 200, and 300 MGD and turbidity level at 6.5 NTU; Pepacton diversion at 300 and 450 MGD with turbidity of 2.5 NTU, Neversink diversion at 100 and 150 MGD with turbidity of 5.5 NTU. In addition, Schoharie and Ashokan were still offline for pre-scheduled repair and rehabilitation activities, New Croton Aqueduct (NCA) diversion was specified at 180-240 MGD through Catskill outage period, and Rondout diversion was specified at 700 MGD. In all, three scenarios were setup.

Results: OST-W2 simulations projected that Rondout Reservoir diversion turbidity would remain at or below two NTU until mid-February thus supporting the use of Cannonsville water (Figure 6.21). These results provided the confidence, and a decision was made to begin diverting from Cannonsville at 200 MGD on January 21, 2021 (Figure 6.19y).

6.5.1.3 January 28, 2021 Runs: Catskill Aqueduct and Delaware Aqueduct Shaft 4 operation

Scenarios: Catskill Aqueduct outage (CatRR project) was scheduled to end on February 5, 2021. To forecast impacts of Ashokan Reservoir diversion and bringing Catskill Aqueduct back online, OST-W2 runs were conducted with the following specifications: Rondout diversion at 600-800 MGD with turbidity of 1.4-2.0 NTU; Delaware Aqueduct Shaft 4 diversion at 0-240 MGD; Catskill Aqueduct at unscheduled (i.e., model-estimated) flow rate with turbidity of 6-8 NTU. In addition, Schoharie diversion was unscheduled, and the New Croton Aqueduct (NCA) diversion was specified at 120 MGD. In all, eight scenarios were setup. It was also important to determine if alum would be needed at Kensico Reservoir.

Results: OST-W2 simulations projected that Kensico diversion turbidity would peak at ~ 2 NTU at 50th percentile level in all of the scenarios and the maximum of all scenarios at 90th percentile level would be ~ 2.6 NTU, about two weeks after the scheduled end of Catskill Aqueduct outage on February 5, 2021 (Figure 6.22). No alum was required in any of the scenarios. The model allowed diversion from the Ashokan East Basin within 25-500 MGD range during this interval. Based on these results, Ashokan diversion was considered feasible without adversely affecting Kensico water quality. Accordingly, Ashokan diversion was planned and executed, gradually increasing from 0 to 500 MGD for the next month with appropriate amount of water coming from Delaware Aqueduct at the Delaware Aqueduct Shaft 4 interconnection.



Scen.	Pep	Can	Nev
1	450	100	100
2	300	300	150
3	450	200	150

Figure 6.21 Projections of Rondout diversion turbidity for a range of operating conditions of Cannonsville, Pepacton, and Neversink reservoirs.

An “open” run with no scheduled flows was also conducted for simulating turbidity in the Ashokan West Basin. As shown in Figure 6.23, it was projected to take five months before the turbidity levels reached < 10 NTU. Modeling evaluation continued during this interval to further adjust Catskill- Delaware Aqueduct Shaft 4 operation.

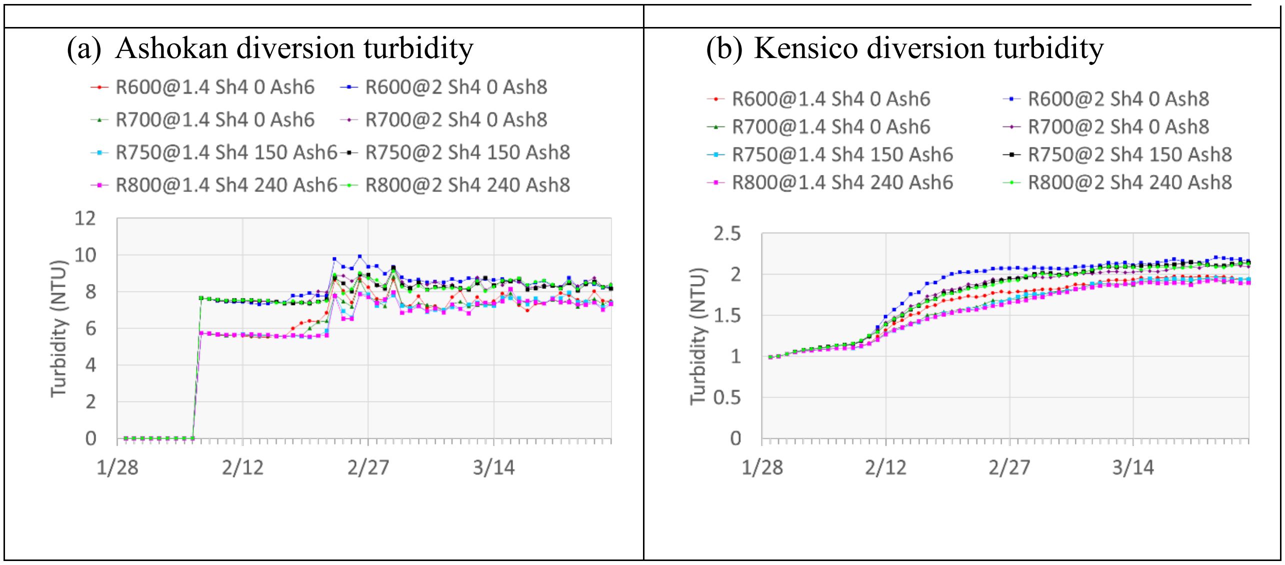


Figure 6.22 Projections of (a) Ashokan and (b) Kensico diversion turbidity for a range of operating conditions of Catskill Aqueduct.

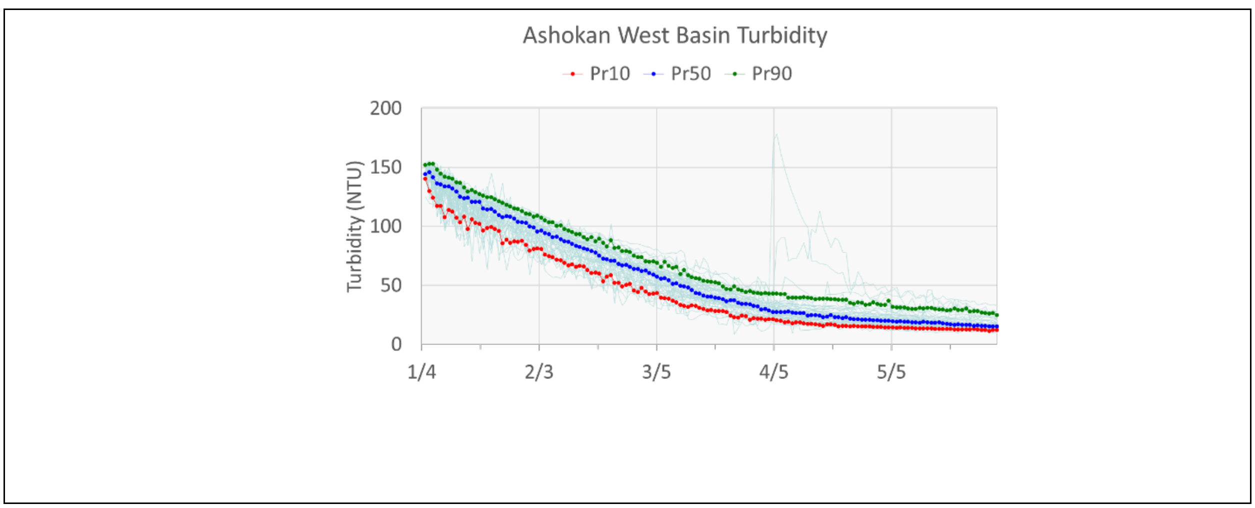


Figure 6.23 Long-term projections of the Ashokan West Basin turbidity for the case of no schedule implemented.

6.5.1.4 February 10, 2021 Runs: Catskill Aqueduct and Delaware Aqueduct Shaft 4 operation – continued evaluation

Scenarios: As the Catskill Aqueduct was being considered for reopening, additional runs were conducted to determine optimum combination of Catskill diversion and Delaware diversion (Delaware Aqueduct Shaft 4). Scenarios considered were: Rondout diversion at 750-800 MGD (1.2 NTU), Delaware Aqueduct Shaft 4 diversion at 150 and 240 MGD for two to four weeks and then offline, Catskill Aqueduct diversion at 150 MGD for two to four weeks and then unscheduled (i.e., model-estimated) with turbidity of 3-5 NTU. In addition, Schoharie diversion was on but kept unscheduled, New Croton Aqueduct diversion was specified at 180 MGD. In all, 12 scenarios were setup. As mentioned in the earlier set of runs, it was important to determine if alum would be needed at Kensico Reservoir.

Results: OST-W2 simulations projected that use of Delaware Aqueduct Shaft 4 would keep the turbidity of Catskill Aqueduct entering Kensico Reservoir (CatIC) ≤ 5 NTU until March 10, 2021. But after that when the Delaware Aqueduct Shaft 4 was offline and Catskill diversion was determined by the model, the turbidity level at CatIC would increase significantly (Figure 6.24a). The increase was attributed to transfer of turbid waters from the Ashokan West Basin into the East Basin in the model as the model was attempting to rebalance the system. At the same time, the model also reduced diversion from Catskill Aqueduct to the required minimum of 25 MGD. Throughout the simulation, Kensico diversion turbidity was projected to remain below 1.6 NTU at 50th percentile level in all of the scenarios (Figure 6.24b) and no alum use was predicted.

Actual Operations: Guided by the above model runs, Catskill diversion from the Ashokan East Basin was allowed during February 10, 2021, to March 6, 2021, at an average rate of 300 MGD (turbidity < 3 NTU), dividing weir gates were opened on March 6, 2021, and Catskill diversion was reduced to minimum required flow (20-60 MGD), turbidity of the diversion increased to ~30 NTU, and Delaware Aqueduct Shaft 4 flow remained in the range of 0 – 250 MGD. Delaware Aqueduct (influent to and effluent from Kensico) turbidity was ~ 1 NTU.

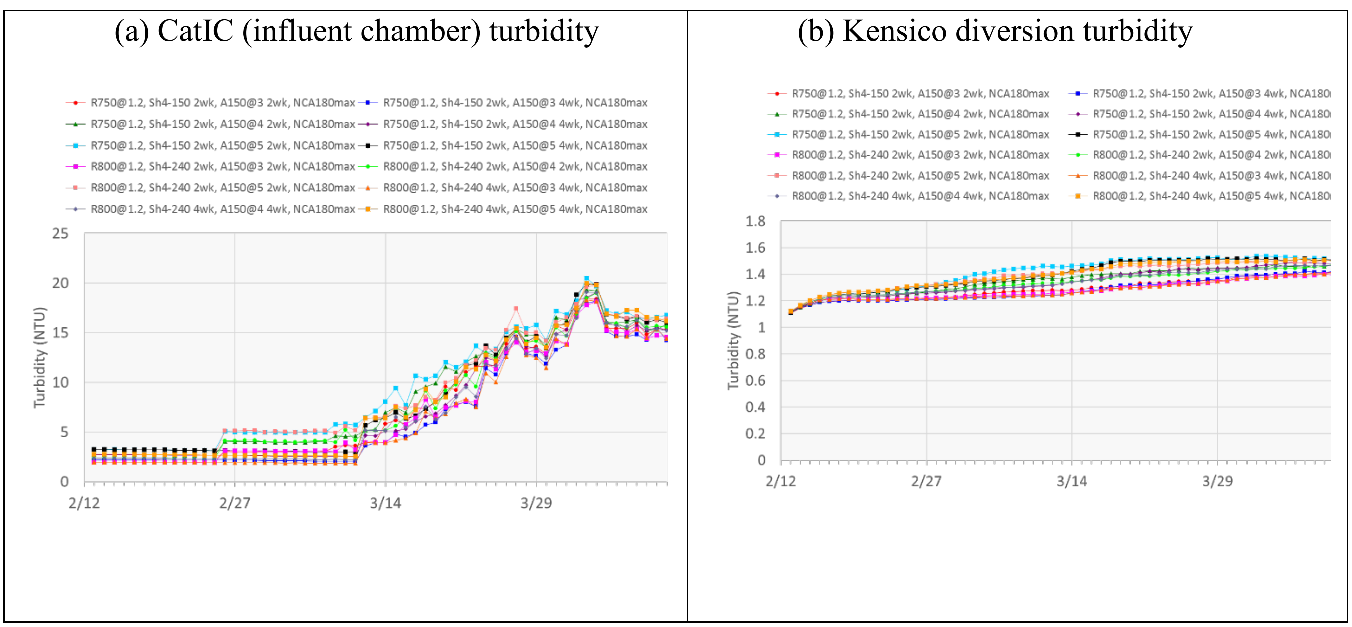


Figure 6.24 Projections of (a) Catskill influent chamber and (b) Kensico diversion turbidity for a range of operating conditions of Catskill Aqueduct and Delaware Aqueduct Shaft 4 Catskill-Delaware Interconnection.

6.5.1.5 March 2, 2021 Runs: Ashokan Reservoir dividing weir gates and spill operation

Scenarios: As the Ashokan West Basin was approaching spill (2 feet below weir crest on February 28, 2021), a run was conducted to evaluate the impact of opening dividing weir gates (DWG) to allow transfer from the Ashokan West Basin into the East Basin. In this run (Run A, Figure 6.25), DWG flow was set to 250 MGD, diversion from the East Basin 450 MGD, and Ashokan Release Channel (ARC) flow 4 MGD until March 12, 2021, and model-determined thereafter.

Results: OST-W2 simulations projected that the Ashokan West Basin would reach full level within one to two weeks from the start of the simulation and then spill into the East Basin (Figure 6.25a). Although, scheduled diversion from the Ashokan East Basin was feasible (Figure 6.25b), diversion turbidity was going to increase significantly after March 12, 2021, (Figure 6.25c) which would demand significant reduction in diversion rate. Turbidity in the Ashokan West Basin was projected to remain elevated until May 31, 2021 (end of this run; Figure 6.25d).

Actual Operations: The results indicated that transfer of turbid water from the Ashokan West to the East Basin was inevitable. At the time, opening DWGs was considered more favorable then allowing the Ashokan West Basin to spill because spilled water could short-circuit and enter the intake on the east side. Hence, DWGs were opened on March 6, 2021, transferring 250 MGD. Incidentally, ice almost entirely covered the Ashokan East Basin at that time, which prevented mixing of the turbid water and causing diversion turbidity to rise quickly. Diversion rate was reduced to 20-60 MGD until April 20, 2021, when the ice cover had melted, the basin was almost completely mixed, and turbidity had dropped below 4 NTU. ARC continued to operate at a rate consistent with CSSO, IRP, and water supply objectives.

6.5.1.6 March 8, 2021 Runs: Increase Ashokan East Basin diversion

Scenarios: After opening DWGs, the Ashokan East Basin diversion was reduced to 60 MGD. However, additional model runs were conducted to assess if higher diversion rate could be sustained. Two scenarios were considered: Scenario A: Catskill (East Basin) 150 MGD with Delaware Aqueduct Shaft 4 150 MGD; Scenario B: Catskill 60 MGD with Delaware Aqueduct Shaft 4 240 MGD.

Results: OST-W2 simulations projected that Kensico diversion turbidity could reach 2 NTU under Scenario A (Figure 6.26) and a decision was made not to increase diversion from the Ashokan East Basin.

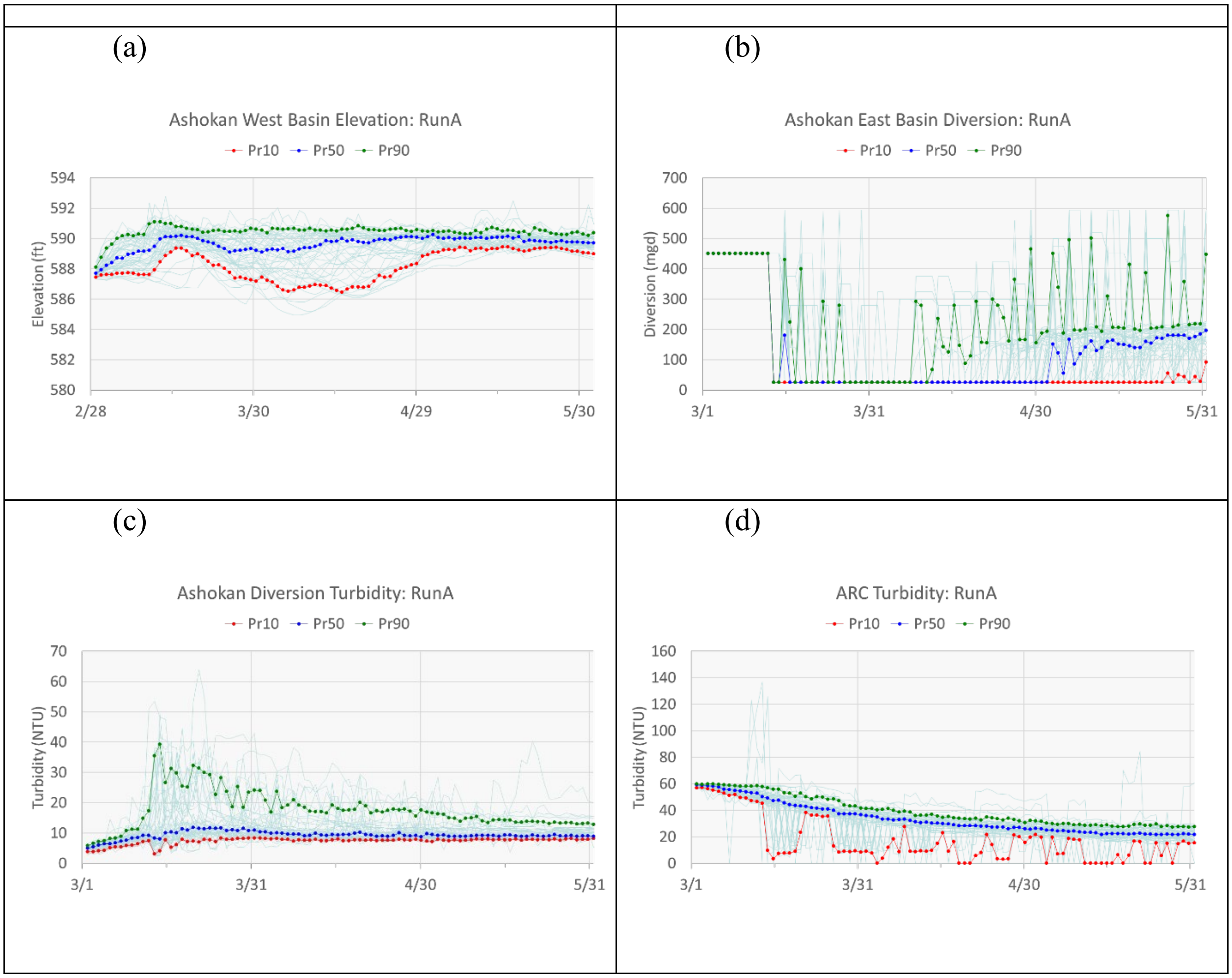


Figure 6.25 Evaluation of dividing weir gates operation (Pr10, Pr50, Pr90 are 10th, 50th, and 90th percentiles of ensemble of projections).

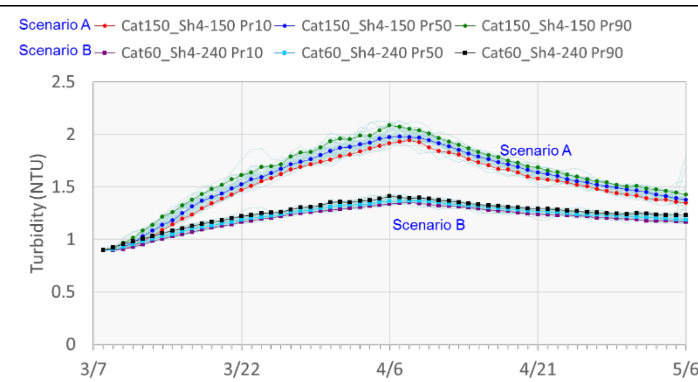


Figure 6.26 Kensico diversion turbidity (Pr10, Pr50, Pr90 are 10th, 50th, and 90th percentiles of ensemble of projections).

6.5.1.7 March 12-31, 2021: Continued Water Quality Evaluation Runs

While the Delaware System had fully recovered from the storm's impact, the Catskill System stayed turbid. DEP continued to monitor and model the situation and adjusted the overall system operations as needed.

6.5.1.8 April 11, 2021: Increase Ashokan East Basin diversion

Scenarios: Water quality in the Ashokan East Basin was gradually improving. Turbidity had reached levels below 10 NTU. Model runs were conducted to assess if or when DEP could increase diversion. Scenarios considered were 20, 60, 100, 150, and 250 MGD from the Ashokan East Basin with corresponding diversion from Delaware Aqueduct Shaft 4 as 175, 140, 100, 50, and 0 MGD.

Results: OST-W2 simulations projected that the Ashokan East Basin turbidity would continue to improve (Figure 6.27a) and diversion could be increased without adversely affecting Kensico turbidity (Figure 6.27b). Thus, on April 23, 2021, it was increased to 200 MGD.

(a) (b)

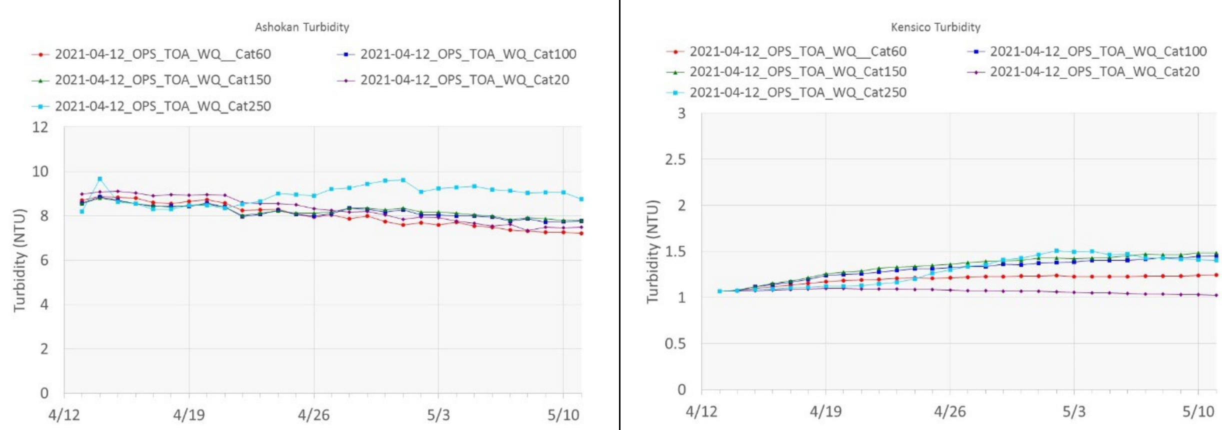


Figure 6.27 Evaluation of increasing Ashokan diversion (a) Ashokan diversion turbidity, and (b) Kensico diversion turbidity.

Verification: Early projections of turbidity in the West Basin of Ashokan Reservoir had indicated it would take approximately five months for water quality to return to normal levels. Later, these projections were verified with observation from sites WS, WM, and WB (three sampling depths on the west of the dividing weir, Figure 6.28). As shown in Figure 6.28, the model had predicted the attenuation of turbidity well, in part due to the Ashokan West Basin being unaffected by the operation of the rest of the water supply system and no major inflow events occurred during this period.

Figure 6.29 shows the observed turbidity in diversion from Kensico Reservoir at Del18DT for December 15, 2020 – July 1, 2021. Throughout this interval, turbidity remained very low at baseline level of about 1 NTU without the use of alum treatment. DEP's application of models and institutional knowledge and resiliency and redundancy of the water supply system is demonstrated here. It is remarkable that despite parts of the system being severely affected by the storm, DEP was able to maintain delivery of high-quality water in the aftermath of the storm.

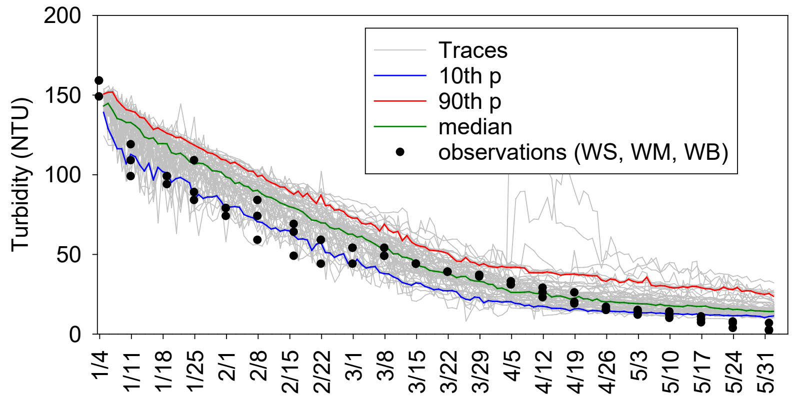


Figure 6.28 Verification of turbidity forecasts for the Ashokan West Basin of Ashokan Reservoir.

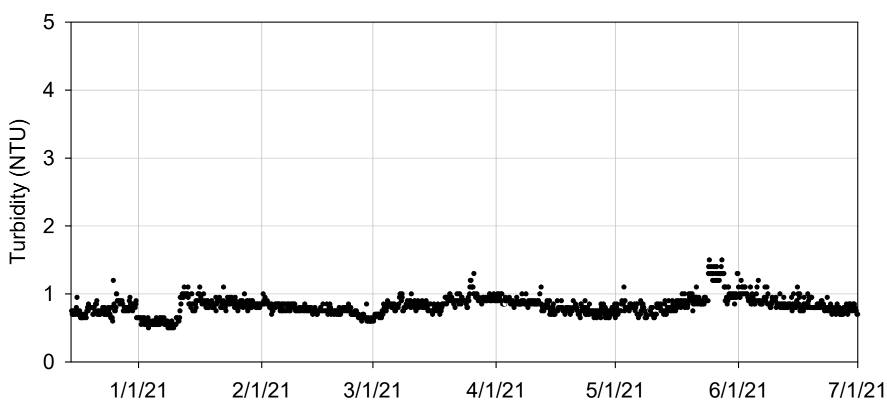


Figure 6.29 Observed Kensico diversion turbidity at Del18DT (4-hour laboratory samples).

6.6 Power BI Visualization of W2 initial conditions

Water quality models (i.e., w2) in OST require that initial conditions of temperature and turbidity be specified for Rondout, Schoharie, Ashokan, and Kensico reservoirs in the longitudinal-vertical dimensions. The initial conditions generally correspond to the first day of model simulation and are guided by DEP's comprehensive water quality monitoring program. In-reservoir monitoring is conducted on a regular basis using manual (1-2 per month) and robotic (every 6 hours) methods. In addition, samples from key-points (taps, diversion points in aqueducts) are also collected for analysis. Diversion points are also monitored continuously for water quality. OST modeler needs to assess the availability as well as quality of these data before using them in OST. The purpose of the Power BI report developed here is to help the modeler quickly visualize what's available and decide which data describe best the initial state of the reservoirs. The Power BI report contains visuals based on the data from the most recent 30 days of manual limnological surveys and 7 days of robotic surveys. The report is refreshed twice daily. Figure 6.30 shows an example page from the report displaying data from Ashokan Reservoir East Basin from July 15-16, 2021. Temperature and turbidity data are shown for sites EARCM, and 4.2 EAE. When available, data from elevation taps and routine monitoring sites will also be shown.

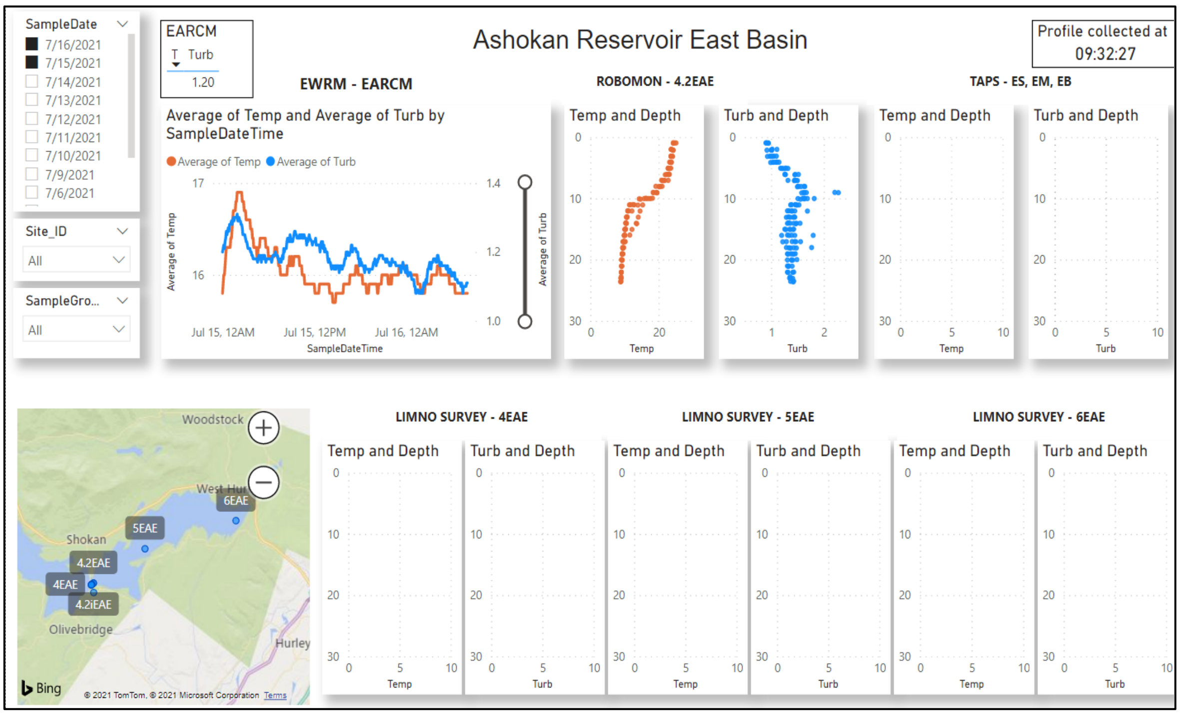


Figure 6.30 A page from Power BI report for initialization of W2 in OST.

6.7 OST-W2 Enhancements

Rondout W2 model: Diverted waters from Cannonsville (C), Pepacton (P), and Neversink (N) reservoirs flow into Rondout Reservoir. Currently, there are no W2 models for these upstream Delaware System reservoirs in OST and thus real-time forecast/simulation of water quality in these reservoirs is not possible. OST was modified to allow inputs of water quality (temperature and turbidity) for the Rondout W2 model specified according to historical median and 90th percentile patterns, a constant value, or a combination of a constant and a pattern. A constant value for PCN turbidity is appropriate, for example, for short-duration operations scenarios runs following a storm, whereas historical patterns or a combination of a constant and a historical pattern is more appropriate for longer duration (>15-30 days) runs. This modification allowed managers to evaluate more realistic scenarios of operations of PCN reservoirs. (Related OCL constant is PCN Turb_Const)

Kensico W2 model: OST was also modified so that W2 runs for Kensico-only can be conducted. This capability is important for managers when it is necessary to quickly evaluate a wide range of scenarios for the operation of Catskill and Delaware aqueducts. This feature significantly reduces OST run time because W2 models for Rondout, Schoharie, and Ashokan reservoirs are kept off. (Related OCL constants are DelAq_Turb_Const and CatAq_Turb_Const)

Scheduling of dividing weir gates opening: OST was modified to allow variable dividing weir gates opening at Ashokan Reservoir. The variable heights of gates openings are specified in OCL pattern files. This feature will be useful for evaluating scenarios where transfer of water from the Ashokan West to the East Basin needs to be specified according to the inflow from Esopus Creek with the goal of avoiding spill and reducing the possibility of short-circuiting in the Ashokan East Basin. (Related OCL constant is Ash_DivWeir_Settings)

6.7.1 Updates and upgrades to the Operations Support Tool (OST)

DEP OST is a software that simulates reservoir levels and water quality and generates an output that is consistent with the different forms of its application, including supporting daily reservoir operations, long-term planning, and climate change impacts to water supply assessment. When applied to support NYC water supply operations, OST is run from today to up to a year into the future. For planning and climate change assessment applications, the tool is driven by either multi-year historical inflows or long-term future simulated inflows, respectively. OST is a decision-support system that links computer models of NYC water supply reservoir operating rules, real-time data of water quality and quantity, and inflow to the reservoirs that drive the system.

6.7.2 Upgrade from GEFSV10 inflow forecasts to GEFSv12

During 2021, the National Weather Services (NWS), through its Northeastern (NERFC) and Middle Atlantic (MARFC) River Forecast Centers (RFCs) in collaboration with NOAA’s Office of Water Prediction developed and delivered to the City the first Global Ensemble Forecast System (GEFS) version 12 based (GEFSv12) HEFS (Hydrologic Ensemble Forecast Service) ensemble forecasts. This new product replaces the old (2014) GEFSv10 HEFS forecasts, used to drive OST when applied to support daily reservoir operations. GEFSv12 was developed using extended meteorological and hydrological data and forcing hindcast ensembles that include the most recent historical record (through 2019); in response to one of the National Academies of Sciences, Engineering, and Medicine (NASEM) OST Expert Panel recommendations. DEP staff tested the newly available ensemble forecasts to evaluate further its skill while working in collaboration with NWS staff to address any problems identified during the testing process.

6.7.3 Inclusion of NWS post-processed inflow forecasts (ENS-POST) in OST

While GEFSv10 HEFS forecasts sent to DEP included only the raw (not post-processed) forecasts, the GEFS-v12 product sent by the NWS includes both, the raw and post-processed forecasts. Post-processing is a required step when developing forecasts that addresses issued related to both (1) flow adjustment from the NWS forecast locations to OST forecast locations and (2) bias correction to address the uncertainty associated with the hydrological model used to convert forecasted climatology into hydrology. While GEFSv10 HEFS forecast was post-processed using DEP's Ensemble Forecast Post-Processor (EPP), NWS post-processing is based on the NWS Ensemble Post-processor (EnsPost) software tool, which is applied and maintained by the two RFCs. This is a very significant achievement. It allows DEP staff to benefit fully from the existing NWS expertise and to be able to shift focus towards other important areas related to forecast and software tools to enhance HEFS implementation in OST, such as ensemble forecast diagnostic and verification tools. DEP and NWS scientists together completed the first verification of the new EnsPost forecast.

6.7.4 Enhancements to OST baseline run to better support RWBT and CAT outages

DEP during 2021 also continued working on model enhancements to make OST better reflect current water supply system rules, infrastructure status and operations, and improve OST flexibility to provide modeling support for various infrastructure outage applications, in particular the Catskill Aqueduct (CAT) and the upcoming Rondout West Branch Tunnel (RWBT) outages. The new enhancements included the integration into OST of an extended (through September 30, 2017) historical inflow file, the 2017 Flexible Flow Management Plan, East of Hudson reservoir key elements and operations, and enhanced turbidity rules, as part of the CATALUM EIS development. The new enhancements also included better simulation of the turbidity load from Pepacton, Cannonsville and Neversink reservoirs into Rondout using historical and currently measured turbidity. With all these updates, a new OST base run was created. The new base run was used to update the 2015 OST model output, which was used to support the RWBT outage planning, including the original environmental impact assessment.

6.7.5 Developed a new version of VoPro tool to help with RWBT outage

OST is an excellent tool for guiding operations and evaluating rules for operating the water supply. However, some actions require quick assessment of short-term actions. DEP developed VoPro to quickly assess short-term operations. DEP used VoPro to draft short-term operations and then, once drafted, enter the operations into OST or use VoPro results alone to guide the undertaking.

VoPro solutions are identical to those of OST because VoPro is based on algorithms, forecasts and data used in OST. The same functional relations are in VoPro and OST. VoPro can use inflow forecasts available to OST. Moreover, local demand patterns in VoPro are identical to those in OST. The model runs on a daily timestep but includes a two-hour time step to compute spills as in OST. Furthermore, storage and elevation initialize from the DEP database.

To run VoPro, a user enters the simulation start date then initializes reservoir storages and selects what inflow forecast to use (Figure 6.31). The user can then apply standard rules of release operations, i.e., if New Croton Reservoir is spilling, set various Croton System reservoir release rates to release rates during a spill. The user then imports the select inflow forecast and then the tool is ready for the user to enter operations into tables. Every time operations are changed in the model, the model is triggered to rerun a water mass balance computation for the selected duration of the VoPro simulation. The entire process of setting up and running the model can be completed in minutes and model output will update instantaneously when an operation is altered.

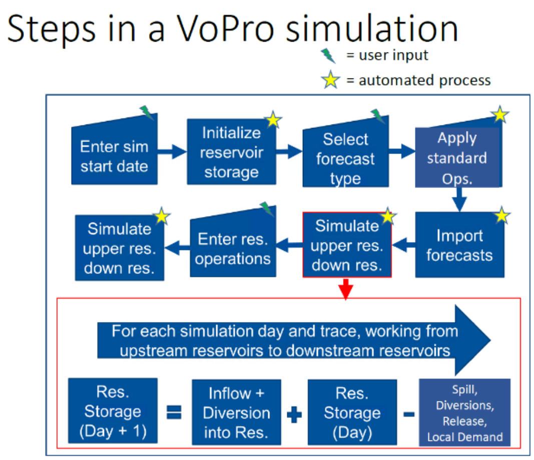


Figure 6.31 Steps involved in a VoPro simulation.

Twelve reservoirs are modeled in Croton VoPro. Croton Falls and Cross River pumping stations and diversions from Rondout and Ashokan are scheduled in a table (Figure 6.32). Local community demands are modeled using patterns found in OST and West Branch and Kensico can be operated in float, bypass, or reservoir mode. Flow rates entered in VoPro are not impacted by hydraulic head or capacity of the aqueduct, except for the Delaware Aqueduct when it is in bypass mode.

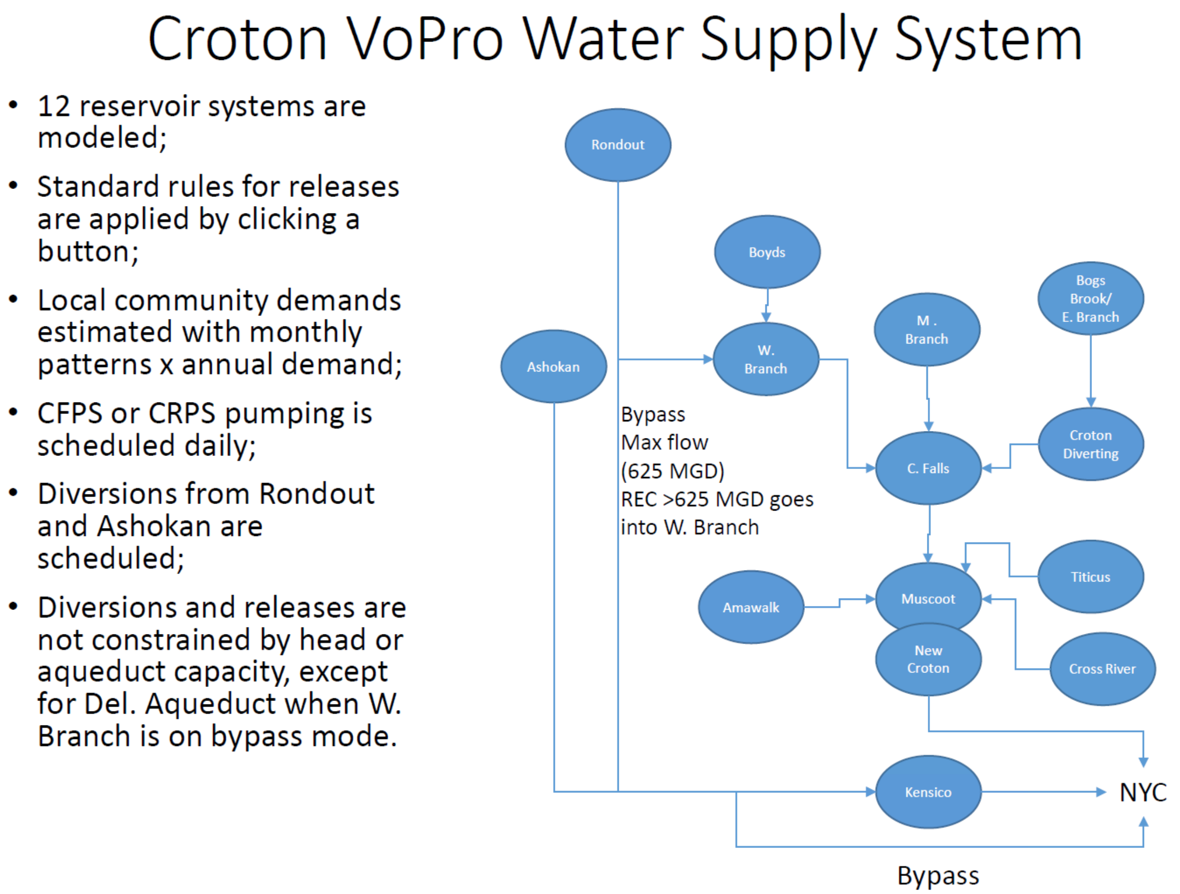


Figure 6.32 Structure of the water supply in Croton VoPro.

DEP designed VoPro with two navigation panes (Figure 6.33, Tabs 1 and 2) with panes having tabs to move among graphic output or different tables to enter operations data (Figure 6.33 Tab 2). Several check boxes, tabs, radio controls, textboxes and buttons are used to initialize the model.

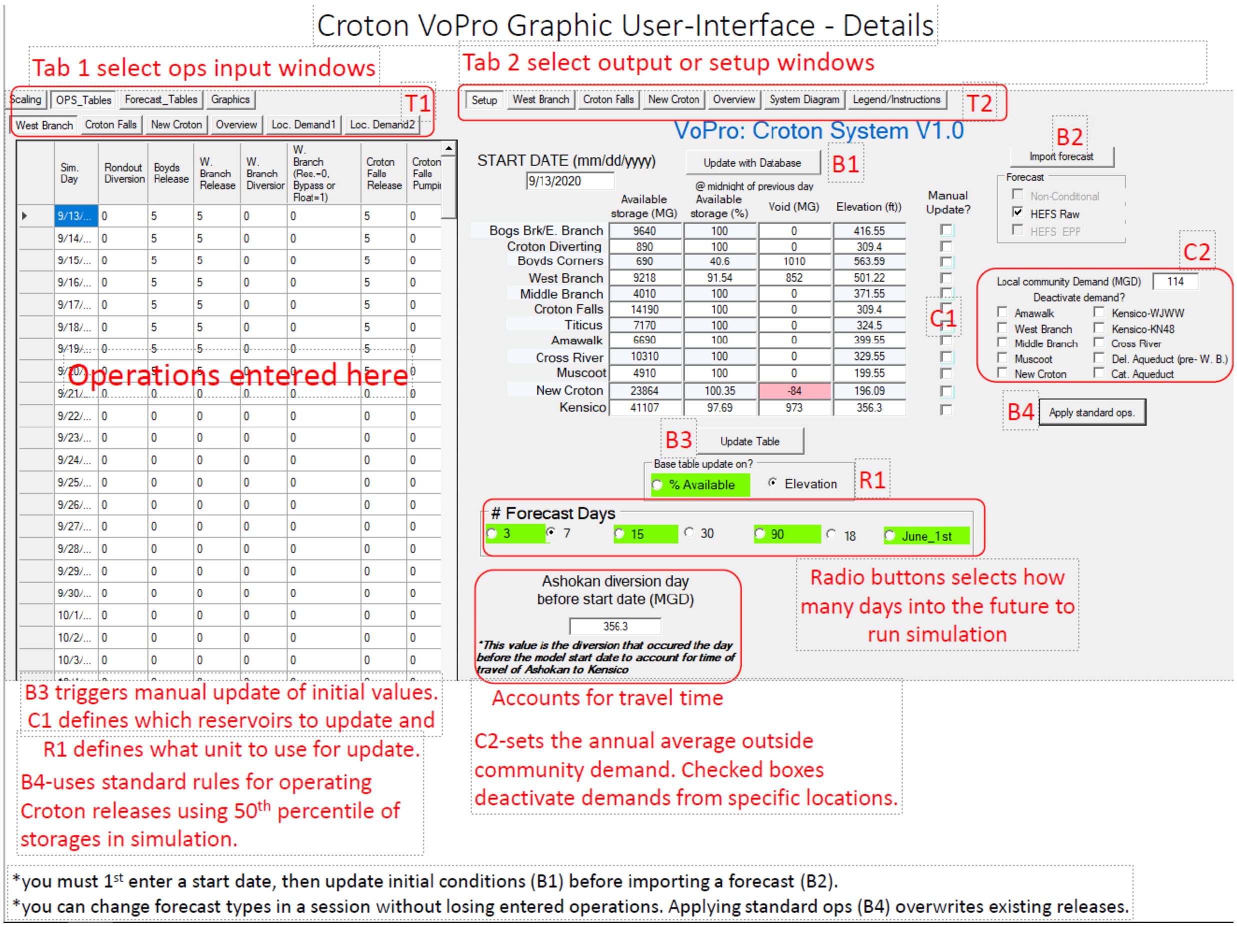


Figure 6.33 Graphic interface to the Croton VoPro tool.

The tabs in the graphical section of the model (Figure 6.33 Tab 2) are organized to focus on running pump stations at Cross River and Croton Falls or to visualize the impact of operations on Kensico. The West Branch tab focuses on West Branch operations and how West Branch releases impact Croton Falls. The Croton Falls tab graphically depicts operations impacting the Croon Falls pumping station. The New Croton tab is used to visualize the impacts of operations on the New Croton Reservoir. Lastly, the overview tab illustrates impacts of operations on all source water reservoirs (Croton Falls, Cross River, New Croton, and Kensico, Figure 6.34). Graphical output includes plots of an ensemble of inflow forecasts along the bottom of the chart (Figure 6.34). Spills are plotted in the charts above inflow. Releases and diversions plotted above spills, and storage in the charts on the top of the panel (Figure 6.34).

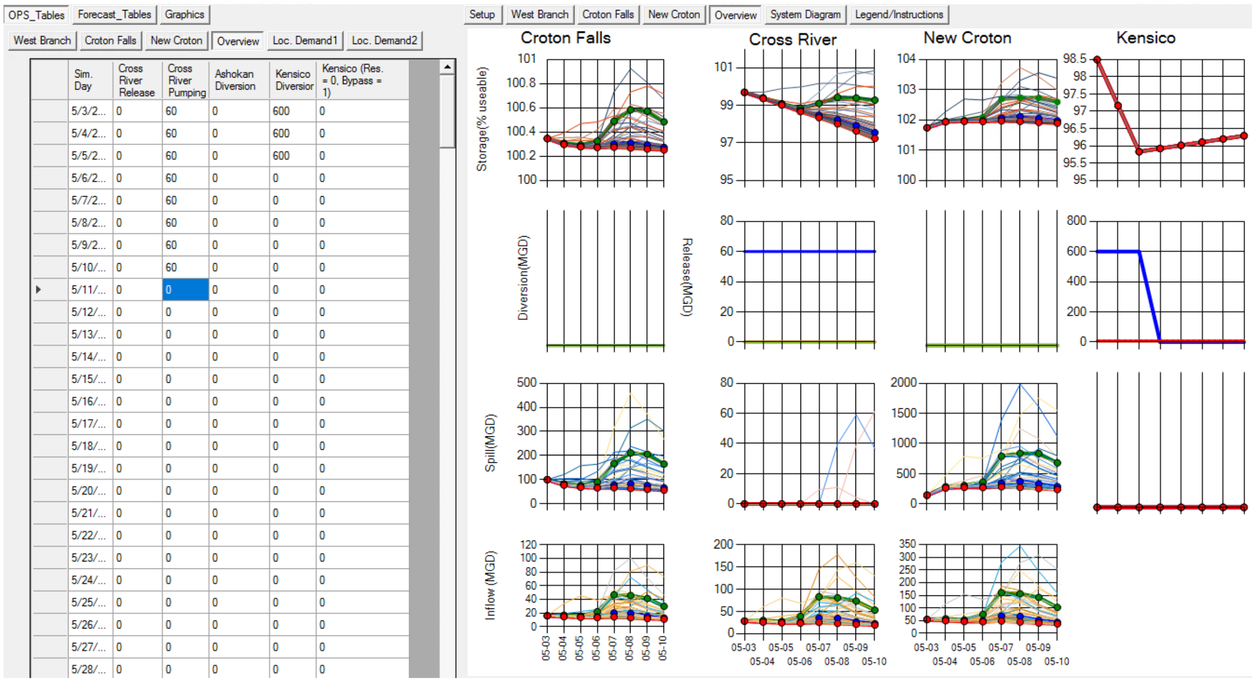


Figure 6.34 Table for manual entry of operations into VoPro (left side) and graphic output from VoPro on the right.

6.8 Application of Models to Support Operational and Planning Decisions

6.8.1 Shandaken Tunnel Outage

The Shandaken Tunnel was shut down for upgrades and repairs during part of autumn 2021 and the spring 2022. DEP forecasted stream flow at summarized current hydrologic conditions at Allaben and Coldbrook on Esopus Creek once per week during the outage to determine if stream flows were high enough to protect the fishery. DEP presented hydrologic conditions and forecasts in a weekly web meeting with NYSDEC.

Weekly briefings included a summary of current hydrologic conditions (Figure 6.35), an assessment of recent performance of OST HEFS forecasts of stream flow (Figure 6.36); interpretation of the most recent HEFS forecast of flow relative to NYSDEC's minimum flow objectives (Figure 6.37); a summary of the NWS's MMEFS 10-day forecast of stream flow (Figure 6.38) and air temperature at Cold Brook; and lastly the NWS's seasonal forecast for precipitation and air temperature in the next month (Figure 6.39). During the tunnel outage, DEP successfully maintained flows at Coldbrook and Allaben at or above the minimum flow targets set by NYSDEC.

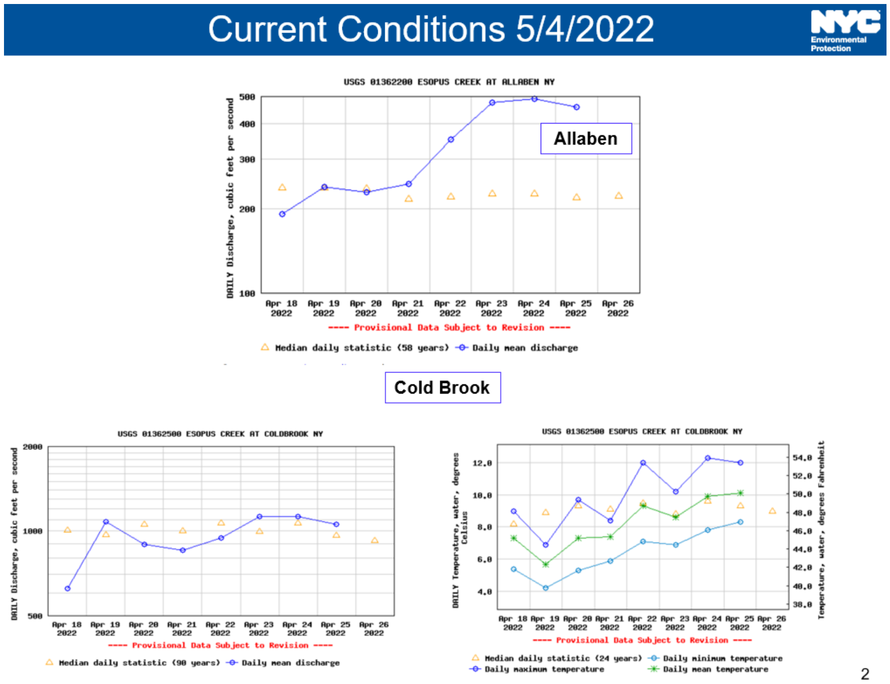


Figure 6.35 Example of briefing slide report on recent flow and water temperature conditions at Allaben and Coldbrook on Esopus Creek.

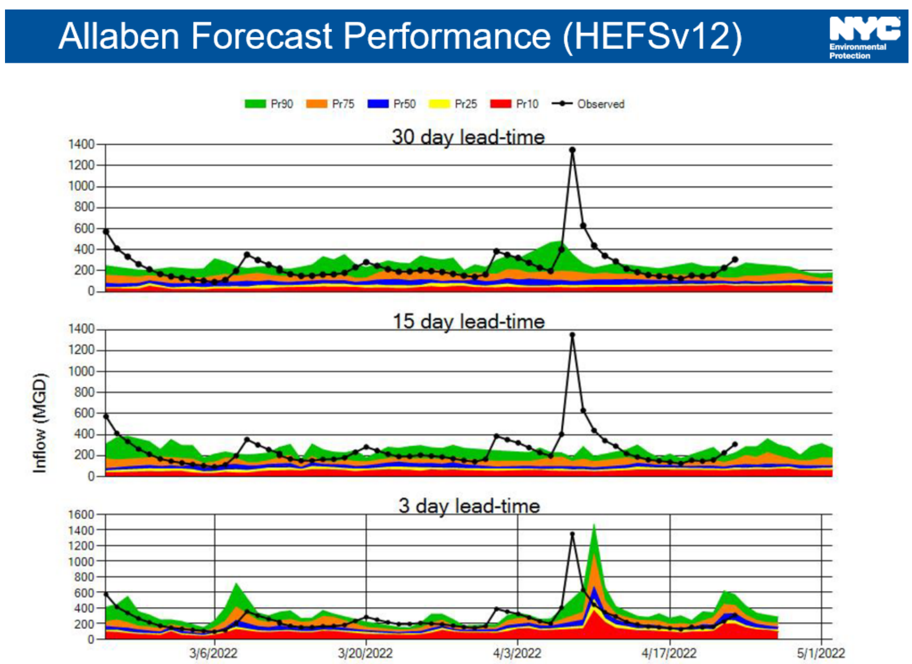


Figure 6.36 Example of an assessment of the recent performance of HEFS flow forecasts for Allaben. Each observed flow in the chart is associated with forecasted inflow at a given lead time from a forecast issued on a specific date (i.e., each date on the plot is percentiles of an ensemble forecast issued 3, 15, or 30 days before the observed flow).

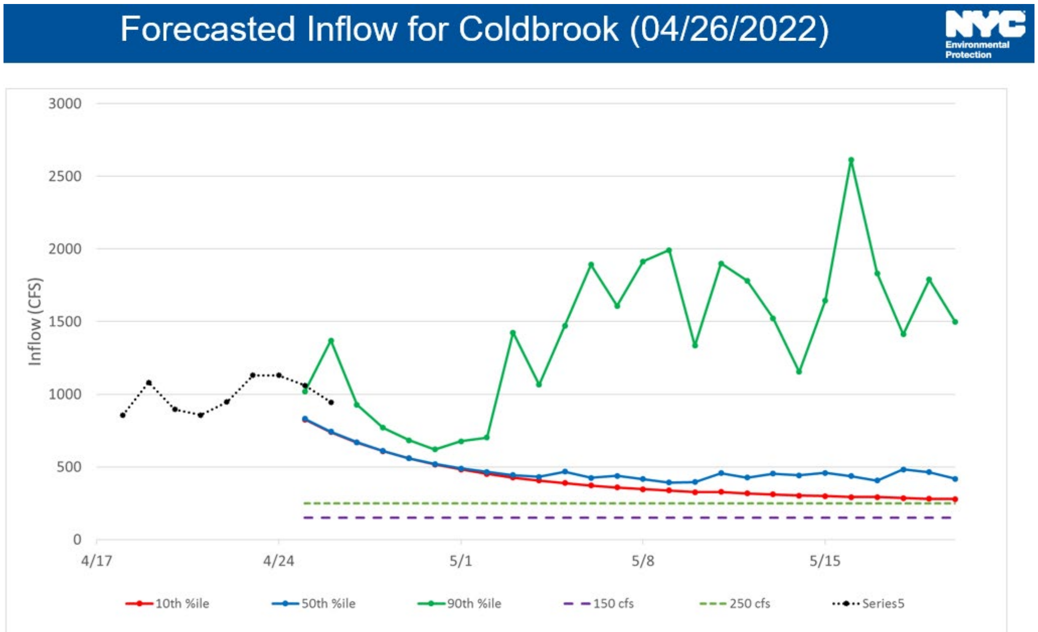


Figure 6.37 Percentiles of forecasted flow from an HEFS forecast issued on the day of or the day before the briefing with NYSDEC. The green dashed line is the 250 CFS minimum flow rate established by NYSDEC.

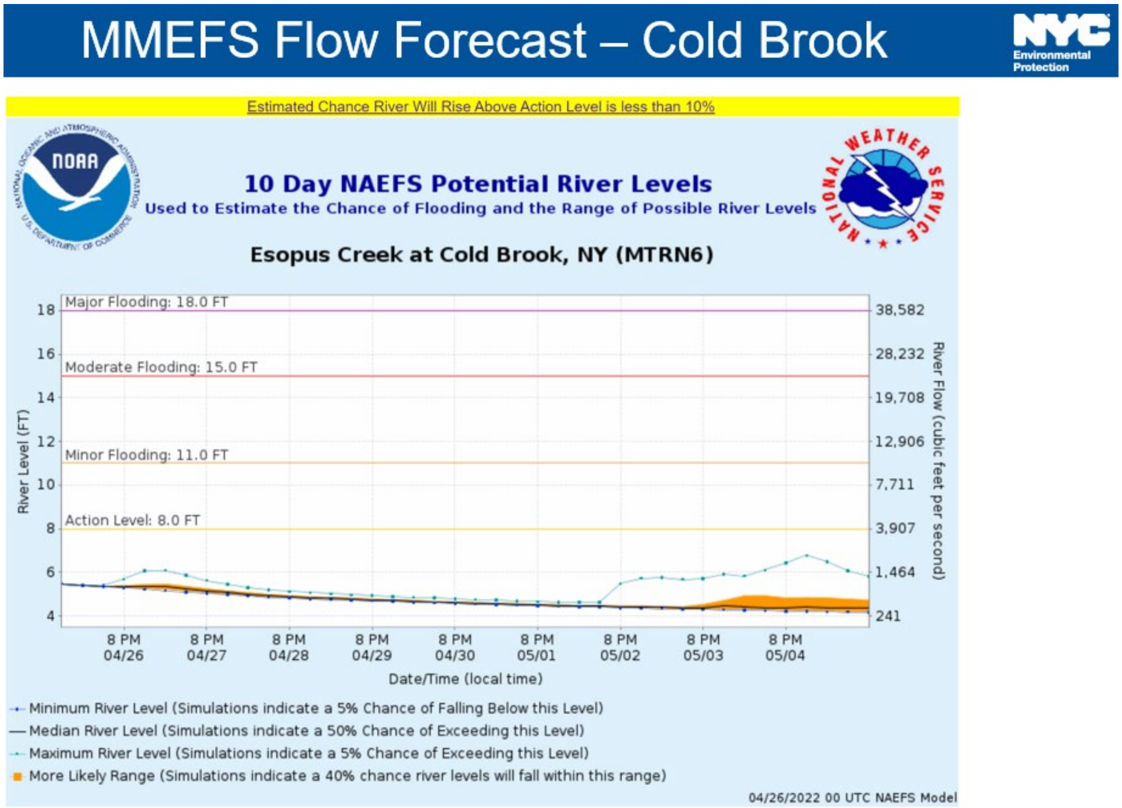


Figure 6.38 An example of NWS MMEFS flow forecast of flow at Coldbrook used in a briefing.

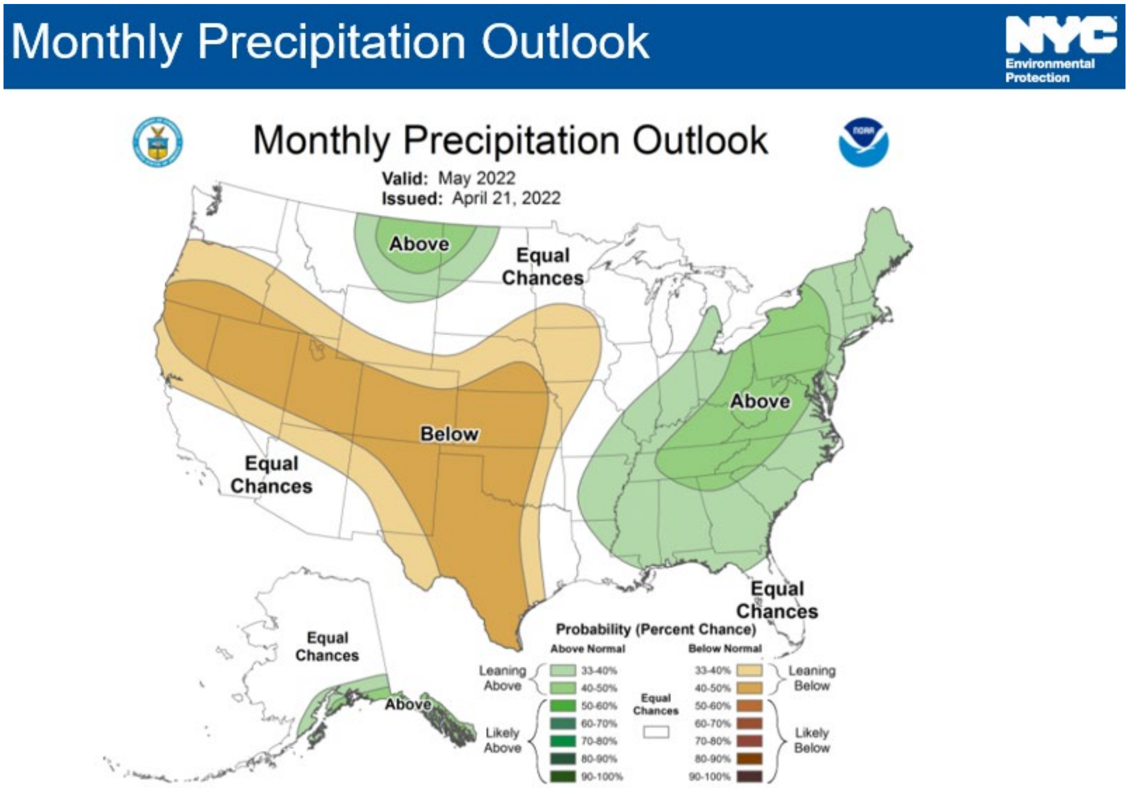


Figure 6.39 An example of an NWS seasonal forecast of precipitation for the next month used in the briefing. In this example, above-normal precipitation is expected in Esopus creek's watershed.

6.8.2 Rondout West Branch Tunnel Outage: OST updates and OST model output dashboard development.

In 2021, DEP improved the rules in OST to better support the Croton Falls and Cross River pump stations. In addition, DEP added information to our current model output dashboard to visualize model output for the Croton System. Lastly, DEP developed a phone application to view modeling forecasts critical to operation of the water supply during the Rondout-West Branch Tunnel outage.

OST East of Hudson drawdown rules did not reflect East of Hudson (EOH) operations recently proposed for the upcoming Rondout-West Branch Tunnel outage. The sequence that EOH reservoirs were drawn down did not support the Croton Falls or Cross River pump stations. Also, minimum operation levels and dead storages for EOH reservoirs had errors. The updated rules have East Branch and Bog Brook reservoirs to keep diverting to maintain Croton Diverting Reservoir above 304.55 feet to maintain flow to Croton Falls Reservoir to support pumping (

Figure 6.40). Middle Branch Reservoir would start releasing once Croton Falls Reservoir is below the connecting channel elevation to maintain Croton Falls Reservoir at 304 feet elevation (Figure 6.40).

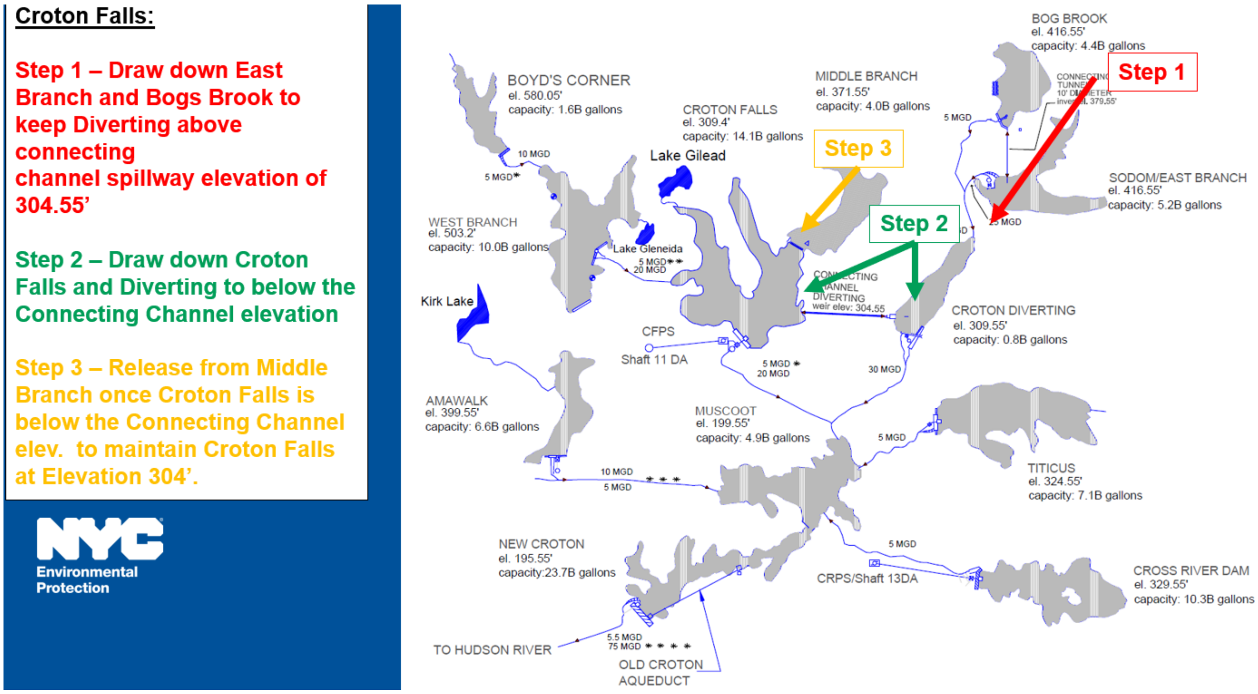


Figure 6.40 New OST rules to support the operation of the Croton Falls pump station.

DEP also updated OST rules to preserve Cross River water to support the Cross River pumping station (Figure 6.41). Also, Titicus and Amawalk reservoirs are now drawn down to keep Muscoot Reservoir spilling. Last, DEP has OST drawing Muscoot Reservoir down when New Croton Reservoir drops below 194 feet in elevation.

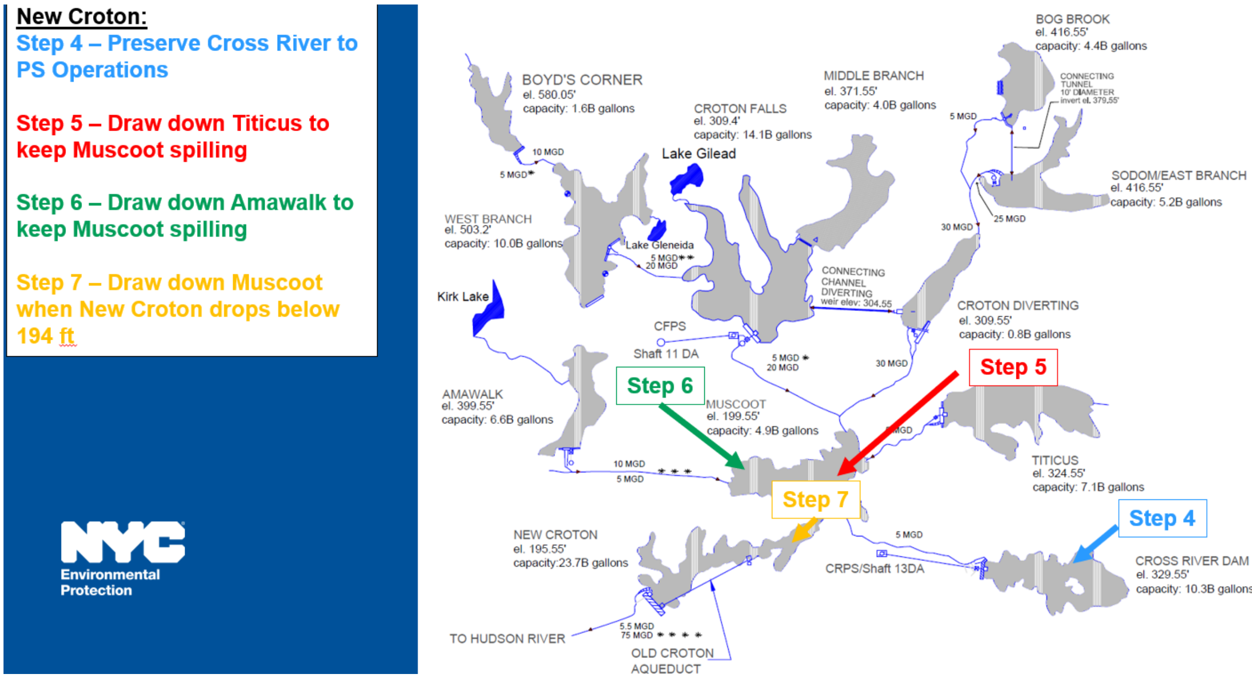


Figure 6.41 New OST rules to better support the Cross River pump station and maintain storage in New Croton reservoir.

DEP added plots to our routine model output summary of Delaware Aqueduct Shaft 4 operation and pumping rates at Croton Falls and Cross River pumping stations. DEP also adding plots of forecasted inflow and storage of all the Croton reservoirs.

In addition to updating our standard report of model output, DEP created a phone application that reports key model output for the Rondout West Branch Tunnel outage (Figure 6.42). For an individual outage simulation, the phone application shows if there was a shortage in meeting demand for water and the forecast minimum water surface elevations at Kensico Reservoir. The application also shows how much water storage buffer DEP has in West Branch and Boyd Corners reservoirs, and how long this water storage buffer could replace water made unavailable during the event part of the system fails (ex., loss of most of Croton Falls pumping capacity).

6.9 Climate Change Indicators for the NYC Water Supply Watershed

Climate change and its effects on the drinking water supply remain a particular concern for DEP. Long-term climate projections predict the average temperature and precipitation in the New York City Water Supply watersheds will likely increase above current levels, accompanied by more extreme weather events.

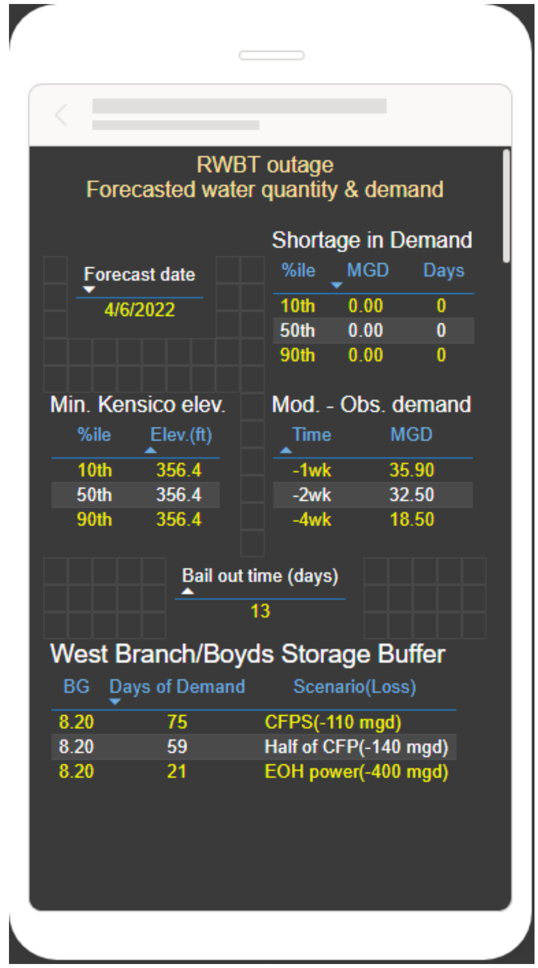


Figure 6.42 Phone application for manager to gain quick access to OST forecast information important to Rondout West Branch Tunnel Outage.

These climatic changes may pose new challenges for the operation of the water supply, some of which DEP may already be facing. To prepare for future climate change, it is important to have a better understanding of how the watershed climate has been changing over the past decades. DEP has undertaken a project to explore trends present in various long-term datasets that may indicate how the watershed has been experiencing the effects of climate change.

The development of climate change indicators began in 2019, and progress has been reported in several water quality annual reports. The Python framework has been written to easily accommodate the addition of additional metrics or locations. Scripts have been written to calculate meteorological and hydrological trends, as well as water quality and water supply operations measures. The meteorological indicators are calculated from a regularly gridded-modeled data source, PRISM, as well as direct NOAA observations from airports located near the watershed.

In 2021, DEP have expanded the set of airports used for meteorological analysis from the initial stations at Albany, Binghamton, and White Plains, to also include Newark (NJ), Burlington (VT), Danbury (CT) and Scranton (PA). DEP chose these additional regional locations to investigate whether there are other regional spatial patterns that can be identified from the trends. Annual average temperature metrics were added to the list of indicators being computed with the NOAA airport data. USGS streamflow gages are used to calculate hydrologic indicators. There were minor revisions to the code for hydrological indicators made during 2021.

To aid in the dissemination of the climate change indicators project for review, a methods document was drafted that details all data sources and methods used. Maps were made to allow for internal reviewers to consider the presence of any spatial patterns that may exist in the data alongside tabular results (Figure 6.43). In total, there are approximately 200 maps accompanied by 1,100 time series plots available to review. Discussions regarding the results produced to date have led to new requirements for time-series anomaly detection and handling. Work has begun on the filtering of NOAA data to remove partial records, and on a review of possible techniques that may be used to aid in anomaly detection.

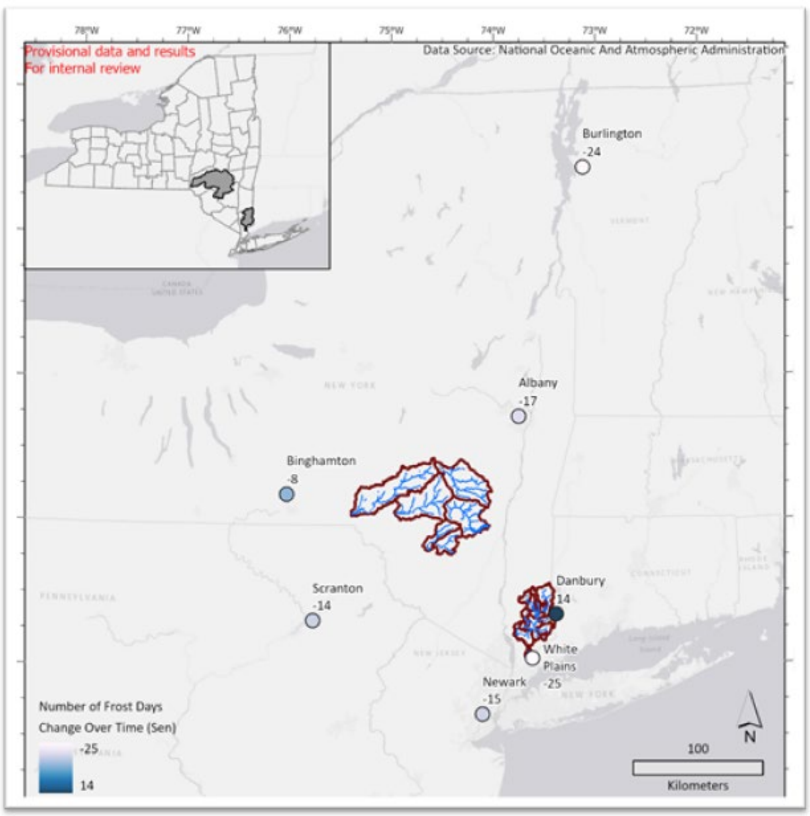


Figure 6.43 Sample map produced for the number of frost days climate change indicator.

The combination of overview maps with time series plots will assist in understanding the trends calculated from the data and suggest areas for improvements of the process. For example, Figure 6.43 shows an increase of frost days in Danbury, which appears from the time series plot (Figure 6.44) to be related to missing data early in the period of record. These issues have been identified as the next stage of investigation for the project in 2022.

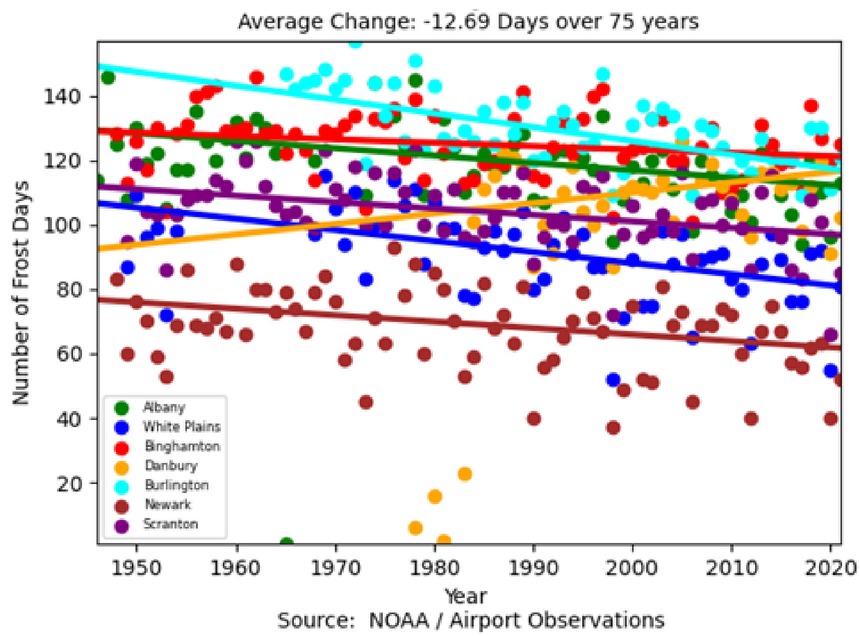


Figure 6.44 Sample plot showing the change of number of frost days over time at each airport.

6.10 Automation of GWLF for streamflow forecast

Building on previous work developing daily-run streamflow forecasts using the Generalized Watershed Loading Function (GWLF) model (NYCDEP 2019), DEP worked in 2021 to upgrade the process with new data. The GWLF model uses temperature and precipitation observations data to predict streamflow and has been developed and calibrated for the NYC reservoirs' watersheds. This section will discuss the efforts to create an operational system to provide reliable daily streamflow forecasts for use in other modeling applications.

The GWLF model requires precipitation, minimum and maximum temperature, solar radiation, and humidity data at a daily time step as input data. Precipitation and temperature observations are derived from the PRISM (Parameter-elevation Relationships on Independent Slopes Model) dataset, a 4-kilometer resolution gridded interpolated product at a daily time step. Precipitation and temperature forecasts are derived from the NOAA GEFS (Global Ensemble Forecast System), version 12. GEFS includes 31 ensemble traces that are produced every six hours for a forecast period of 10 days at a 0.25-degree (~25 kilometer) resolution with a three-hour time step. Solar radiation and humidity are derived from PRISM and GEFS data using MtClim software (Hungerford et al. 1989).

The data sources and model preparation workflow require a robust processing framework capable of managing the varied data sources and external software. DEP has developed Python code to automate the preparation of input data for GWLF, execute the model, and process and summarize the results, supported by a SQL server database used to store raw input data and simulation outputs. Raw meteorological data are downloaded each morning from PRISM and NOAA web servers and imported to DEP's local database. Input data must then be aggregated from their raw format to a daily basin value. PRISM data are compiled by calculating the average precipitation value, the lowest recorded minimum temperature, and highest recorded maximum temperature of all grid cells in each basin. GEFS data are compiled using an area-weighted average for each basin to account for the larger spatial resolution of the data grid. The spatially weighted averages are then temporally averaged to compute a daily time series of temperature and precipitation, after which MtClim is applied to compute additional variables. The Python software then instantiates the GWLF model for all ensemble traces in each basin. Model results are uploaded to database tables for future reuse, and daily streamflow forecast plots are produced and emailed to a distribution list.

While the overall workflow is like previous versions, it has been adapted to accommodate GEFS version 12, which was first published by NOAA in September 2020. New code had to be written and tested that could properly download and prepare GEFS data, and revisions to database tables were needed for this dataset. The GWLF model itself was also revised to simulate streamflow for 14 of the 16 East of Hudson reservoir basins, excluding Kirk Lake and Kensico reservoir, so the Python scripts were likewise revised to run the models for both EOH and WOH basins.

With all processing scripts prepared, the model was run for all available GEFS data in hindcast mode. These historical forecasts will be used to adjust future model runs to correct for bias in the input data. The bias correction process will measure the goodness of fit of the model results in relation to observed streamflow, and determine the best method to correct the data, either through additional pre-processing of meteorology data, or post-processing of the GWLF simulation results. DEP will write additional code once the bias correction verification work is completed that will apply the correction factors to improve the forecast skill for GWLF.

Work has also begun to make the GWLF streamflow data available to other models as an input dataset. The Operations Support Tool (OST) and VoPro models, which are used by BWS Source Water Operations Directorate, require streamflow data to inform operational decisions. These models require streamflow data as an input and can be adapted to utilize the GWLF results. Efforts to incorporate the data are underway in 2022.

6.11 Water Quality Modeling: Publications and Presentations in 2021

6.11.1 Papers published in peer-reviewed journals in 2021-2022:

Wang, K., R. K. Gelda, R. Mukundan, and S. Steinschneider. 2021. Inter model Comparison of Turbidity Discharge Rating Curves and the Implications for Reservoir Operations Management. J. American Water Resources Assoc., 57(3), 430-448.

Frei, A., Mukundan, R., Chen, J., Gelda, R.K., Owens, E.M., Gass, J. and Ravindranath, A., 2022. A cascading bias correction method for global climate model simulated multi-year precipitation variability. Journal of Hydrometeorology. https://journals.ametsoc.org/view/journals/hydr/aop/JHM-D-21-0148.1/JHM-D-21-0148.1.xml

Shakhawat, M., 2022. Natural Organic Matter (NOM) Precursors Characterization in Source Water by Surrogate Measurements and Disinfection Byproducts (DBPs) Analysis. M. S. Thesis University of Massachusetts. Available at https://scholarworks.umass.edu/cee_ewre/111/

6.11.2 Conference Presentations

Gelda, R. K., 2021. Development and testing of a turbidity model for Cannonsville Reservoir. Paper presented at Watershed Science and Technical Conference. September 2021 online.

Mukundan, R., 2021. Modeling Evaluation of Watershed Protection Programs in the Cannonsville Watershed. Paper presented at Watershed Science and Technical Conference. September 2021 online.

Moknatian, M. and R. Mukundan. 2021. Uncertainty Analysis of SWAT-HS simulated streamflow for NYC West-of-Hudson Watersheds. Paper presented at Watershed Science and Technical Conference. September 2021 online.

Moknatian, M, R. Mukundan, and E. M. Owens 2021. Uncertainty Analysis on Streamflow Simulations Using Multiple Objective Functions and Bayesian Model Averaging for NYC Water Supply Basins. Paper presented at the American Geophysical Union Annual Meeting. December 2021.

6.12 Contract updates

6.12.1 EOH Bathymetry

Under an intergovernmental agreement with the United States Geological Survey (USGS) registered in 2017, bathymetric surveys of the 13 reservoirs and three controlled lakes in the East of Hudson system were conducted. The USGS used a multibeam echosounder to survey to achieve near-complete coverage of each reservoir with high spatial resolution (1 meter) and high accuracy. The field data collection was conducted between 2017-2019. Prior to 2021, USGS completed most of the data processing and submitted to DEP draft data products for review. In 2021, USGS incorporated DEP feedback on the data, and provided the draft report for review. The project was completed in June 2021 with the submission of the final report and all data deliverables as specified in the scope of work.

6.12.2 CUNY

The CUNY sub-contract with the University of Massachusetts resulted in a master's thesis by one of Dr. David Reckhow's students. This study utilized data from the DBP monitoring program in the Neversink watershed to characterize natural organic matter (NOM) precursors using surrogate measurements and disinfection byproducts (DBPs) analysis. To investigate the nature of NOM precursors, ultraviolet absorbance at 254nm (UV_{254}), dissolved organic carbon (DOC), dissolved organic nitrogen (DON), and fluorescence excitation emission matrix (EEM) were measured for storm event water samples from Neversink watershed at Claryville. Surrogate measurements demonstrated the presence of high aromatic content in the source water. Analysis of trihalomethanes (THM), haloacetic acids (HAA), and nitrogenous DBPs (N-DBPs) characterized the NOM precursors as having allochthonous origins attributed to mostly lignin derived from hydrophobic humic substances. Details of this work can be found in Shakhawat (2022). After an extended break due to the ongoing pandemic, sampling will resume in 2022.

6.12.3 USGS

DEP continues to provide support for maintaining several stream gages found within the water supply. This work also includes water quality sampling at a few key locations on the Esopus.

7. Innovation and Research

The analytical, monitoring, and research activities of DEP are supported through a variety of contracts, staff participation in research projects conducted by the Water Research Foundation (WRF), and interactions with national and international groups such as the Water Utility Climate Alliance (WUCA) and the Global Lake Ecological Observatory Network (GLEON). Research engagement with external groups is a critical component of the Bureau of Water Supply's commitment to emerging research and technology in the water supply industry and provides opportunities to partner with subject matter experts. The ongoing internal research efforts, along with research partners and projects coordinated within WQI are described in this chapter.

7.1 2020-2021 Research Agenda

DEP is committed to conducting innovative research to stay at the forefront of the industry and influence national policymaking. To facilitate that effort, BWS developed a Research Agenda to align its research with operational and regulatory priorities. The agenda describes the most critical challenges issues facing BWS including disinfection byproducts, Lead and Copper Rule Revisions, Hillview Consent Order, taste and odor compounds in the Croton System, *Legionella*, emerging contaminants, and climate change.

7.2 2020-2021 Research Inventory

BWS leads DEP's efforts to catalogue all research taking place across the agency. To achieve this, BWS developed an inventory of past, current, and proposed research to increase awareness of ongoing studies and to foster collaboration throughout the agency and with professional and academic peers. The inventory catalogues the agency's research utilizing an organizational framework that provides for a flexible and refined hierarchy. Broadly speaking, all research projects have been classified within four core subject areas that reflect the efforts underway and serve as a framework for research priorities moving forward:

- **Environment** is inclusive of all studies pertaining to the interface of the natural environment with the water supply and includes terrestrial, aquatic, climatological, air, and water resources such as streams, lakes (reservoirs) and wetlands.

- **Innovation** covers all new and emerging technologies, novel methods, and strategies to better manage and operate the City's water supply, as well as studies and research pertaining to emerging challenges.

- **Public Health** captures projects committed to ensuring safe, clean water is delivered to all users. It includes research related to water quality, treatment, and regulatory requirements.

- **Sustainability** includes opportunities for the water supply to be self-sustaining in the areas of energy, infrastructure, financing, and hydrology

As of October 2021, BWS had 52 active or planned research projects. Across the core subjects, the Research Inventory includes 15 research areas (Figure 7.1).

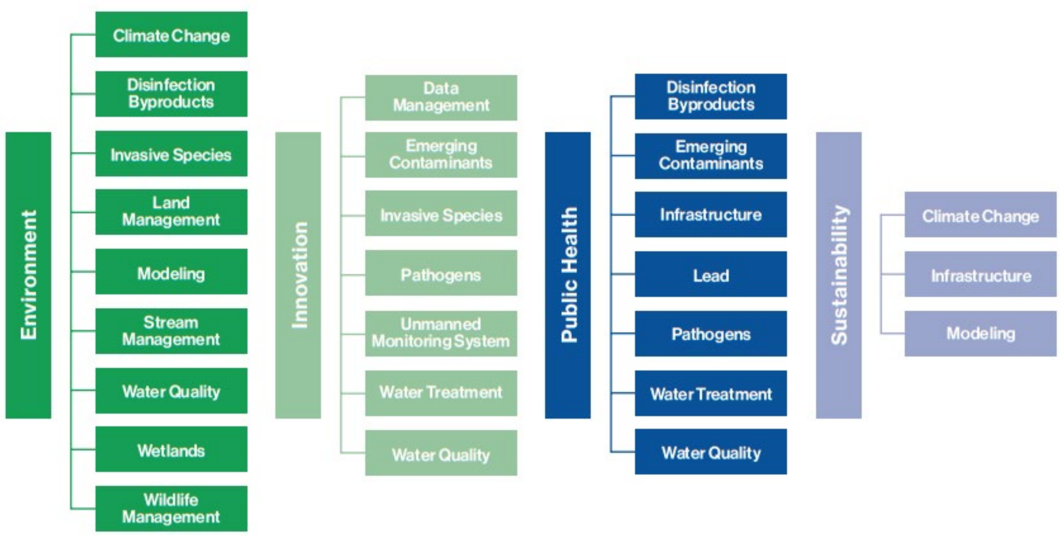


Figure 7.1 Research Inventory Research Areas.

7.3 Research Advisory Council

In 2020, BWS created the Research Advisory Council (RAC) to establish and manage a research process and act as a forum to communicate and support research initiatives. The RAC is a staff-level group with representation from all directorates: Executive, Management Services and Budget, Planning, Source Water Operations, Water Quality & Innovation, Water Treatment Operations, Watershed Protection Programs, and Environmental Health and Safety. The RAC is comprised of 16 appointed members and 5 at-large members, each serving for two-year terms.

7.3.1 Research Proposal Process

In 2021, the RAC created a research proposal process to streamline and standardize how research projects are initiated in BWS to support our Research Agenda. Under this process, proposed research projects are reviewed by senior staff members before submission to the RAC for review. The RAC then appoints a Peer Input Team to provide feedback to the researcher. These reviews are intended to identify opportunities to strengthen the proposed research and ensure a robust and scientifically sound study. Once RAC feedback is incorporated into the research proposal and supervisor approval is finalized, the research can begin. Guidance documents including instructions, process, peer input, and forms were developed by the RAC and are available to all staff in BWS.

7.4 2021 BWS Conference

BWS holds an annual internal conference, inviting staff to present on critical research underway within the bureau. The theme of the April 20-21, 2021 conference was *Integration: Past, Present and Future*.

The conference program included a retrospective of the bureau's federal monitor oversight as a result of Clean Water Act violations, decentralized research and collaboration, workforce development, the history of integrated planning of the Catskill water supply and Croton water supply, the Catskill Repair and Rehabilitation project, start-up and operations of the Croton Filtration Plant and current challenges, and the U.S. Department of Justice's Consent Order to cover Hillview Reservoir.

In 2021, 173 BWS staff participated in the two-day conference, learning from the past, learning more about the present, and considering the role integration will play in the future within our directorates, BWS, and the agency.

7.5 2021 BWS Webinars

In addition to the annual conference, BWS also highlights ongoing research or related activities with monthly "Thirsty Thursday" webinars. In 2021, 526 staff participated in eight webinars (Table 7.1).

Table 7.1 2021 Thirsty Thursday Webinars

Month	Topic
January	Development and Deployment of NYC's COVID-19 Raw Sewage Surveillance System
February	Research Advisory Council - Charge, Structure, and Process
March	EPA's New Lead and Copper Rule: Changes and Implications for New York City
June	Ashokan Reservoir Releases
September	RAC: Research Proposal Process
October	Modeling Evaluation of Watershed Protection Programs in the Cannonsville Watershed
November	How the COVID Pandemic Changed City Procurement
December	Delaware Aqueduct Shutdown - RWBT Bypass Connection and Operational Changes

7.6 Innovation in Research

7.6.1 Data Modernization

BWS collects millions of data points annually across numerous systems monitoring the water supply. As data volume, velocity, and variety continue to expand, optimizing and reviewing how information is stored, used, and shared is critical. More than 100 applications and database systems are managed across the various business work units within BWS. Often, when data are needed across business unit boundaries, data are copied or collected in duplicate to fulfill a reporting or support function. A modern data warehouse is being developed to facilitate a centralized storage location for critical datasets used in both decision support and in performing long term trends and analysis. Data warehouses are designed specifically for enterprise-wide reporting and analysis of extremely large datasets. A modern data warehouse typically resides in a cloud-based environment where numerous resources can be integrated including AI and machine learning and analytics (e.g., Power BI).

The BWS Data Modernization effort began in 2019 and started with several workshops with industry experts to discuss similar efforts across the public sector and high-level review of BWS-use cases. As a result of initial discussions, BWS formed a data governance committee tasked with documenting all databases and modeling how data moves within BWS. In 2021, work was completed in modeling business process workflows that involved movement or transformation of BWS owned or utilized data assets. Figure 7.2 below shows an example of a portion of a data flow model that demonstrates movement of data into and out of the WWQO Laboratory Information Management System (LIMS). While the figure is intended for demonstration purposes, it does show how data are created in the field and lab, how these data enter the database through various applications, and how these data are subsequently used both internal and external to WWQO. In coordination with DEP's Bureau of Business Information Technology (BIT), and consulting with IT industry partners, establishing a data governance framework was an important first step in starting to modernize the data landscape across portions of BWS.

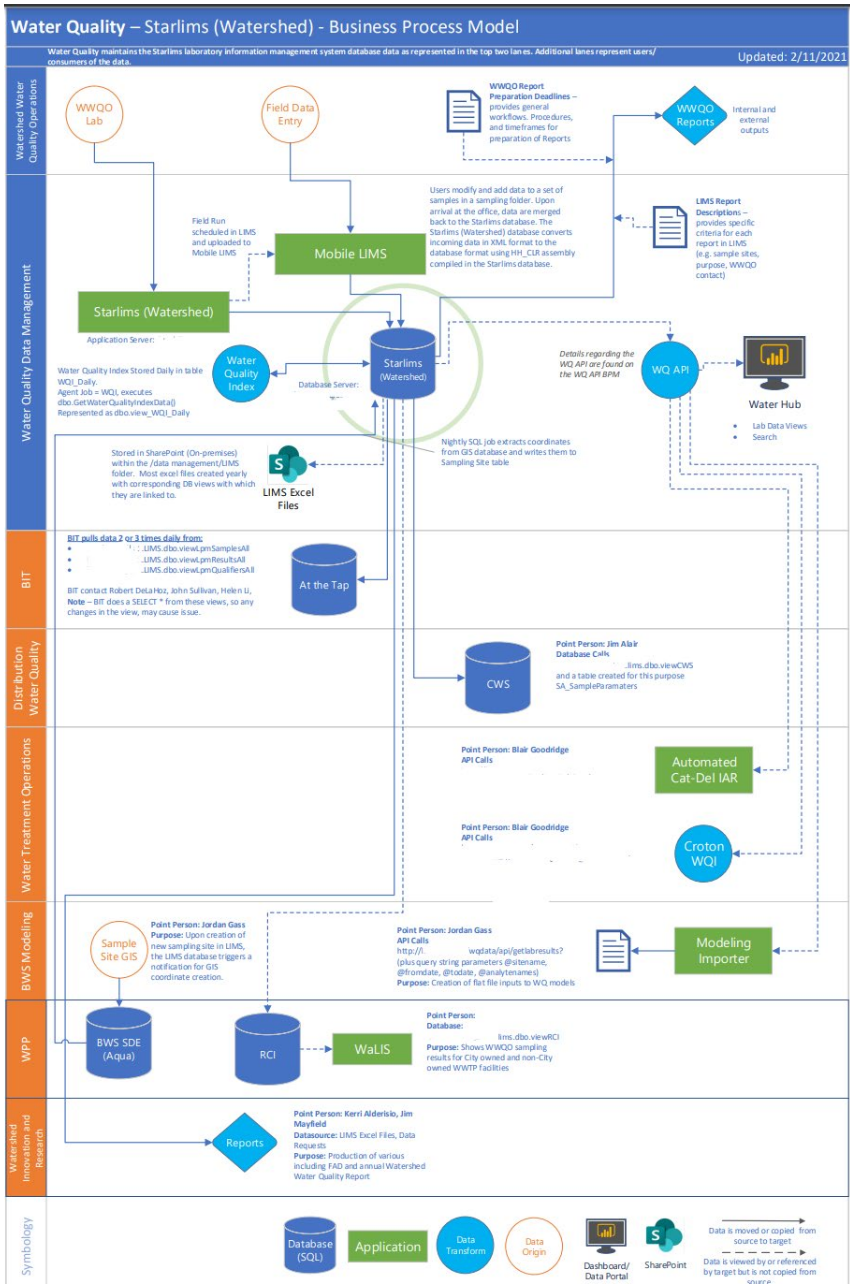


Figure 7.2 Data flow model to and from LIMS.

7.6.2 Digital Research Library

An important component of the agency's research priorities is to ensure access to academic journals. BWS led an evaluation of several products and ultimately selected RightFind software because it includes unlimited access to a shared library, document annotation, document tagging, collaborative commenting, and a user-friendly interface and ensures copyright compliance. BWS led the effort to procure this software in 2021 and hopes to finalize the annual subscription in 2022.

7.7 Working Groups

7.7.1 Enhanced Treatment Working Group

The Enhanced Treatment Working Group consists of staff from multiple directorates with diverse scientific and professional expertise. The objective of the working group is to better understand the causes and potential mitigations for taste and odor events which are primarily a challenge in the Croton System. Initially, the group focused on developing enhanced monitoring plans and evaluating treatment alternatives. The goals were group expanded to include collaboration to other subject areas including: (1) evaluating multiple treatment techniques, (2) evaluating multiple technologies and methods, (3) collaborating externally with other water utilities and research experts, and (4) traveling to various locations to visualize real world applications.

7.7.2 Drone Task Force

The Bureau of Water Supply (BWS) is exploring the use of unmanned aircraft systems (UAS), or drones, to collect data within New York City (NYC) water supply watersheds. To enhance collaboration and ensure support for development of a program, BWS formed a Drone Task Force in 2019 consisting of members from various directorates and backgrounds from around the bureau. Since its formation, the Drone Task Force has developed an internal policy for approval of drone flights, explored drone applications via pilot studies, and continues to evaluate the feasibility and need for a drone program. Examples of drone applications include site surveying (horizontal and vertical geolocation), dam safety inspections, remote installation inspections (e.g., RoboMon buoys), and a variety of areal extent mapping applications including but not limited to invasive aquatic and terrestrial species, turbidity plumes, reservoir ice over, stream bank erosion, and forestry (e.g., changes in forest canopy height due to knockdowns, defoliation due to invasive insects).

During 2021 the Water Innovation and Research (WIR) group piloted a project using water chestnut, an invasive aquatic plant species, as a test case for drone mapping of aquatic invasive areal coverage in reservoirs. Drone imagery allowed classification and areal extent mapping of water chestnut in a 50-acre cove of Muscoot Reservoir, showing promise as a tool for potential monitoring of other aquatic invasive plant species in NYC reservoirs.

Currently, BWS is developing a 3-year contract that will support drone usage for a wide range of watershed projects. A project justification for drone use on any given project and evaluated fit of drone capabilities to the project goals will be the criteria used to select projects to be funded.

7.7.3 Salinity Task Force

Formed in 2020, the BWS Salinity Task Force (STF) continued to meet in 2021 to develop a Salinity Management Strategy. This initiative was intended to better understand the drivers of salinity increase in the City's watersheds, and to identify recommendations to work towards a regional approach to salinity management. The STF is comprised of staff appointed by the various directorates in BWS. The task force's goal is to examine, measure, and understand the trends of salinity for the NYC watersheds and water supply, and to develop a strategy to monitor and reduce salinity. While the STF found a sustained increase in chloride concentrations in all NYC reservoirs, the highest increases were in the EOH watersheds. These increases ranged in magnitude and the causes for observed increases are connected to anthropogenic causes: the use of road deicers in winter and Water Resource Recovery Facilities (WRRFs).

7.7.4 R Data Analysis Group

The overarching goal of the R Data Analysis Group (RDAG) is to continue to develop the DEP's internal data analysis and management skill sets for scientific reporting. This internal working group serves to improve legacy knowledge transfer to the next generation of data analysts/scientists using the open-source R statistical software for statistical analysis and data visualization. Accomplishments for 2021 included the Business Information Technology bureau creating a virtual server for RDAG members to access the R software, inviting colleagues interested in participation, creating a Teams channel to serve as a knowledge repository and venue for group interaction, and providing interested colleagues with links to a series of instructional videos for introductory information. The RDAG subject matter expert goals for the upcoming year include preparation of monthly projects. Each month will focus upon a single topic, provide multiple examples of methodologies that can be utilized, and exercises utilizing those methodologies. These topics will begin with data importing, data cleaning and wrangling, graphical representation, and statistical analysis.

7.8 Water Research Foundation

The Water Research Foundation (www.waterrf.org) is "the leading research organization advancing the science of all things water to meet the evolving needs of its subscribers and the water sector. WRF is a nonprofit, charitable, and educational organization which funds, manages, and publishes research on the technology, operation, and management of drinking water, wastewater, reuse, and stormwater collection, treatment and supply systems — all in pursuit of ensuring water quality and improving water services to the public." DEP has been a subscriber and participant in the research conducted under the WRF since the early 1990s, both as project advisory committee (PAC) members and as a participating utility (PU), to remain current with cutting-edge research for the benefit of the City's drinking water.

The following sections describe DEP's engagement with WRF quantitatively through metrics and scholarships. In addition, WRF coordinated a workshop on how to optimize the system against DBPs and their precursors. Finally, DEP participated in 32 Water Research Foundation projects. These projects provide insight into pathogens, emerging contaminants, and corrosivity of source water that can interact with distribution system features and may have operational implications. The current projects in which WQI is involved are described below.

7.8.1 Metrics

BWS tracks involvement with The Water Research Foundation year-over-year to measure engagement and identify areas or opportunities for growth (Table 7.2).

Table 7.2 Water Research Foundation Projects 2019 – 2021.

Metric	2019	2020	2021
New Staff Accounts	18	32	1
External Organizations included in DEP's Subscription	5	5	5
Staff Serving on WRF Planning/Research Bodies	17	24	32
Webinar Participation	65	215	287

7.8.2 WRF Workshop – Disinfection Byproducts

WRF organized a DBP Expert Panel Workshop on behalf of BWS on June 7-8, 2021. Ultimately, the goal of the workshop was to review past and current monitoring and research advise the bureau on potential improvements to research and compliance strategies. Specific objectives were to (1) evaluate DEP's operations and research recommendations to date, (2) identify advancements in instrumentation or other mechanisms to track DBP precursors, (3) identify opportunities to decrease the presence of DBP precursors, (4) offer advisement on meeting the challenges of simultaneously complying with the D/DBP Rule, Lead and Copper Rule, and Surface Water Treatment Rule, and (5) identify research gaps.

Seven subject matter experts participated in the workshop (Table 7.3) and provided input on improved data management, artificial intelligence for predictive modeling, additional DBPfp work including trend analysis and a review of treatment alternatives for optimizing water quality under varying conditions.

Table 7.3 DBP Expert Panel Workshop Subject Matter Experts.

Expert Panelists	
William Becker Vice President and Drinking Water Practice Leader Hazen and Sawyer	Dr. Tanju Karanfil Professor EEES and Vice President for Research Clemson University
Angela Cheung Division Manager of Water Supply and Treatment San Francisco Public Utilities Commission	Andrew DeGraca Water Quality Division Director San Francisco Public Utilities Commission
Zaid K. Chowdhury Water Treatment Practice Leader Garver	Steve Via Director of Federal Affairs AWWA Government Affairs
Katie Spahr Research Program Manager The Water Research Foundation	

7.8.3 SEE IT Scholarship

DEP was awarded two LIFT Scholarship Exchange Experience for Innovation & Technology (SEE IT) scholarships from WRF. One $2,826.25 scholarship is to visit the City of Phoenix Water Services Department's water filtration plant which was is comparable to the scope and scale of the Croton Water Filtration Plant. The second scholarship for $2,700 supports a visit by Bureau of Wastewater Treatment staff to Hampton Roads Sanitation District and associated Water Resource Recovery Facilities (WRRFs). Unfortunately, due to COVID-19 travel restrictions, DEP was unable to fulfill these scholarships in 2021 but will do so in 2022.

7.8.4 WRF Project Participation

Table 7.4 summarizes all WRF project participation in 2021.

Table 7.4 2021 WRF Project Participation.

Title	Description	Participation[1]
PFAS in Water	PFAS One Water Risk Communication Messaging for Water Sector Professionals (5124) - This project is focused on developing plug-and-play tools and communication materials that water utilities across the United States can use to communicate their PFAS risk and solutions to their customers. The effort thus far is focused on creating universal tools for traditional communications, social media, bill inserts, websites, and presentations. All of this will be done ahead of UCMR5 results so that water utilities will have the tools they need to communicate their results and talk about it with their elected leaders and customers.	PAC
Emerging Disinfection Byproducts	Technologies and Approaches to Minimize Brominated and Iodinated DBPs in Distribution Systems. This project aims to develop creative and novel techniques and approaches to minimize the formation of currently unregulated brominated and iodinated disinfection byproducts (DBPs) in the distribution system considering practical applicability and economic feasibility in the operation of existing treatment systems.	PU
Cyanobacterial Blooms & Cyanotoxins	Assessment of Molecular Techniques to Detect and Predict Cyanotoxin-Producing Blooms	PAC
Lead & Copper Management	Using Phosphate-Based Corrosion Inhibitors and Sequestrants to Meet Multiple Water Treatment Objective	PAC
Defining Exposures of Microplastics/ Fibers (MPs) in Treated Waters and Wastewaters: Occurrence, Monitoring, and Management Strategies	Project Objectives: • Characterize typical MP numbers, types and sizes in secondary and tertiary treated wastewater, recycled water, drinking water supplies (ambient waters) and treated drinking water • Develop reliable monitoring and sampling guidelines, based on MP sizes and source media • If needed, develop a decision-making framework for MP reduction strategies from the whole water supply cycle • Describe the relative effectiveness of various technologies and legislation to mitigate sources and pathways of MPs	PAC
Impact of a Haloacetic Acid MCL Revision on DBP Exposure and Health Risk Reduction	The objectives of this project are to develop: • A holistic assessment of the potential impacts of potential new regulatory levels for HAA5, HAA6Br, or HAA9. • A defensible database and analysis available to water systems for discussion with regulatory authorities. • An understanding of the benefits of compliance technologies for a future rule, which will allow water systems to make preliminary evaluations of water treatment improvements they may have to incorporate after the regulations are revised. • Guidance to water systems and regulators on consequences of implementing changes to respond to a revised maximum contaminant level (MCL) for haloacetic acids (HAAs)	PU

Title	Description	Participation[1]
Advancing Low-Energy Biological Nitrogen and Phosphorus Removal	The main objective of this project is to conduct research needed to advance the most promising intensive and efficient low-energy nutrient treatment process(es) and innovative process control approach(es) that utilities can employ and reliably operate at their facilities with a balance of cost-effective investments and appropriate levels of process control complexity. While the scope of this project is open to all low-energy biological nutrient removal intensification processes, we encourage proposers to consider the processes and research topics listed in the research approach of the RFP.	PU
Investigation of Alternative Management Strategies to Prevent PFAS From Entering Drinking Water Supplies and Wastewater	Project Objectives: • Identify potential point sources • Identify effective pre-treatment and mitigation measures such as BMPs and permitting at point sources • Investigate impacts of wastewater effluent PFAs on drinking water utilities • Develop a roadmap of multiple strategies to mitigate PFAS at point source or prior to entry to drinking water and wastewater treatment facilities	PAC
Guidance for Using Pipe Loops to Inform Lead and Copper Corrosion Control Treatment Decisions	Project Objectives: To provide "fit for purpose" guidance for corrosion control pipe loop construction, operation, sampling, and data interpretation to inform pipe loop implementation for corrosion control studies.	PU
Assessment of Vulnerability of Source Waters to Toxic Cyanobacterial Outbreaks	Project Objectives: • Develop a risk assessment for the prediction of the occurrence of different types of cyanobacteria and the progress toward bloom development. • Develop a model that uses the conventional understanding of the major factors triggering and supporting the growth of cyanobacteria • Calibrate and validate the model with data from a variety of source waters, geographical area, and environmental factors.	PAC/PU
Analysis of Corrosion Control Treatment for Lead and Copper Control **Completed in 2021**	Project Objectives: • Evaluate analysis tools for and risks from changing and/or implementing corrosion control treatment (CCT). • Explore the potential impact of various source water or treatment changes to CCT. • Develop a framework for how to assess current CCT and under what circumstances CCT should be reevaluated. • Explore the impacts to both lead and copper.	PU

Title	Description	Participation[1]
Sampling and Monitoring Strategies for Opportunistic Pathogens in Drinking Water Distribution Systems	The goal of this project is to establish an optimized sampling and monitoring protocol providing a practical guideline for drinking water utilities to manage the detection of opportunistic pathogens in distribution systems	PAC
Evaluating Key Factors that Affect the Accumulation and Release of Lead from Galvanized Pipes **Completed in 2021**	The objective of this project is to better understand the scenarios where Galvanized Pipes can contribute to lead at the tap, the magnitude of lead release from Galvanized Pipes, and factors that can impact accumulation and lead release from Galvanized Pipes.	PAC
Designing Sensor Networks and Locations on an Urban Sewershed Scale with Big Data Management and Artificial Intelligence Applications	The water sector is undergoing a transformation to digital where data and data management are driving every aspect of a utility's work. To address this new way of conducting business, this project will consolidate insights gained from the WRF projects *Designing Sensor Networks and Locations on an Urban Sewershed Scale* (4835) and *Leveraging Other Industries - Big Data Management* (4836) into demonstration projects at multiple facilities. The demonstrations are designed to validate sensor-based, real-time monitoring/metering and models/decision support systems on sewershed/sub-sewershed scales, including the application of analytics to solve sewershed network management issues. Based on the insights gained from the demonstrations, a sensor-based network and data management framework will be developed. The framework will provide a clear architectural roadmap and guidance for advancing data and information management, practices, automation of quality assurance/quality control, data use mapping, database management, and data integration for the water sector. The framework will incorporate new and emerging monitoring/metering technologies for real-time decision-making.	PAC
Opportunistic Pathogens in Premise Plumbing	This project aims to develop methods for accurately detecting and quantifying bacterial and protozoan OPs in drinking water systems, with a particular focus on L. pneumophila, P. aeruginosa, nontuberculous mycobacteria, and Acanthamoeba spp. These four OPs represent the greatest health and economic burden posed among those occurring in premise plumbing.	PAC

Title	Description	Participation[1]
Long Term Water Demand Forecasting Practices for Water Resources and Infrastructure Planning	This project aims to describe models, methods and practices currently used to forecast long-term demand in support of water resources and infrastructure planning and management. To the extent possible, the project deliverables will discuss how current practices have evolved over time. The research team will consider the accuracy of different forecasting approaches by comparing actual with model-estimated demands and comment on the relative effectiveness of different approaches. The team will also identify the extent to which forecasting models, methods, practices, and communications influence decisions about utility plans and actions. Finally, this project will develop recommendations to help improve the role and effectiveness of demand forecasting practices and different types of communication strategies on water resource and infrastructure planning and decision-making.	PU

[1]PAC: Project Advisory Committee; PU: Participating Utility

7.9 American Water Works Association (AWWA)

The American Water Works Association is an international, nonprofit, scientific and educational society dedicated to providing total water solutions assuring the effective management of water. Founded in 1881, the association is the largest organization of water supply professionals in the world. The membership includes over 4,300 utilities that supply roughly 80% of the nation's drinking water and treat almost half of the nation's wastewater.

7.9.1 Technical Advisory Workgroups (TAWs)

Table 7.5 lists the technical advisory working groups with DEP participants.

Table 7.5 AWWA Technical Advisory Working Groups in 2021.

AWWA Committees	
Committee Name	**Participant**
Disinfection By-Products	Lori Emery, Director, Water Quality & Innovation, Bureau of Water Supply
Distribution Systems	Salome Freud, Deputy Director, Distribution Water Quality and Operations, Water Quality and Innovation, Bureau of Water Supply Anne Seeley, Section Chief, Health Assessment and Policy Coordination, Water Quality and Innovation, Bureau of Water Supply
Lead and Copper Rule	Salome Freud, Deputy Director, Distribution Water Quality and Operations, Water Quality and Innovation, Bureau of Water Supply
Microbiological Contaminants Research	Kerri Alderisio, Research Microbiologist, Watershed Water Quality and Operations, Water Quality and Innovation, Bureau of Water Supply
Organisms in Water	Kerri Alderisio, Research Microbiologist, Watershed Water Quality and Operations, Water Quality and Innovation, Bureau of Water Supply
UV Disinfection for Wastewater	Matthew Burd, Advisor for Process, Wastewater Resource Recovery Operations, Source Water Operations, Bureau of Water Supply
Water Resources and Source Water Protection	Jeffrey Graff, Project Manager, Watershed Lands and Community Planning, Watershed Protection Programs, Bureau of Water Supply

AWWA Committees	
Committee Name	**Participant**
AWWA Water Utility Council	Paul V. Rush, Deputy Commissioner, Bureau of Water Supply
NYSAWWA Water Utility Council	Salome Freud, First Deputy Director, Water Quality & Innovation, Bureau of Water Supply

7.10 Town+Gown

Created in 2009-2010, Town+Gown is a city-wide university-community partnership program, resident at the New York City Department of Design and Construction (DDC), that brings academics and practitioners together to create actionable knowledge in the built environment. Under the terms of the consortium contract, BWS is able to issue requests for proposals (RFPs) for research initiatives.

7.10.1 Croton Filtration Bench-Scale Analysis

Croton Water Filtration Plant (CFP) has been effective in maintaining compliance with current drinking water regulations since it was placed in operation in 2015. However, reservoirs in the Croton System have been impacted by the invasive species *Hydrilla* (currently treated with the aquatic herbicide fluridone), taste and odor causing chemicals such as geosmin and 2-methylisoborneol (MIB) and cyanotoxins such as microcystin. In addition, perfluorinated compounds (PFCs) such as perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) are concerning municipalities nationwide because of their persistence, mobility, and potential health effects. The findings from this bench-scale analysis indicate that the existing process train was is effective at removing fluridone, and moderately effective at removing Geosmin/MIB and PFCs.

7.10.2 Water Resource Recovery Facility Assessment

There are numerous public and privately owned WRRFs in watersheds. All facilities are subject to the Watershed Rules and Regulations, and DEP provided funding in the 1990s to install tertiary treatment to minimize the risk of introducing pathogens into source waters. Since that time, nearly all the WRRFs in the watershed have been upgraded to include sand filtration, disinfection, phosphorus removal and microfiltration (or equivalent). The purpose of this study is to identify specific treatment modifications that would allow DEP to reduce costs without reducing the level of treatment achieved for pathogens and other contaminants of concern. A review of newer and equally efficient wastewater treatment technologies is under evaluation pursuant to the state SPDES permit effluent limits.

7.10.3 A Regional-scale Assessment of Nutrient Loading for NYC Watersheds

In 2021 the RAC reviewed a study to account for patterns (e.g., seasonal, annual) and trends (i.e., change through time) in watershed nutrient export (i.e., nitrogen and phosphorus) to evaluate the influence and interaction of City watershed protection programs and climatological change over time. Additionally, this study will support the identification of high nutrient source areas and give insights into watershed protection program planning for the future.

The goal is to apply a nutrient export approach using watershed models and anthropogenic nutrient input toolboxes coupled with results from trend analysis to describe the potential causes of observed nutrient trends in the NYC watershed. This was recommended by the National Academy of Sciences, Engineering, and Medicine in a consensus study report prepared as part of a review of the NYC Watershed Protection Program (NASEM, 2020). The desired outcome is to determine where the greatest sources (areas and types) of nutrients are located and how nutrient loads to reservoirs have changed over time to provide guidance for future watershed protection and other initiatives.

7.11 Research Partners

7.11.1 Virginia Tech

BWS is coordinating with Virginia Tech on several research projects including a Smart One Water program through the National Science Foundation, data governance, and a Future of Water summit. The goal of the proposed Smart One Water Engineering Research Center is to advance measurement and decision support technologies for adaptive management of engineered and natural water systems driven by societal needs for resilience, sustainability, and social justice. Recent natural disasters, cyber-security breaches, and aging infrastructure failures are a reminder that natural, technological, and anthropogenic hazards have great impacts on our society and economy. Smart One Water seeks to create a system of systems approach to integrate cyber-social-environmental components of water resources management. As part of the next phase of this program, Virginia Tech is using the Delaware River Basin as a test bed, along with Biscayne Bay in Florida and the Upper Colorado River Basin states.

7.11.2 Cardiff University

In 2021, BWS continued to build a collaboration with researchers from Cardiff University who have been helping water utilities in the United Kingdom (UK) study taste and odor issues. Cardiff University has been developing genomic methods of analysis that determine not only the presence of algal species, but also their ability to produce certain taste and odor compounds. BWS and Cardiff University held multiple discussions throughout 2021, which focused on a specific type of field analysis using eDNA filters that is coupled with two types of analysis. The first analysis uses next generation sequencing (NGS) to determine relative abundance of species presence to track changes in the algal communities over time. An additional analysis that uses RNA determines what portion of the cells present can produce the taste and odor compounds geosmin and 2-methylisoborneol. At the end of the year, Cardiff University applied for an Engineering and Physical Sciences Research Council grant which would enable Cardiff University to visit DEP and demonstrate both field and lab analysis to BWS staff. That grant was awarded to Cardiff University for use in 2022.

7.11.3 Global Lake Ecological Observatory Network (GLEON)

The overall mission of GLEON is to "understand, predict, and communicate the role and response of lakes in a changing global environment." GLEON fosters the sharing of ideas and tools for interpreting high-frequency sensor data and other water quality and environmental data. Several collaborations have developed from DEP's participation in annual meetings convened by GLEON. In 2021, DEP staff attended the "all hands" virtual meeting from October 4-8. Information about GLEON research can be found at: http://gleon.org/research/projects/.

7.11.4 Wadsworth Center for Laboratories and Research

NYC DEP Water Quality scientists reached out to scientists at the Wadsworth Center for Laboratories and Research (NYS DOH) to further examine stool samples that had been submitted from NYC residents diagnosed with cryptosporidiosis. The goal was to identify the species, and possibly genotypes, in stool specimens from 2015 - 2018 and compare them to previous research identifying species and genotypes from samples collected in the watershed. As with many projects, there were delays due to priorities associated with the COVID-19 pandemic. In 2021, work continued, and final data analysis was completed on the 513 specimens. DEP and the Wadsworth staff also collaborated on a presentation for the 2022 interagency annual Pathogen Technical Working Group meeting.

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Appendix A. WWQO Monitoring Reintegration Plan

WWQO Monitoring Program Reintegration Plan

Implementation Date	3/20/2020	6/22/2020	9/01/2020	11/02/2020	REQUESTED 7/22/202 APPROVED 7/27/2021	9/3/2021	
Reintegration Levels	(Current) Level 1	(Intermediate) Level 2	(Intermediate) Level 3	(Intermediate) Level 4	(Intermediate) Level 5	(Intermediate) Level 6	(Full Return) Level 7
COVID-19 Reduced Monitoring Plan							
Regulatory Compliance Monitoring	X						
Operations Support (WWQMP Reduced)	X						
At The Tap	X						
Watershed Water Quality Operations Monitoring Programs							
Watershed Water Quality Monitoring Plan (Changes require approval from NYSDOH)							
Regulatory Compliance (not included in reduced monitoring plan)							
Cryptosporidium Infectivity		X					
WRR – Phosphorous Restricted Basin		L				X	
WRR – Coliform Restricted Basin		L				X	
FAD Monitoring							
BMP Assessments		X					
Water Quality Status and Trends							
Streams - direct inputs to reservoirs only				X			
Streams - all others							X
Reservoirs		X					
Keypoints		X					
Benthic Biomonitoring				X			
Kensico Surveillance			X				
FAD WWTP Monitoring (not City-owned)						L[3]	X[3]
Conversion of Septic to Sewer Evaluation						X	
Pathogen Monitoring							
Pathogen - KP Monitoring Source Waters (in reduced monitoring p	X						
Watershed Pathogen Source Origin							X[1]
Pathogen - Long-term (Oo)cyst Monitoring at WWTPs							X[1]
Modeling Support (Changes require notification to NYSDOH)							
Stream Monitoring (data collected for other purposes under priority 2)							X
Reservoir Monitoring (data collected for other purposes under priority 2)							X
Keypoint/Release Monitoring (data collected for other purposes under priority 2)							X
Watershed Surveillance Monitoring (Changes require notification to NYSDOH)							
Operations Support (non-reduced)		X					
Kensico Turbidity Curtain Monitoring (UEC Visual observation only)							X
Croton Streams – Status and Trends (direct inputs to resv. only)				X			
Croton Streams – Status and Trends (all others)							
Croton Reservoirs – Status and Trends					L	X	
Croton Benthic Biomonitoring – Status and Trends				X			
Croton WWTP Monitoring							*
Supplemental Contaminant Monitoring							
VOC/SVOC and Glyphosate							X
Metals							X
Non-Regulated DEP Facility Potable Water Monitoring			X				
Zebra Mussel Monitoring (EOH)					L	X	
Zebra Mussel Monitoring (WOH)							*
Spiny Water Flea Monitoring							X[1]
Projects Monitoring (DEP discretionary projects; No discussion with NYSDOH required)							
Robomon Program (Non-terminal Reservoirs and CNC/BRK not deployed)		X					
EWRM Program (Non-Regulatory)		X					
DBPfp Monitoring Program			X				
Kensico Stream Storm Event Monitoring			X				
Cyanotoxin Monitoring Program				L[2]	L[3]		X
FlowCAM Phytoplankton Monitoring Program						L[2]	X
Ultra-Sonic Buoy Monitoring Program (data colleced under other obj.)			X				
New Croton Fluridone Application Monitoring		X[1]					
Emerging Contaminants Monitoring Program		L[2]					X
Croton Falls Pumping Station Operation Monitoring	X[1]						
Cross River Pumping Station Operation Monitoring	X[1]						
Kensico Shoreline Stabilization Project		X[1]					
Croton Treatment Plant Start-Up Monitoring			X[1]				
Alum Treatment Monitoring	X[1]						
Catskill Aqueduct Chlorine Monitoring	X[1]						
Monitoring of Operations to Improve the Water Quality of Croton Falls Reservoir					Began 8/9/2021		

X - Full Objective
L - Limited Objective
1 - as needed.
2 - DEL18DT and CROGH only
3 - quarterly; seasonal
* - Permanent Reduction

Appendix B. 2021 Robotic Monitoring – Locations and Types

Site	Location	System	Monitoring Type	Parameters
3SS	Schoharie	Catskill	Reservoir Profiling Buoy	Temp, SpCon, Turb
S5i	Schoharie Creek	Catskill	Stream Hut	Temp, SpCon, Turb
S10-RF	Batavia Kill Creek	Catskill	Stream Hut	Temp, Turb
S10-LC	Batavia Kill Creek	Catskill	Stream Hut	Temp, Turb
1.4EAW	Ashokan West Basin	Catskill	Reservoir Profiling Buoy	Temp, SpCon, Turb
3.1EAW	Ashokan West Basin	Catskill	Reservoir Profiling Buoy	Temp, SpCon, Turb
4.2EAE	Ashokan East Basin	Catskill	Reservoir Profiling Buoy	Temp, SpCon, Turb
3.1EAW SI	Ashokan	Catskill	Reservoir Fixed Depth Buoy	Temp, SpCon, Turb, BGA, DO, Chl a, fDOM
3.2EAW	Ashokan	Catskill	Reservoir Fixed Depth Buoy	Temp, SpCon, Turb (2 depths)
4.2EAE	Ashokan	Catskill	Under Ice Buoy	Temp, SpCon, Turb (2 depths)
E16i	Esopus Creek	Catskill	Stream Hut	Temp, SpCon, Turb
1.5NN	Neversink	Delaware	Reservoir Profiling Buoy	Temp, SpCon, Turb, BGA, DO, Chl a, fDOM
NCG	Neversink River	Delaware	Stream Hut	fDOM, SpCon, Temp, Turb
4WDC	Cannonsville	Delaware	Reservoir Profiling Buoy	Temp, SpCon, Turb, BGA, DO, Chl a, fDOM
CBS	West Branch Delaware	Delaware	Stream Hut	fDOM, SpCon, Temp, Turb
1RR	Rondout	Delaware	Reservoir Profiling Buoy	Temp, SpCon, Turb
0.25RR	Rondout	Delaware	Reservoir Fixed Depth Buoy	Temp, SpCon, Turb
C1	Rondout	Delaware	Reservoir Fixed Depth Buoy	Temp, SpCon, Turb
C2	Rondout	Delaware	Reservoir Fixed Depth Buoy	Temp, SpCon, Turb
1RR	Rondout	Delaware	Under Ice Buoy	Temp, SpCon, Turb (2 depths)
RDOA	Rondout Creek	Delaware	Stream Hut	Temp, Turb

Site	Location	System	Monitoring Type	Parameters
4BRK	Kensico	Catskill-Delaware	Reservoir Profiling Buoy	Temp, SpCon, Turb
4.1BRK	Kensico	Catskill-Delaware	Reservoir Profiling Buoy	Temp, SpCon, Turb
2BRK	Kensico	Catskill-Delaware	Reservoir Fixed Depth Buoy	Temp, Turb
2.9BRK	Kensico	Catskill-Delaware	Reservoir Fixed Depth Buoy	Temp, Turb
2.05BRK	Kensico	Catskill-Delaware	Reservoir Fixed Depth Buoy	Temp, Turb
2.10BRK	Kensico	Catskill-Delaware	Reservoir Fixed Depth Buoy	Temp, Turb
2.18BRK	Kensico	Catskill-Delaware	Reservoir Fixed Depth Buoy	Temp, Turb
WS1BRK	Kensico	Catskill-Delaware	Reservoir Fixed Depth Buoy	Turb
WS2BRK	Kensico	Catskill-Delaware	Reservoir Fixed Depth Buoy	Turb
WS3BRK	Kensico	Catskill-Delaware	Reservoir Fixed Depth Buoy	Turb
WS4BRK	Kensico	Catskill-Delaware	Reservoir Fixed Depth Buoy	Turb
WS5BRK	Kensico	Catskill-Delaware	Reservoir Fixed Depth Buoy	Turb
WS6BRK	Kensico	Catskill-Delaware	Reservoir Fixed Depth Buoy	Turb
1CNC	New Croton	Croton	Reservoir Profiling Buoy	Temp, SpCon, Turb, BGA, DO, Chl a, fDOM
4CNC	New Croton	Croton	Reservoir Profiling Buoy	Temp, SpCon, Turb, BGA, DO, Chl a, fDOM

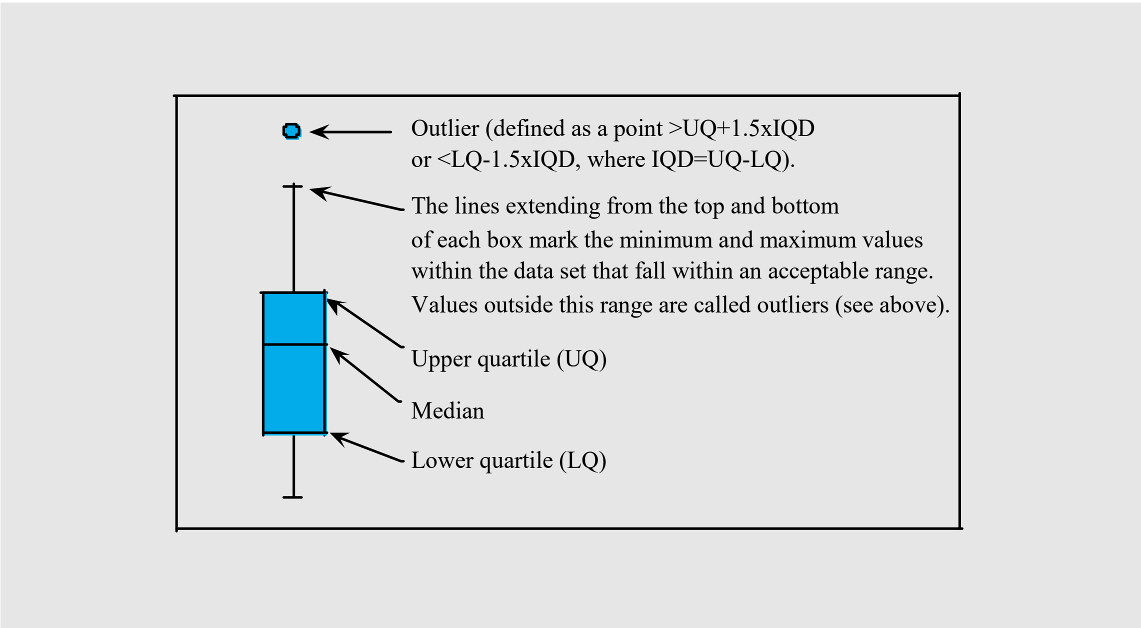
Appendix C. List of Sites for Watershed Water Quality Operations (WWQO) Early Warning Remote Monitoring (EWRM)

Site	Location	System	Water Type	Parameters
SRR1CM	Schoharie Intake Chamber	Catskill	Raw	Turbidity, pH, Temperature, Specific conductivity
SRR2CM	Shandaken Tunnel Outlet (STO)	Catskill	Raw	Turbidity, pH, Temperature, Specific conductivity
EARRAW	Catskill Aqueduct	Catskill	Raw	Turbidity, pH, Temperature, Specific conductivity
EARCM	Catskill Aqueduct	Catskill	Raw/ Treated	Turbidity, pH, Temperature, Specific conductivity, Chlorine dioxide, Total Chlorine Residual
M-1	Ashokan Release Channel	Catskill	Raw	Turbidity
AEAP	Esopus Creek Upstream STO	Catskill	Raw	Turbidity
RDRRCM	Delaware Aqueduct at Rondout Effluent Chamber (REC)	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity
NRR2CM	Neversink Tunnel Outlet	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity
PRR2CM	East Delaware Tunnel Outlet	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity
WDTOCM	West Delaware Tunnel Outlet	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity
RR1-RR4	REC Elevation Taps	Delaware	Raw	Turbidity
CDIS4-DEL	Cat/Del Interconnect at Shaft 4 (Delaware)	Delaware	Raw	pH, Temperature, Turbidity (only logging Turbidity)

Site	Location	System	Water Type	Parameters
CDIS4-CAT	Cat/Del Interconnect at Shaft 4 (Catskill)	Catskill	Raw	Turbidity, pH, Temperature, Specific conductivity, Chlorine Dioxide, Total Chlorine Residual
CDIS4- Combined	Cat/Del Interconnect at Shaft 4 (Catskill)	Catskill	Raw	pH, Temperature, Chlorine Dioxide, Total Chlorine Residual, Turbidity, Specific conductivity (only logging Turbidity)
CWB1.5	West Branch Reservoir	Delaware	Raw	Pump used to collect grab samples.
DEL9	Delaware Shaft 9	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity, Total Chlorine Residual, Dechlorination analyzer, Dissolved oxygen
DEL10	Delaware Shaft 10	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity, Elevation
DEL17	Delaware Shaft 17	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity, Total Chlorine Residual, Dechlorination analyzer, Dissolved oxygen
DEL18DT	Delaware Shaft 18 Downtake	Catskill/ Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity, Flow, Elevation, Fish biomonitoring system
DEL19LAB	Delaware Shaft 19 Lab	Catskill/ Delaware	Pre-Treated	Turbidity, pH, Temperature, Specific conductivity, Free Chlorine Residual, Fluoride Residual

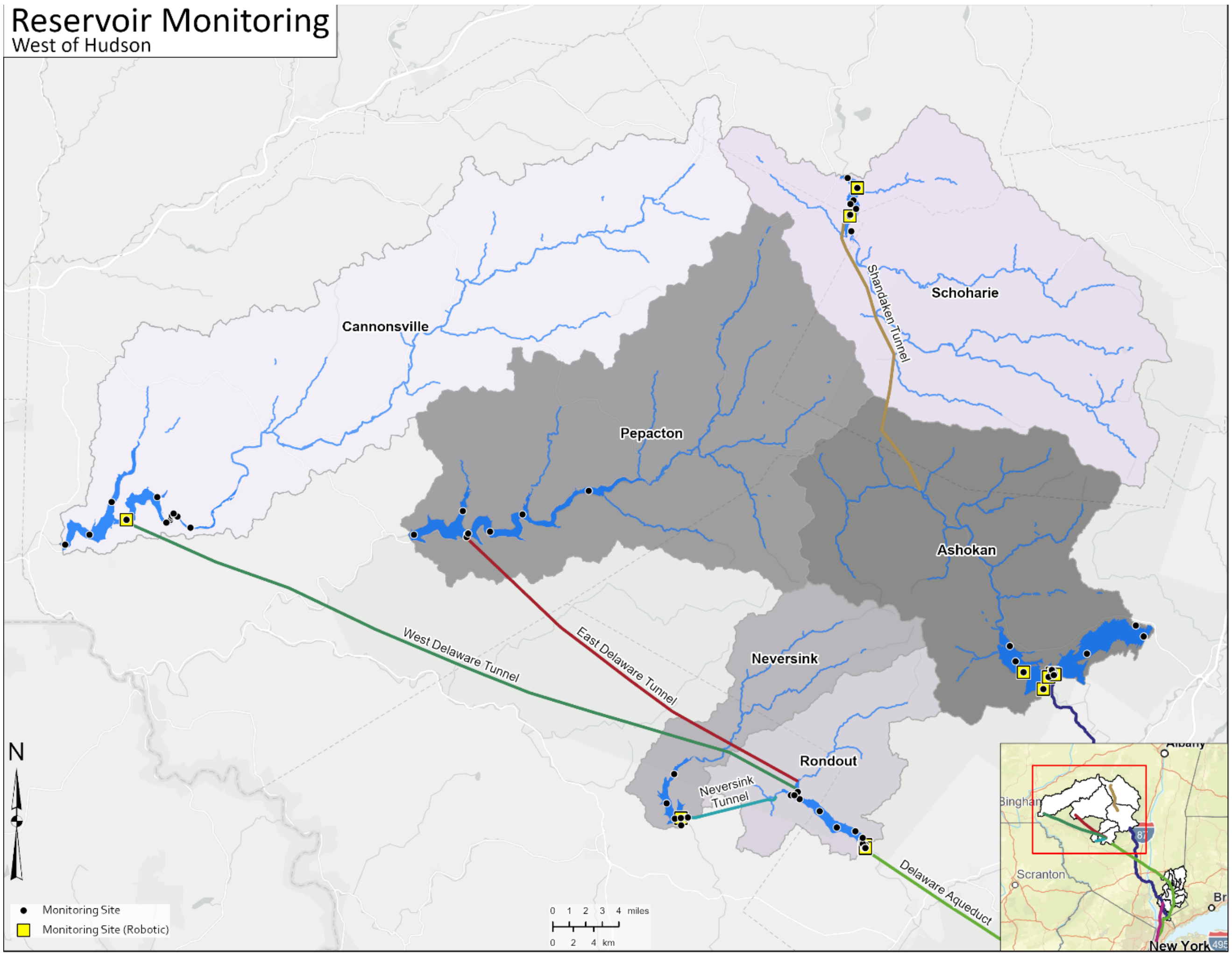
Site	Location	System	Water Type	Parameters
DELSFBLAB	Delaware South Forebay Lab	Catskill/ Delaware	Pre-Treated	Turbidity, pH, Temperature, Specific conductivity, Free Chlorine Residual, Fluoride Residual
CCCLAB	Catskill Connection Chamber Lab	Catskill/ Delaware	Pre-Treated	Turbidity, pH, Temperature, Specific conductivity, Free Chlorine Residual, Fluoride Residual
CROFALLSVC	Croton Falls Valve Chamber	Croton	Raw	Turbidity
CROSSRVVC	Cross River Valve Chamber	Croton	Raw	Turbidity
CATALUM	Catskill Alum Plant	Catskill	Raw	Turbidity
CATIC	Catskill Influent Chamber	Catskill	Raw	pH, Temperature
CROGH	CLGH Raw Water	Croton	Raw	Turbidity, pH, Temperature, Specific conductivity, Dissolved oxygen, Fish biomonitoring system
CRO1T	New Croton Dam	Croton	Raw	Turbidity, pH, Temperature, Specific conductivity, Dissolved oxygen
CRO1B	New Croton Dam	Croton	Raw	Turbidity, pH, Temperature, Specific conductivity, Dissolved oxygen
CRO183	CLGH	Croton	Raw	Turbidity, pH, Temperature
CRO163	CLGH	Croton	Raw	Turbidity, pH, Temperature, Specific conductivity,
CRO143	CLGH	Croton	Raw	Turbidity, pH, Temperature, Specific conductivity, Dissolved oxygen

Appendix D. Key to Boxplots and Summary of Non-Detect Statistics Used in Data Analysis

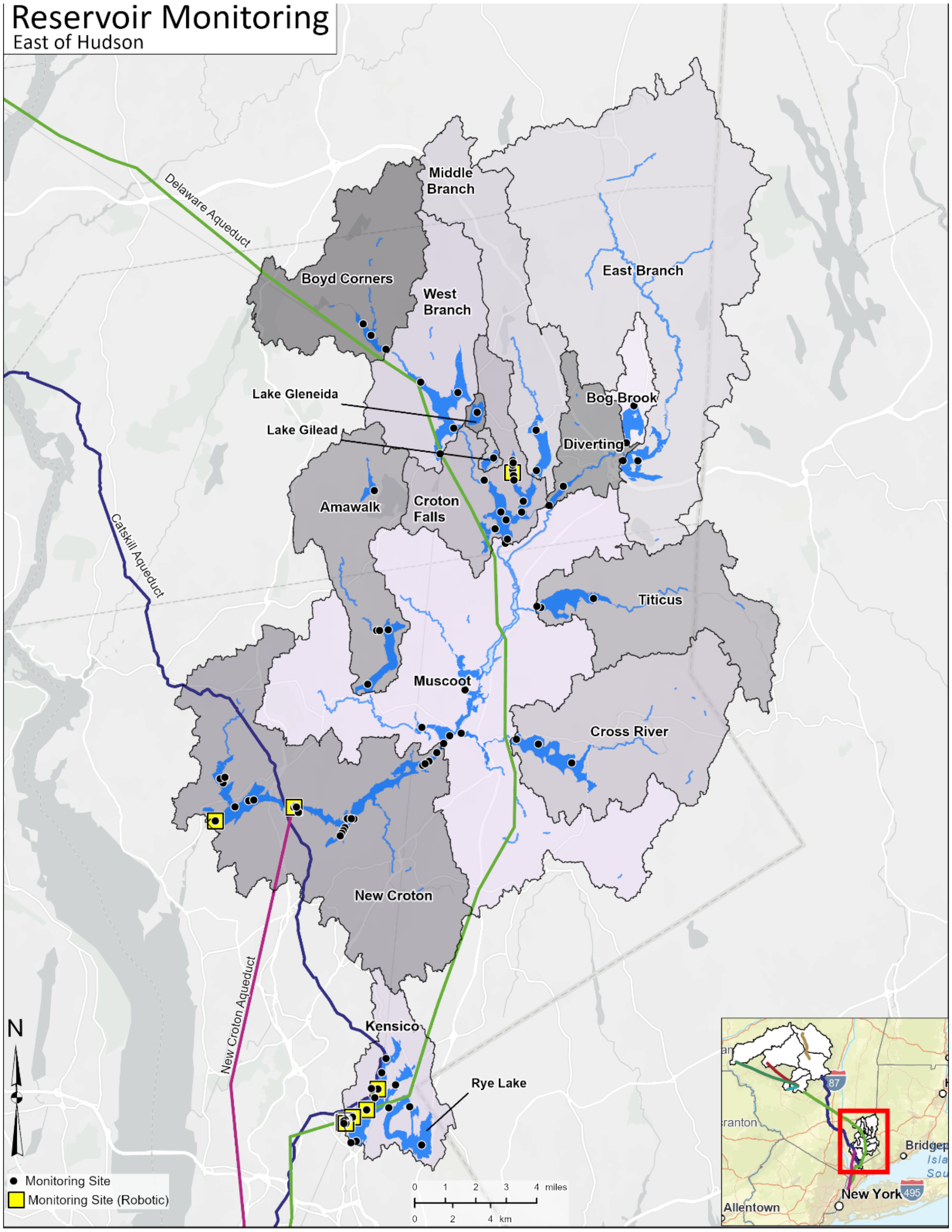


Water quality data are often left-censored in that many analytical results occur below the instrument's detection limit. Substituting some value for the detection limit results, and then using parametric measures such as means and standard deviations, will often produce erroneous estimates. In this report we used methods described in Helsel (2005), to estimate summary statistics for analytes where left censoring occurred (e.g., fecal and total coliforms, ammonia, nitrate, suspended solids). If a particular site had no censored values for a constituent, the summary statistics reported are the traditional mean and percentiles.

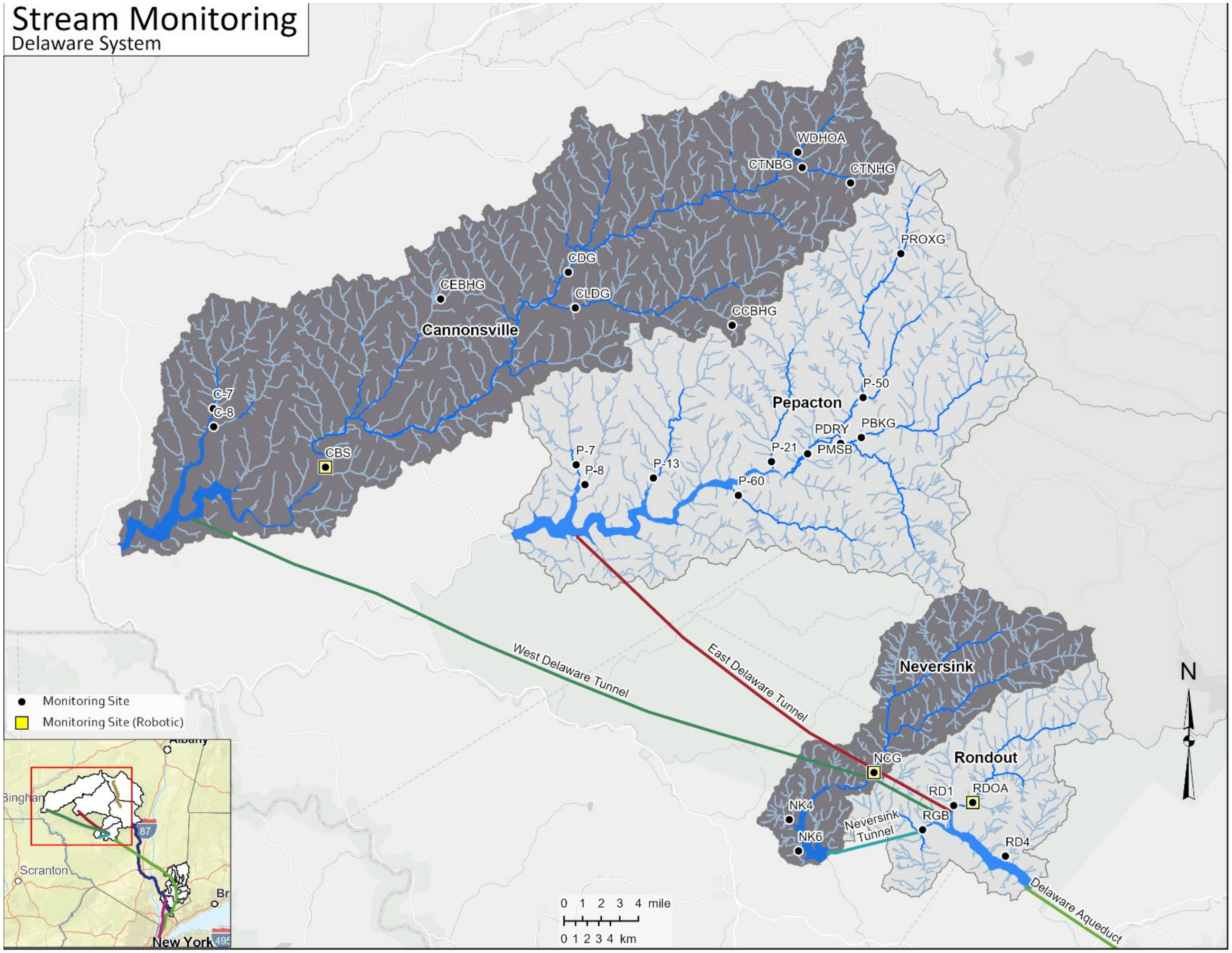
Appendix E. Sampling Locations



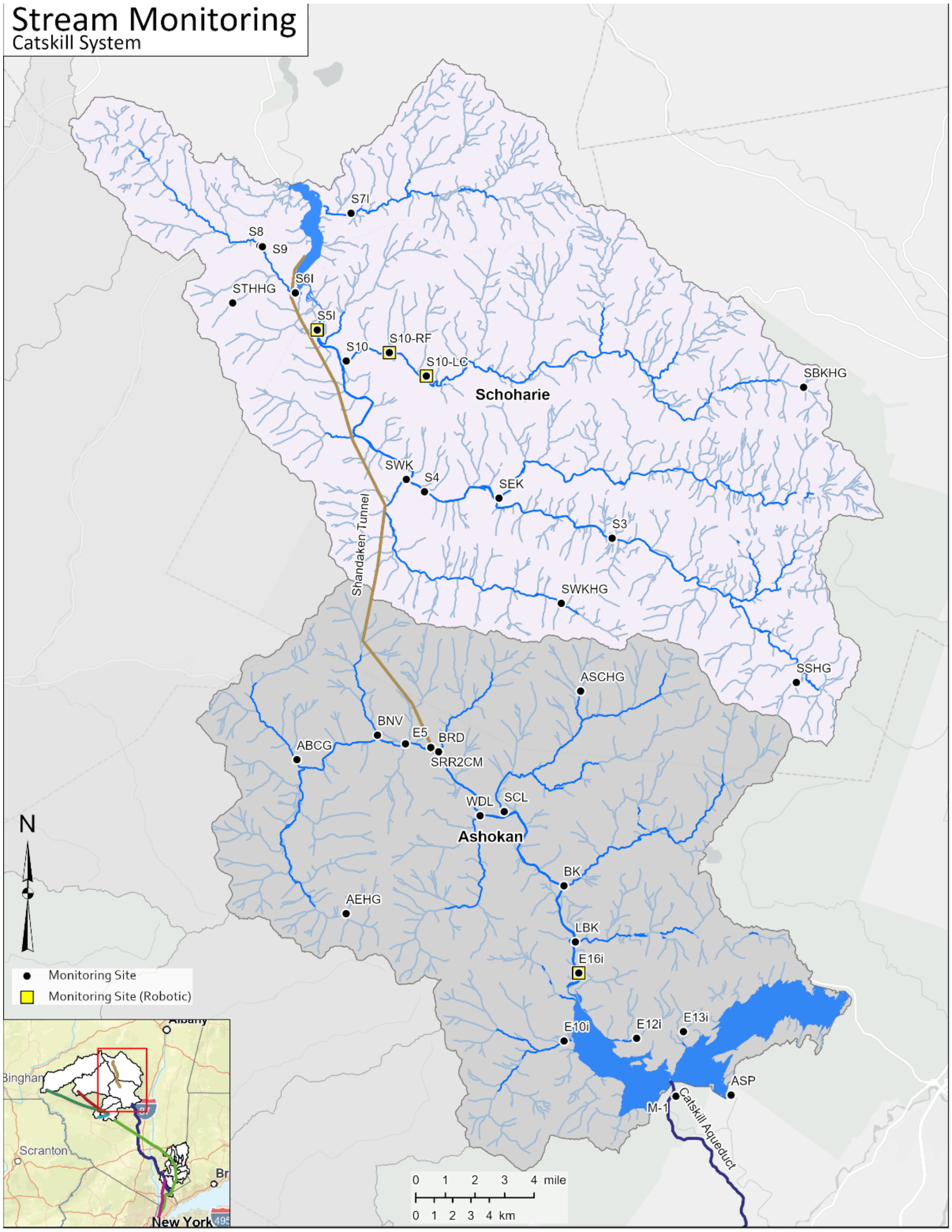
Appendix Figure 1 WOH reservoir monitoring sites [see WWQMP (DEP 2018) for detailed maps].



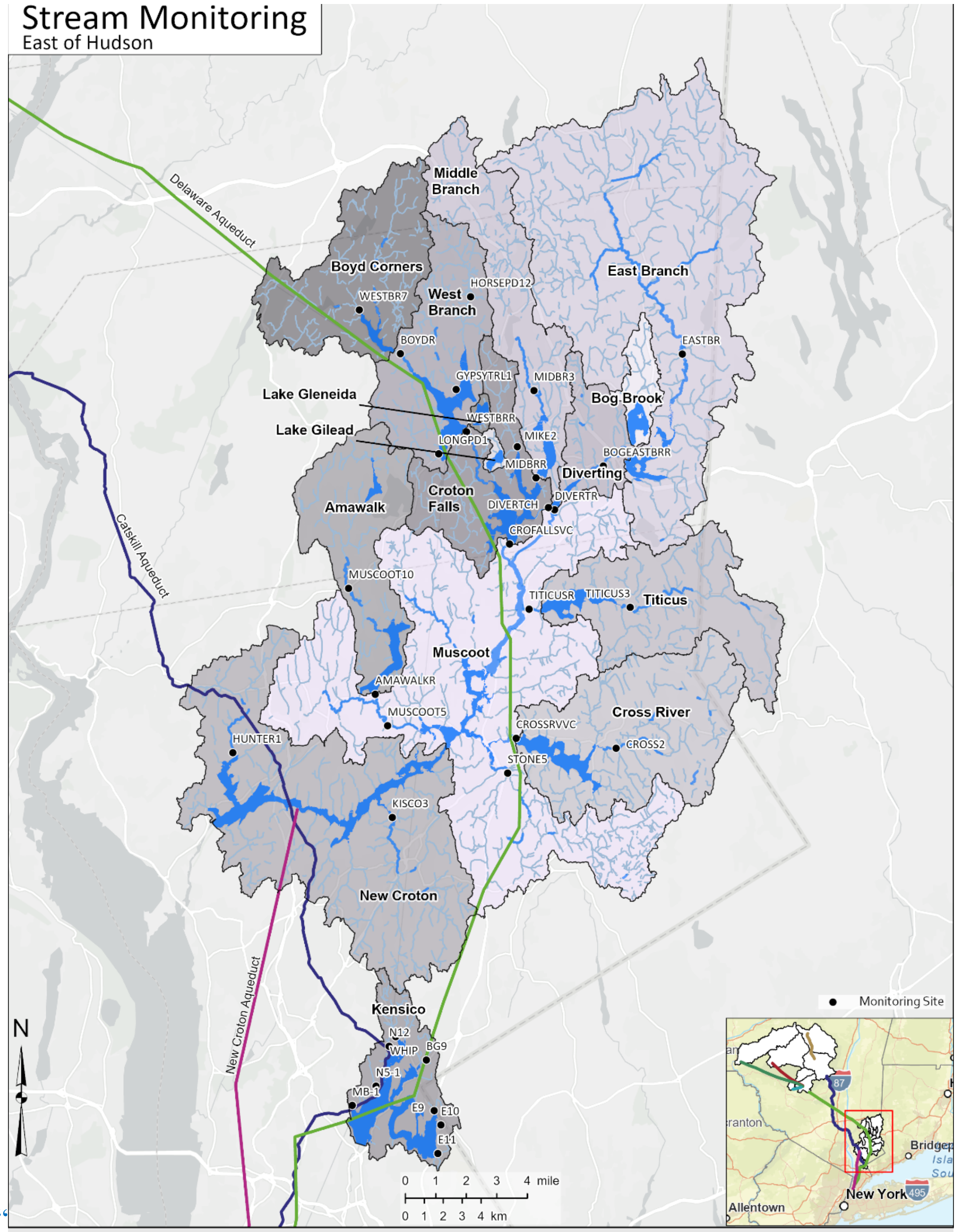
Appendix Figure 2 EOH reservoir monitoring sites [see WWQMP (DEP 2018) for detailed maps].



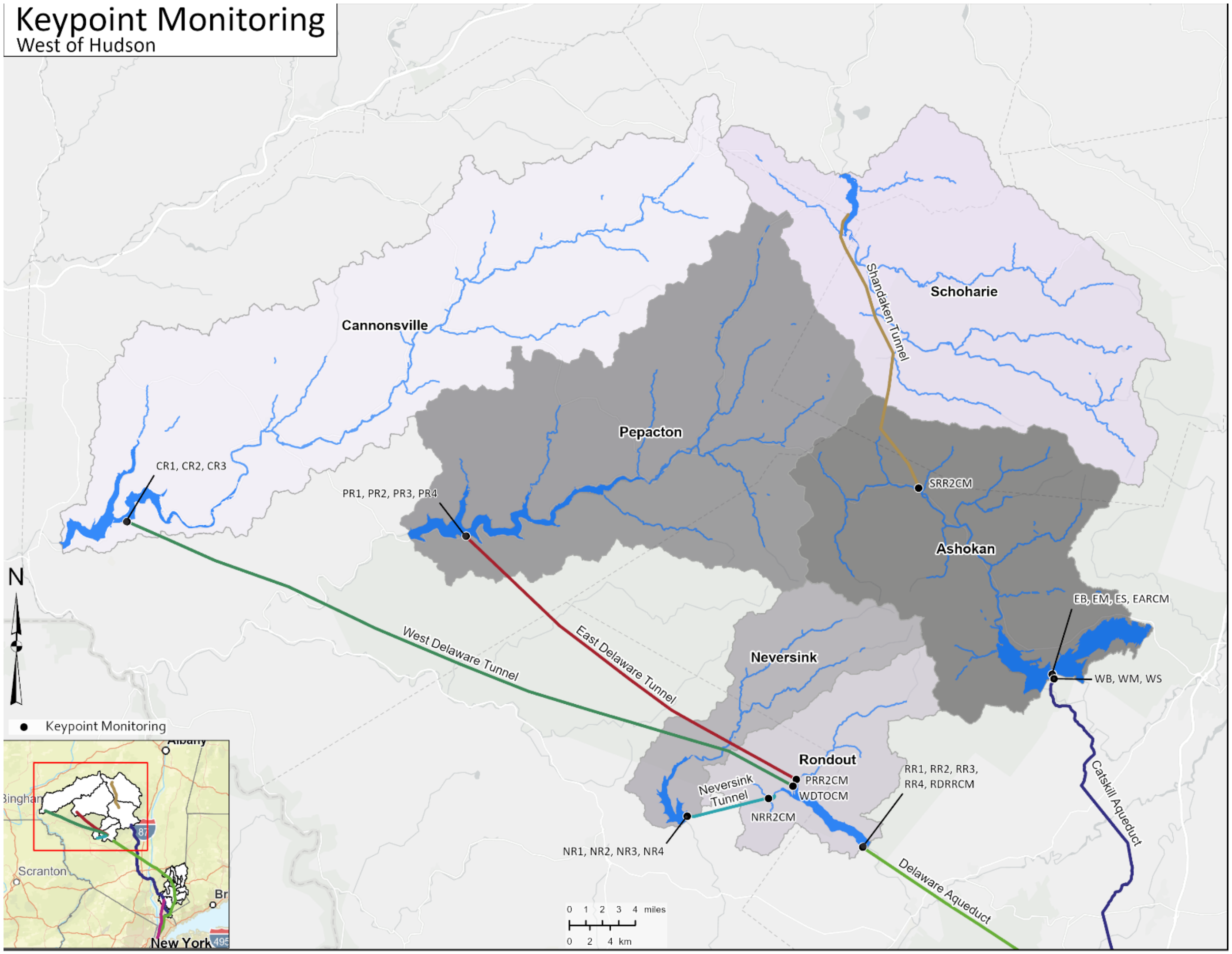
Appendix Figure 3 Delaware System stream monitoring sites [see WWQMP (DEP 2018) for detailed maps].



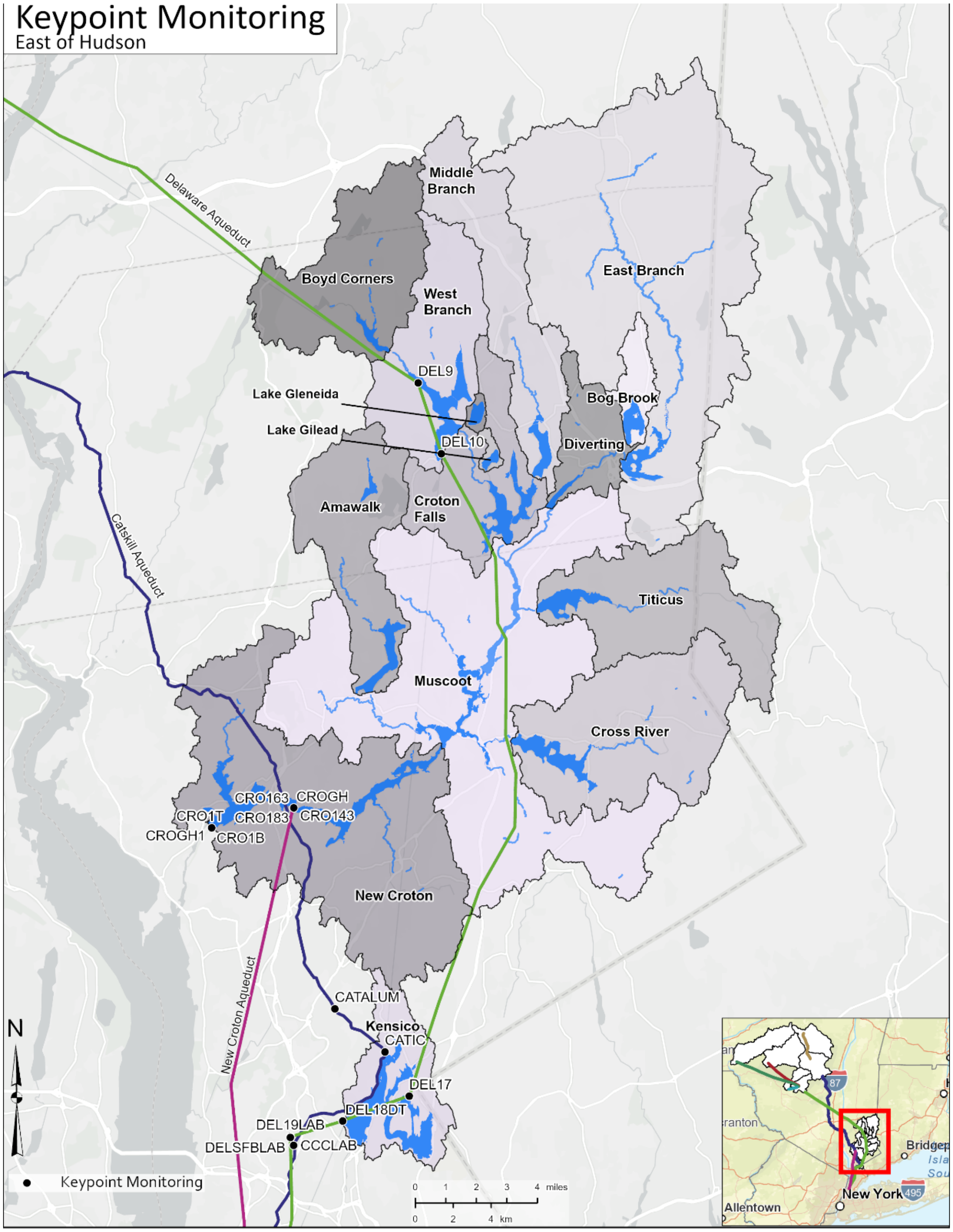
Appendix Figure 4 Catskill System stream monitoring sites [see WWQMP (DEP 2018) for detailed maps].



Appendix Figure 5 EOH stream monitoring sites [see WWQMP (DEP 2018) for detailed maps].



Appendix Figure 6 WOH aqueduct keypoint monitoring sites [see WWQMP (DEP 2018) for detailed maps].



Appendix Figure 7 EOH aqueduct keypoint monitoring sites [see WWQMP (DEP 2018) for detailed maps].

Appendix F. Monthly Coliform-Restricted Calculations for Non-Terminal Reservoirs

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
Amawalk	A (2400, 5000)	Apr-21	0	0	No Samples	
		May-21	0	0	No Samples	
		Jun-21	0	0	No Samples	
		Jul-21	0	0	No Samples	
		Aug-21	0	0	No Samples	
		Sep-21	5	0	E120	0
		Oct-21	5	0	E60	0
		Nov-21	0	0	No Samples	
Bog Brook	AA (50, 240).	Apr-21	0	0	No Samples	
		May-21	0	0	No Samples	
		Jun-21	0	0	No Samples	
		Jul-21	0	0	No Samples	
		Aug-21	0	0	No Samples	
		Sep-21	5	0	E40	0
		Oct-21	5	0	E20	0
		Nov-21	0	0	No Samples	
Boyd Corners	AA (50, 240)	Apr-21	6	0	>=E20	0
		May-21	7	0	E20	0
		Jun-21	6	0	<20	0
		Jul-21	6	0	E20	17
		Aug-21	5	0	<20	0
		Sep-21	6	0	E80	0
		Oct-21	6	0	E80	17
		Nov-21	7	0	E60	14
Croton Falls	A/AA (50, 240).	Apr-21	8	0	E10	0
		May-21	8	0	E15	0
		Jun-21	8	0	E20	0
		Jul-21	8	0	>=E10	12
		Aug-21	8	0	>=E50	12

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
		Sep-21	8	0	E100	38
		Oct-21	11	0	E50	0
		Nov-21	8	0	E50	0
Cross River	A/AA (50, 240)	Apr-21	6	0	E5	0
		May-21	6	0	E18	0
		Jun-21	6	0	E20	0
		Jul-21	6	0	E20	0
		Aug-21	6	0	E40	0
		Sep-21	6	0	E20	0
		Oct-21	6	0	E50	0
		Nov-21	6	0	E150	17
Diverting	AA (50, 240)	Apr-21	0	0	No Samples	
		May-21	0	0	No Samples	
		Jun-21	0	0	No Samples	
		Jul-21	0	0	No Samples	
		Aug-21	0	0	No Samples	
		Sep-21	5	0	>=490	100
		Oct-21	5	0	E700	80
		Nov-21	5	0	E400	80
East Branch	AA (50, 240).	Apr-21	0	0	No Samples	
		May-21	0	0	No Samples	
		Jun-21	0	0	No Samples	
		Jul-21	0	0	No Samples	
		Aug-21	0	0	No Samples	
		Sep-21	6	0	E110	17
		Oct-21	6	0	E110	17
		Nov-21	0	0	No Samples	
Lake Gilead	A (2400, 5000)	Apr-21	0	0	No Samples	
		May-21	0	0	No Samples	
		Jun-21	0	0	No Samples	
		Jul-21	0	0	No Samples	
		Aug-21	0	0	No Samples	

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF	Median Total Coliform (coliforms 100mL^{-1})	Percentage > Standard
		Sep-21	5	0	E120	0
		Oct-21	5	0	<20	0
		Nov-21	0	0	No Samples	
Lake Gleneida	AA (50, 240)	Apr-21	0	0	No Samples	
		May-21	0	0	No Samples	
		Jun-21	0	0	No Samples	
		Jul-21	0	0	No Samples	
		Aug-21	0	0	No Samples	
		Sep-21	0	0	No Samples	
		Oct-21	5	0	<20	0
		Nov-21	0	0	No Samples	
Kirk Lake	B (2400, 5000)	Apr-21	0	0	No Samples	
		May-21	0	0	No Samples	
		Jun-21	0	0	No Samples	
		Jul-21	0	0	No Samples	
		Aug-21	0	0	No Samples	
		Sep-21	5	0	E200	0
		Oct-21	5	0	E20	0
		Nov-21	0	0	No Samples	
Muscoot	A (2400, 5000).	Apr-21	0	0	No Samples	
		May-21	0	0	No Samples	
		Jun-21	0	0	No Samples	
		Jul-21	6	0	>=E105	0
		Aug-21	6	0	>=E80	0
		Sep-21	6	0	E110	0
		Oct-21	6	0	E60	0
		Nov-21	7	0	E380	0
Middle Branch	A (2400, 5000)	Apr-21	0	0	No Samples	
		May-21	0	0	No Samples	
		Jun-21	0	0	No Samples	
		Jul-21	0	0	No Samples	
		Aug-21	0	0	No Samples	

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
		Sep-21	5	0	E100	0
		Oct-21	5	0	E800	0
		Nov-21	5	0	E100	0
Titicus	AA (50, 240)	Apr-21	0	0	No Samples	
		May-21	0	0	No Samples	
		Jun-21	0	0	No Samples	
		Jul-21	0	0	No Samples	
		Aug-21	0	0	No Samples	
		Sep-21	5	0	E40	40
		Oct-21	5	0	E60	0
		Nov-21	0	0	No Samples	
Cannonsville	A/AA (50, 240)	Apr-21	15	0	E4	0
		May-21	15	0	E12	7
		Jun-21	15	0	<10	0
		Jul-21	15	0	>=E50	20
		Aug-21	15	0	E40	7
		Sep-21	15	0	5	0
		Oct-21	14	0	20	14
		Nov-21	15	0	E300	60
Pepacton	A/AA (50, 240).	Apr-21	16	0	E2	0
		May-21	16	0	E2	0
		Jun-21	16	0	>=E2	0
		Jul-21	16	0	8	12
		Aug-21	16	0	E10	6
		Sep-21	16	0	>=E30	6
		Oct-21	16	0	E50	0
		Nov-21	16	0	E60	12
Neversink	AA (50, 240)	Apr-21	13	0	E1	0
		May-21	13	0	E4	0
		Jun-21	13	0	E12	0
		Jul-21	13	0	130	31
		Aug-21	13	0	<20	0
		Sep-21	12	0	<20	0

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
		Oct-21	12	0	E10	0
		Nov-21	13	0	E50	0
Schoharie	AA (50, 240).	Apr-21	0	0	No Samples	
		May-21	12	0	E20	0
		Jun-21	12	0	E30	17
		Jul-21	12	0	>=1700	100
		Aug-21	12	0	E100	25
		Sep-21	11	0	E300	64
		Oct-21	12	0	E145	17
		Nov-21	12	0	280	67

Sampling Note: All other nonterminal reservoirs not listed were not sampled due to COVID-19 pandemic. Analysis Note: The total of the N and CONF for each table row represents the total number samples analyzed. CONF indicates the number of samples with confluent growth where counts are indeterminate. Median calculations are based on "N" and exclude these CONF samples.
Notes: The reservoir class is defined by 6 NYCRR Chapter X, Subchapter B. For those reservoirs that have dual designations, the higher standard was applied. 6NYCRR Part 703 requires a minimum of five samples per month. Both the median value and >20% of the total coliform counts for a given month need to exceed the stated value for a reservoir to exceed the standard. Codes associated with data reporting include the following: E: Estimated count based on non-ideal plate; >=: plate count may be biased low based on heavy growth; >: observed count replaced with dilution-based value; <: below detection limit.

Appendix G. Phosphorus Restricted Basin Assessment Methodology

A phosphorus restricted basin is defined in the New York City Watershed Regulations, amended April 4, 2010, as "(i) the drainage basin of a source water reservoir in which the phosphorus load to the reservoir results in the phosphorus concentration in the reservoir exceeding 15 micrograms per liter, or (ii) the drainage basin of a reservoir other than a source water reservoir or of a controlled lake in which the phosphorus load to the reservoir or controlled lake results in the phosphorus concentration in the reservoir or controlled lake exceeding 20 micrograms per liter in both instances as determined by the Department pursuant to its annual review conducted under §18-48 (e) of Subchapter D" (DEP 2010). The phosphorus restricted designation prohibits new or expanded wastewater treatment plants with surface discharges in the reservoir basin. The list of phosphorus restricted basins is updated annually in the Watershed Water Quality Annual Report.

A summary of the methodology used in the phosphorus restricted analysis will be given here; the complete description can be found in *A Methodology for Determining Phosphorus Restricted Basins* (DEP 1997). The data utilized in the analysis are from the routine limnological monitoring of the reservoirs during the growing season, which is defined as May 1 through October 31. Any recorded concentration below the analytical limit of detection is set equal to half the detection limit to conform to earlier analyses following the prescribed methodology. The detection limit for DEP measurements of total phosphorus is assessed each year by the DEP laboratories, and typically ranges between 2-5 $\mu g\ L^{-1}$. The phosphorus concentration data for the reservoirs approaches a lognormal distribution; therefore, a geometric mean is used to characterize the annual phosphorus concentrations. Appendix Table 1 provides the annual geometric mean for the past six years.

The five most recent annual geometric means are averaged arithmetically, and this average constitutes one assessment. This "running average" method weights each year equally, reducing the effects of unusual hydrological events or phosphorus loading, while maintaining an accurate assessment of the current conditions in the reservoir. Should any reservoir have less than three surveys during a growing season, the annual average may or may not be representative of the reservoir, and the data for the under-sampled year are removed from the analysis. In addition, each five-year assessment must incorporate at least three years of data.

To provide some statistical assurance that the five-year arithmetic mean is representative of a basin's phosphorus status, given the interannual variability, the five-year mean plus the standard error of the five-year mean is compared to the New York State guidance value of 20 $\mu g\ L^{-1}$ (15 $\mu g\ L^{-1}$ for potential source waters). A basin is considered **unrestricted** if the five-year mean plus standard error is below the guidance value of 20 $\mu g\ L^{-1}$ (15 $\mu g\ L^{-1}$ for potential source waters). A basin is considered phosphorus **restricted** if the five-year mean plus standard error is equal to or greater than 20 $\mu g\ L^{-1}$ (15 $\mu g\ L^{-1}$ for potential source waters), unless the Department, using its best professional judgment, determines that the phosphorus restricted designation is due to an unusual and unpredictable event unlikely to occur in the future. A reservoir basin designation, as phosphorus restricted or unrestricted, may change through time based on the outcome of this annual assessment. However, a basin must have two consecutive assessments (i.e., two years in a row) that result in the new designation to change the designation.

Appendix G. Table 1 Geometric Mean Total Phosphorus Data used in the Phosphorus Restricted Assessments based on reservoir samples taken during the growing season (May 1 - Oct. 31).

Reservoir Basin	2016 $\mu g\ L^{-1}$	2017 $\mu g\ L^{-1}$	2018 $\mu g\ L^{-1}$	2019 $\mu g\ L^{-1}$	2020 $\mu g\ L^{-1}$	2021 $\mu g\ L^{-1}$
Non-Source Waters (Delaware System)						
Cannonsville Reservoir	17.0	15.4	14.3	15.6	14.3	15.3
Pepacton Reservoir	10.8	10.3	10.1	9.8	9.4	9.4
Neversink Reservoir	8.0	7.3	6.5	6.5	6.8	7.0
Non-Source Waters (Catskill System)						
Schoharie Reservoir	12.5	12.2	14.9	12.3	9.9	18.1
Non-Source Waters (Croton System)						
Amawalk Reservoir	29.8	26.3	25.4	17.3	NS	NS
Bog Brook Reservoir	28.4	27.8	19.4	14.1	NS	NS
Boyd Corners Reservoir	11.3	15.1	14.0	11.5	11.2	14.0
Diverting Reservoir	37.4	31.6	28.7	23.2	NS	43.3
East Branch Reservoir	23.5	25.1	27.5	21.6	NS	NS
Middle Branch Reservoir	34.1	28.4	29.4	18.3	NS	NS
Muscoot Reservoir	30.6	36.5	30.6	28.9	NS	40.2
Titicus Reservoir	23.7	25.2	25.0	23.1	NS	NS
Lake Gleneida	27.0	25.5	21.5	14.9	NS	NS
Lake Gilead	34.6	33.6	32.7	20.5	NS	NS
Kirk Lake	27.3	23.3	20.9	18.4	NS	NS
Source Waters (all systems)						
Ashokan West Basin	12.6	8.2	8.3	7.8	7.8	9.9
Ashokan East Basin	10.3	8.1	7.6	7.4	7.0	7.0
Cross River Reservoir	19.0	23.2	21.1	16.8	19.7	20.9
Croton Falls Reservoir	18.0	23.2	21.5	15.3	21.5	20.5
Kensico Reservoir	7.6	8.8	7.9	6.8	7.7	8.4
New Croton Reservoir	22.1	22.5	26.2	19.5	NS	NS
Rondout Reservoir	10.0	9.0	8.1	7.8	7.3	8.1
West Branch Reservoir	13.4	14.2	11.8	9.5	10.0	11.3

NS=Insufficient Data:Total phosphorus sampling was reduced in 2020 and 2021 because of COVID-19 pandemic sampling reductions. Years with no samples or fewer than three surveys are not included in the calculation of the geometric mean.

Appendix H. Comparison of Reservoir Water Quality Results to Benchmarks

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
Non-Source Waters (Delaware System)								
Cannonsville Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	118	50	42	NA	18	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	119	10	8	NA	8	
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	119	2	2	NA	4	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	119	1	1	0.3	0.26	KM
	Ammonia (as N) (mg L^{-1})	0.1	119	0	0	0.05	0.02	ROS
	Fecal Coliform (coliforms mL^{-1})	20	115	11	10	NA	9	KM
	Turbidity (NTU)	5	119	12	10	NA	3.5	
	Total suspended solids (mg L^{-1})	8	48	1	2	5	2.2	KM
	Alkalinity (mg L^{-1})	NA	18	0	0	>=10	17.6	
	Dissolved Organic Carbon (mg L^{-1})	4	118	2	2	3	2.2	
	Sulfate (as SO4) (mg L^{-1})	15	18	0	0	10	4.0	
	pH (SU)	6.5-8.5	119	15	13	NA	7.25	
	Dissolved sodium (mg L^{-1})	16	18	0	0	3	7.7	
	Chloride (mg L^{-1})	12	18	8	44	8	11.6	
	Total dissolved solids (mg L^{-1})[3]	50	119	117	98	40	62	
	Chlorophyll *a* (µg L^{-1})	12	40	2	5	7	6.3	
	Total phytoplankton (ASU mL^{-1})	2000	56	0	0	NA	459	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	56	4	7	NA	228	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	56	0	0	NA	72	KM
Pepacton Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	128	17	13	NA	10	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	128	1	1	NA	6	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	128	0	0	NA	3	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	128	0	0	0.3	0.12	KM
	Ammonia (as N) (mg L^{-1})	0.1	128	0	0	0.05	0.01	ROS
	Fecal Coliform (coliforms mL^{-1})	20	126	1	1	NA	3	ROS
	Turbidity (NTU)	5	128	4	3	NA	1.6	
	Total suspended solids (mg L^{-1})	8	64	0	0	5	0.9	ROS
	Alkalinity (mg L^{-1})	NA	21	0	0	>=10	13.7	
	Dissolved Organic Carbon (mg L^{-1})	4	128	0	0	3	1.7	
	Sulfate (as SO4) (mg L^{-1})	15	21	0	0	10	3.0	
	pH (SU)	6.5-8.5	128	19	15	NA	7.15	
	Dissolved sodium (mg L^{-1})	16	21	0	0	3	5.2	

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Chloride (mg L^{-1})	12	21	0	0	8	8.3	
	Total dissolved solids (mg L^{-1})[3]	50	128	12	9	40	47	
	Chlorophyll *a* (µg L^{-1})	12	40	1	2	7	3.8	
	Total phytoplankton (ASU mL^{-1})	2000	64	1	2	NA	251	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	64	1	2	NA	113	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	64	0	0	NA	44	KM
Neversink Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	77	0	0	NA	7	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	78	0	0	NA	4	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	78	0	0	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	78	0	0	0.3	0.16	KM
	Ammonia (as N) (mg L^{-1})	0.1	78	0	0	0.05	0.01	ROS
	Fecal Coliform (coliforms mL^{-1})	20	78	3	4	NA	5	KM
	Turbidity (NTU)	5	110	3	3	NA	1.5	
	Total suspended solids (mg L^{-1})	8	24	0	0	5	0.9	ROS
	Alkalinity (mg L^{-1})	NA	12	0	0	>=10	3.5	
	Dissolved Organic Carbon (mg L^{-1})	4	109	2	2	3	2.4	
	Sulfate (as SO4) (mg L^{-1})	15	12	0	0	10	2.1	
	pH (SU)	6.5-8.5	78	63	81	NA	6.22	
	Dissolved sodium (mg L^{-1})	16	12	0	0	3	2.1	
	Chloride (mg L^{-1})	12	12	0	0	8	3.4	
	Total dissolved solids (mg L^{-1})[3]	50	110	0	0	40	19	
	Chlorophyll *a* (µg L^{-1})	12	32	0	0	7	3.6	
	Total phytoplankton (ASU mL^{-1})	2000	48	0	0	NA	160	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	48	0	0	NA	63	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	48	0	0	NA	41	KM
Non-Source Waters (Catskill System)								
Schoharie Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	83	51	61	NA	24	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	56	4	7	NA	9	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	53	1	2	NA	5	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	53	0	0	0.3	0.10	KM
	Ammonia (as N) (mg L^{-1})	0.1	53	1	2	0.05	<0.02	>80%
	Fecal Coliform (coliforms mL^{-1})	20	82	37	45	NA	35	KM
	Turbidity (NTU)	5	83	71	86	NA	22.0	
	Total suspended solids (mg L^{-1})	8	83	34	41	5	11.4	
	Alkalinity (mg L^{-1})	NA	9	0	0	>=10	18.6	
	Dissolved Organic Carbon (mg L^{-1})	4	83	7	8	3	3.2	
	Sulfate (as SO4) (mg L^{-1})	15	9	0	0	10	2.6	

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	pH (SU)	6.5-8.5	71	2	3	NA	7.05	
	Dissolved sodium (mg L^{-1})	16	9	0	0	3	5.3	
	Chloride (mg L^{-1})	12	9	0	0	8	7.5	
	Total dissolved solids (mg L^{-1})[3]	50	83	21	25	40	46	
	Chlorophyll *a* (µg L^{-1})	12	28	1	4	7	2.3	
	Total phytoplankton (ASU mL^{-1})	2000	42	0	0	NA	107	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	42	0	0	NA	74	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	42	0	0	NA	22	KM
Non-Source Waters (Croton System)								
Amawalk Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	10	10	100	NA	36	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		
	Fecal Coliform (coliforms mL^{-1})	20	10	2	20	NA	14	
	Turbidity (NTU)	5	0			NA		
	Total suspended solids (mg L^{-1})	8	0			5		
	Alkalinity (mg L^{-1})	NA	0			>=40		
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	pH (SU)	6.5-8.5	10	0	0	NA	7.60	
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	40	0			30		
	Total Dissolved Solids	175	0			150		
	Chlorophyll *a* (µg L^{-1})	15	0			10		
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		
Bog Brook Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	4	3	75	NA	40	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		
	Fecal Coliform (coliforms mL^{-1})	20	10	0	0	NA	2	KM
	Turbidity (NTU)	5	0			NA		

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Total suspended solids (mg L^{-1})	8	0			5		
	Alkalinity (mg L^{-1})	NA	0			>=40		
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	pH (SU)	6.5-8.5	6	1	17	NA	7.59	
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	40	0			30		
	Total Dissolved Solids	175	0			150		
	Chlorophyll *a* (µg L^{-1})	15	0			10		
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		
Boyd Corners Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	17	7	41	NA	15	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	17	0	0	NA	6	
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	17	0	0	NA	2	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	17	0	0	0.3	0.03	KM
	Ammonia (as N) (mg L^{-1})	0.1	17	0	0	0.05	0.02	ROS
	Fecal Coliform (coliforms mL^{-1})	20	49	1	2	NA	2	ROS
	Turbidity (NTU)	5	17	0	0	NA	1.0	
	Total suspended solids (mg L^{-1})	8	7	0	0	5	1.3	KM
	Alkalinity (mg L^{-1})	NA	7	0	0	>=40	34.9	
	Dissolved Organic Carbon (mg L^{-1})	7	17	0	0	6	4.6	
	Sulfate (as SO4) (mg L^{-1})	25	7	0	0	15	5.7	
	pH (SU)	6.5-8.5	18	0	0	NA	7.12	
	Dissolved sodium (mg L^{-1})	20	7	5	71	15	23.6	
	Chloride (mg L^{-1})	40	7	5	71	30	38.8	
	Total dissolved solids (mg L^{-1})[3]	175	17	0	0	150	140	
	Chlorophyll *a* (µg L^{-1})	15	8	0	0	10	6.5	
	Total phytoplankton (ASU mL^{-1})	2000	8	0	0	NA	578	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	8	1	12	NA	415	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	8	0	0	NA	115	
Diverting Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	17	17	100	NA	43	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	7	0	0	NA	11	
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	7	0	0	NA	3	
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		
	Fecal Coliform (coliforms mL^{-1})	20	15	4	27	NA	13	
	Turbidity (NTU)	5	7	1	14	NA	3.9	
	Total suspended solids (mg L^{-1})	8	0			5		
	Alkalinity (mg L^{-1})	NA	0			>=40		
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	pH (SU)	6.5-8.5	18	1	6	NA	7.52	
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	40	0			30		
	Total Dissolved Solids	175	0			150		
	Chlorophyll *a* (µg L^{-1})	15	0			10		
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		
East Branch Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	6	6	100	NA	48	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		
	Fecal Coliform (coliforms mL^{-1})	20	12	0	0	NA	4	KM
	Turbidity (NTU)	5	0			NA		
	Total suspended solids (mg L^{-1})	8	0			5		
	Alkalinity (mg L^{-1})	NA	0			>=40		
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	pH (SU)	6.5-8.5	6	0	0	NA	7.06	
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	40	0			30		
	Total Dissolved Solids	175	0			150		
	Chlorophyll *a* (µg L^{-1})	15	0			10		
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Total Phosphorus (as P) (µg L^{-1})	15	15	15	100	NA	42	

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
Middle Branch Reservoir	Total Dissolved Phosphorus (as P) ($\mu g\ L^{-1}$)	15	0			NA		
	Soluble Reactive Phosphorus (as P) ($\mu g\ L^{-1}$)	15	0			NA		
	Nitrate+Nitrite (as N) ($mg\ L^{-1}$)	0.5	0			0.3		
	Ammonia (as N) ($mg\ L^{-1}$)	0.1	0			0.05		
	Fecal Coliform (coliforms mL^{-1})	20	15	0	0	NA	3	KM
	Turbidity (NTU)	5	0			NA		
	Total suspended solids ($mg\ L^{-1}$)	8	0			5		
	Alkalinity ($mg\ L^{-1}$)	NA	0			>=40		
	Dissolved Organic Carbon ($mg\ L^{-1}$)	7	0			6		
	Sulfate (as SO4) ($mg\ L^{-1}$)	25	0			15		
	pH (SU)	6.5-8.5	15	1	7	NA	7.28	
	Dissolved sodium ($mg\ L^{-1}$)	20	0			15		
	Chloride ($mg\ L^{-1}$)	40	0			30		
	Total Dissolved Solids	175	0			150		
	Chlorophyll *a* ($\mu g\ L^{-1}$)	15	0			10		
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		
Muscoot Reservoir	Total Phosphorus (as P) ($\mu g\ L^{-1}$)	15	31	31	100	NA	46	
	Total Dissolved Phosphorus (as P) ($\mu g\ L^{-1}$)	15	12	2	17	NA	30	
	Soluble Reactive Phosphorus (as P) ($\mu g\ L^{-1}$)	15	12	1	8	NA	8	KM
	Nitrate+Nitrite (as N) ($mg\ L^{-1}$)	0.5	0			0.3		
	Ammonia (as N) ($mg\ L^{-1}$)	0.1	0			0.05		
	Fecal Coliform (coliforms mL^{-1})	20	31	6	19	NA	13	
	Turbidity (NTU)	5	18	4	22	NA	3.4	
	Total suspended solids ($mg\ L^{-1}$)	8	0			5		
	Alkalinity ($mg\ L^{-1}$)	NA	0			>=40		
	Dissolved Organic Carbon ($mg\ L^{-1}$)	7	0			6		
	Sulfate (as SO4) ($mg\ L^{-1}$)	25	0			15		
	pH (SU)	6.5-8.5	26	0	0	NA	7.38	
	Dissolved sodium ($mg\ L^{-1}$)	20	0			15		
	Chloride ($mg\ L^{-1}$)	40	0			30		
	Total dissolved solids ($mg\ L^{-1}$)[3]	175	6	6	100	150	306	
	Chlorophyll *a* ($\mu g\ L^{-1}$)	15	4	4	100	10	42.5	
	Total phytoplankton (ASU mL^{-1})	2000	13	1	8	NA	1068	

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Dominant phytoplankton genus (ASU mL^{-1})	1000	13	1	8	NA	606	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	13	1	8	NA	222	
Titicus Reservoir	Total Phosphorus (as P) ($\mu g\ L^{-1}$)	15	10	9	90	NA	46	
	Total Dissolved Phosphorus (as P) ($\mu g\ L^{-1}$)	15	0			NA		
	Soluble Reactive Phosphorus (as P) ($\mu g\ L^{-1}$)	15	0			NA		
	Nitrate+Nitrite (as N) ($mg\ L^{-1}$)	0.5	0			0.3		
	Ammonia (as N) ($mg\ L^{-1}$)	0.1	0			0.05		
	Fecal Coliform (coliforms mL^{-1})	20	10	2	20	NA	8	KM
	Turbidity (NTU)	5	0			NA		
	Total suspended solids ($mg\ L^{-1}$)	8	0			5		
	Alkalinity ($mg\ L^{-1}$)	NA	0			>=40		
	Dissolved Organic Carbon ($mg\ L^{-1}$)	7	0			6		
	Sulfate (as SO4) ($mg\ L^{-1}$)	25	0			15		
	pH (SU)	6.5-8.5	10	1	10	NA	7.54	
	Dissolved sodium ($mg\ L^{-1}$)	20	0			15		
	Chloride ($mg\ L^{-1}$)	40	0			30		
	Total Dissolved Solids	175	0			150		
	Chlorophyll *a* ($\mu g\ L^{-1}$)	15	0			10		
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		
Lake Gleneida	Total Phosphorus (as P) ($\mu g\ L^{-1}$)	15	3	1	33	NA	34	
	Total Dissolved Phosphorus (as P) ($\mu g\ L^{-1}$)	15	0			NA		
	Soluble Reactive Phosphorus (as P) ($\mu g\ L^{-1}$)	15	0			NA		
	Nitrate+Nitrite (as N) ($mg\ L^{-1}$)	0.5	0			0.3		
	Ammonia (as N) ($mg\ L^{-1}$)	0.1	0			0.05		
	Fecal Coliform (coliforms mL^{-1})	20	5	0	0	NA	<1	>80%
	Turbidity (NTU)	5	0			NA		
	Total suspended solids ($mg\ L^{-1}$)	8	0			5		
	Alkalinity ($mg\ L^{-1}$)	NA	0			>=40		
	Dissolved Organic Carbon ($mg\ L^{-1}$)	7	0			6		
	Sulfate (as SO4) ($mg\ L^{-1}$)	25	0			15		
	pH (SU)	6.5-8.5	5	0	0	NA	7.14	
	Dissolved sodium ($mg\ L^{-1}$)	20	0			15		
	Chloride ($mg\ L^{-1}$)	40	0			30		

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Total Dissolved Solids	175	0			150		
	Chlorophyll *a* (µg L^{-1})	15	0			10		
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Total Phosphorus (as P) (µg L^{-1})	15	6	6	100	NA	99	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		
	Fecal Coliform (coliforms mL^{-1})	20	10	0	0	NA	6	KM
	Turbidity (NTU)	5	0			NA		
	Total suspended solids (mg L^{-1})	8	0			5		
	Alkalinity (mg L^{-1})	NA	0			>=40		
Lake Gilead	Dissolved Organic Carbon (mg L^{-1})	7	0			6		
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	pH (SU)	6.5-8.5	10	2	20	NA	7.17	
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	40	0			30		
	Total Dissolved Solids	175	0			150		
	Chlorophyll *a* (µg L^{-1})	15	0			10		
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Total Phosphorus (as P) (µg L^{-1})	15	2	2	100	NA	44	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		
Kirk Lake	Fecal Coliform (coliforms mL^{-1})	20	10	1	10	NA	21	KM
	Turbidity (NTU)	5	0			NA		
	Total suspended solids (mg L^{-1})	8	0			5		
	Alkalinity (mg L^{-1})	NA	0			>=40		
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		
	Sulfate (as SO4) (mg L^{-1})	25	0			15		

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	pH (SU)	6.5-8.5	10	0	0	NA	7.31	
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	40	0			30		
	Total Dissolved Solids	175	0			150		
	Chlorophyll *a* (µg L^{-1})	15	0			10		
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		
Source Waters (all system)								
Ashokan West Basin Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	77	25	32	NA	15	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	77	0	0	NA	5	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	77	0	0	NA	3	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	77	0	0	0.3	0.13	KM
	Ammonia (as N) (mg L^{-1})	0.1	77	0	0	0.05	<0.02	>80%
	Fecal Coliform (coliforms mL^{-1})	20	77	6	8	NA	8	KM
	Turbidity (NTU)	5	77	50	65	NA	16.4	
	Total suspended solids (mg L^{-1})	8	77	19	25	5	7.3	
	Alkalinity (mg L^{-1})	NA	18	0	0	>=10	11.8	
	Dissolved Organic Carbon (mg L^{-1})	4	76	0	0	3	2.0	
	Sulfate (as SO4) (mg L^{-1})	15	12	0	0	10	2.7	
	pH (SU)	6.5-8.5	57	17	30	NA	6.78	
	Dissolved sodium (mg L^{-1})	16	12	0	0	3	4.2	
	Chloride (mg L^{-1})	12	12	0	0	8	6.5	
	Total dissolved solids (mg L^{-1})[3]	50	77	1	1	40	36	
	Chlorophyll *a* (µg L^{-1})	12	24	0	0	7	2.9	
	Total phytoplankton (ASU mL^{-1})	2000	40	0	0	NA	133	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	40	0	0	NA	58	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	40	0	0	NA	33	KM
Ashokan East Basin Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	64	2	3	NA	9	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	63	0	0	NA	4	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	64	0	0	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	64	0	0	0.3	0.04	ROS
	Ammonia (as N) (mg L^{-1})	0.1	63	0	0	0.05	<0.02	>80%
	Fecal Coliform (coliforms mL^{-1})	20	64	0	0	NA	1	ROS
	Turbidity (NTU)	5	64	8	12	NA	3.1	
	Total suspended solids (mg L^{-1})	8	64	0	0	5	1.9	KM
	Alkalinity (mg L^{-1})	NA	11	0	0	>=10	12.8	

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Dissolved Organic Carbon (mg L^{-1})	4	64	0	0	3	1.9	
	Sulfate (as SO4) (mg L^{-1})	15	9	0	0	10	2.8	
	pH (SU)	6.5-8.5	64	13	20	NA	7.04	
	Dissolved sodium (mg L^{-1})	16	9	0	0	3	4.9	
	Chloride (mg L^{-1})	12	9	0	0	8	7.5	
	Total dissolved solids (mg L^{-1})[3]	50	64	0	0	40	39	
	Chlorophyll *a* (µg L^{-1})	12	24	0	0	7	2.7	
	Total phytoplankton (ASU mL^{-1})	2000	40	0	0	NA	227	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	40	0	0	NA	90	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	40	0	0	NA	52	KM
Rondout Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	80	2	2	NA	9	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	56	0	0	NA	4	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	56	0	0	NA	2	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	56	0	0	0.3	0.18	KM
	Ammonia (as N) (mg L^{-1})	0.1	54	0	0	0.05	<0.02	>80%
	Fecal Coliform (coliforms mL^{-1})	20	80	0	0	NA	3	KM
	Turbidity (NTU)	5	80	0	0	NA	0.9	
	Total suspended solids (mg L^{-1})	8	32	0	0	5	0.8	ROS
	Alkalinity (mg L^{-1})	NA	12	0	0	>=10	9.8	
	Dissolved Organic Carbon (mg L^{-1})	4	56	0	0	3	2.0	
	Sulfate (as SO4) (mg L^{-1})	15	12	0	0	10	3.1	
	pH (SU)	6.5-8.5	80	16	20	NA	6.84	
	Dissolved sodium (mg L^{-1})	16	12	0	0	3	5.1	
	Chloride (mg L^{-1})	12	12	0	0	8	8.0	
	Total dissolved solids (mg L^{-1})[3]	50	80	0	0	40	41	
	Chlorophyll *a* (µg L^{-1})	12	24	0	0	7	3.6	
	Total phytoplankton (ASU mL^{-1})	2000	48	0	0	NA	221	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	48	0	0	NA	87	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	48	0	0	NA	52	KM
West Branch Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	72	14	19	NA	13	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	72	0	0	NA	5	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	72	0	0	NA	<2	>80%
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	72	0	0	0.3	0.13	KM
	Ammonia (as N) (mg L^{-1})	0.1	72	1	1	0.05	0.01	ROS
	Fecal Coliform (coliforms mL^{-1})	20	72	1	1	NA	3	KM
	Turbidity (NTU)	5	72	0	0	NA	1.1	
	Total suspended solids (mg L^{-1})	8	9	0	0	5	1.0	ROS

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Alkalinity (mg L^{-1})	NA	15	0	0	>=10	18.6	
	Dissolved Organic Carbon (mg L^{-1})	4	72	3	4	3	2.5	
	Sulfate (as SO4) (mg L^{-1})	15	15	0	0	10	4.2	
	pH (SU)	6.5-8.5	72	10	14	NA	6.87	
	Dissolved sodium (mg L^{-1})	16	15	1	7	3	10.2	
	Chloride (mg L^{-1})	12	15	9	60	8	16.9	
	Total dissolved solids (mg L^{-1})[3]	50	72	45	62	40	65	
	Chlorophyll *a* (µg L^{-1})	12	32	2	6	7	5.0	
	Total phytoplankton (ASU mL^{-1})	2000	43	0	0	NA	359	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	43	1	2	NA	233	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	43	0	0	NA	74	KM
Cross River Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	48	43	90	NA	25	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	24	2	8	NA	10	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	24	0	0	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	24	0	0	0.3	0.10	ROS
	Ammonia (as N) (mg L^{-1})	0.1	24	5	21	0.05	0.10	ROS
	Fecal Coliform (coliforms mL^{-1})	20	48	3	6	NA	5	KM
	Turbidity (NTU)	5	48	4	8	NA	2.5	
	Total suspended solids (mg L^{-1})	8	9	0	0	5	2.1	
	Alkalinity (mg L^{-1})	NA	9	0	0	>=40	52.8	
	Dissolved Organic Carbon (mg L^{-1})	7	24	0	0	6	3.8	
	Sulfate (as SO4) (mg L^{-1})	25	9	0	0	15	7.6	
	pH (SU)	6.5-8.5	42	8	19	NA	7.41	
	Dissolved sodium (mg L^{-1})	20	9	7	78	15	20.7	
	Chloride (mg L^{-1})	40	9	7	78	30	39.7	
	Total dissolved solids (mg L^{-1})[3]	175	48	2	4	150	167	
	Chlorophyll *a* (µg L^{-1})	15	16	1	6	10	8.5	
	Total phytoplankton (ASU mL^{-1})	2000	16	1	6	NA	638	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	16	1	6	NA	359	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	16	0	0	NA	139	KM
Croton Falls Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	64	42	66	NA	23	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	64	2	3	NA	7	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	64	0	0	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	64	10	16	0.3	0.31	KM
	Ammonia (as N) (mg L^{-1})	0.1	64	8	12	0.05	0.05	KM
	Fecal Coliform (coliforms mL^{-1})	20	67	0	0	NA	2	ROS
	Turbidity (NTU)	5	67	5	7	NA	3.0	

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Total suspended solids (mg L^{-1})	8	9	0	0	5	2.1	KM
	Alkalinity (mg L^{-1})	NA	18	0	0	>=40	68.2	
	Dissolved Organic Carbon (mg L^{-1})	7	64	0	0	6	3.9	
	Sulfate (as SO4) (mg L^{-1})	25	18	0	0	15	9.6	
	pH (SU)	6.5-8.5	67	14	21	NA	7.78	
	Dissolved sodium (mg L^{-1})	20	18	18	100	15	40.0	
	Chloride (mg L^{-1})	40	18	18	100	30	70.8	
	Total dissolved solids (mg L^{-1})[3]	175	67	65	97	150	284	
	Chlorophyll *a* (µg L^{-1})	15	24	9	38	10	15.9	
	Total phytoplankton (ASU mL^{-1})	2000	27	2	7	NA	874	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	27	3	11	NA	494	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	27	0	0	NA	205	KM
Kensico Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	173	1	1	NA	9	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	173	0	0	NA	5	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	173	0	0	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	173	0	0	0.3	0.11	KM
	Ammonia (as N) (mg L^{-1})	0.1	173	0	0	0.05	0.01	ROS
	Fecal Coliform (coliforms mL^{-1})	20	172	0	0	NA	1	ROS
	Turbidity (NTU)	5	173	0	0	NA	0.8	
	Total suspended solids (mg L^{-1})	8	56	0	0	5	<1.0	>80%
	Alkalinity (mg L^{-1})	NA	24	0	0	>=10	13.5	
	Dissolved Organic Carbon (mg L^{-1})	4	173	1	1	3	2.0	
	Sulfate (as SO4) (mg L^{-1})	15	24	0	0	10	3.8	
	pH (SU)	6.5-8.5	173	36	21	NA	6.89	
	Dissolved sodium (mg L^{-1})	16	24	0	0	3	7.1	
	Chloride (mg L^{-1})	12	24	11	46	8	11.9	
	Total dissolved solids (mg L^{-1})[3]	50	173	134	77	40	53	
	Chlorophyll *a* (µg L^{-1})	12	56	0	0	7	2.2	
	Total phytoplankton (ASU mL^{-1})	2000	72	0	0	NA	295	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	72	0	0	NA	158	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	72	0	0	NA	71	KM
New Croton Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	63	61	97	NA	36	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	63	14	22	NA	18	
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	60	4	7	NA	6	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	60	4	7	0.3	0.19	KM
	Ammonia (as N) (mg L^{-1})	0.1	63	14	22	0.05	0.14	KM
	Fecal Coliform (coliforms mL^{-1})	20	112	11	10	NA	7	KM

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Turbidity (NTU)	5	113	2	2	NA	1.8	
	Total suspended solids (mg L^{-1})	8	21	0	0	5	1.8	KM
	Alkalinity (mg L^{-1})	NA	10	0	0	>=40	68.1	
	Dissolved Organic Carbon (mg L^{-1})	7	113	0	0	6	3.9	
	Sulfate (as SO4) (mg L^{-1})	25	9	0	0	15	8.5	
	pH (SU)	6.5-8.5	115	8	7	NA	7.51	
	Dissolved sodium (mg L^{-1})	20	8	8	100	15	36.3	
	Chloride (mg L^{-1})	40	9	9	100	30	64.4	
	Total dissolved solids (mg L^{-1})[3]	175	115	115	100	150	256	
	Chlorophyll *a* (µg L^{-1})	15	20	1	5	10	9.2	
	Total phytoplankton (ASU mL^{-1})	2000	83	0	0	NA	356	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	83	0	0	NA	172	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	83	0	0	NA	88	KM

Reservoirs included in this analysis are required by WWQMP as per 3.2.1. Status of Stream Water Quality and 5.8. Croton System Streams – Water Quality Status

[1]Means for data containing non-detects were estimated using techniques recommended in Helsel (2005) using an R program developed for U.S. Environmental Protection Agency (Bolks et al. 2014).

[2]Note indicates which analysis method was used to determine the statistics when there were censored data. KM indicates Kaplan-Meier, ROS indicates robust regression on order statistics, and >80% indicates that the mean could not be calculated for the following reasons: 1) the data contains greater than 80% censored data or 2) there are 5 or fewer samples with greater than 50% censored. In these cases, the detection limit, preceded by "<", is reported. A blank cell in the Note column indicates that the 2021 mean was calculated as the standard arithmetic average.

[3]Total dissolved solids estimated from specific conductivity according to the USGS in van der Leeden et al. (1990)

Appendix I. Comparison of Stream Water Quality Results to Benchmarks

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
Catskill System - Ashokan Basin								
E10I (Bushkill at West Shokan)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.08	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	10	83	NA	8.4	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.1	KM
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	2.9	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.6	
	Chloride (mg L^{-1})	50	12	0	0	10	3.3	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	23	
E16I (Esopus Brook at Coldbrook)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	11	0	0	0.4	0.15	KM
	Ammonia (as N) (mg L^{-1})	0.25	11	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	11	1	9	NA	13.9	
	Dissolved Organic Carbon (mg L^{-1})	25	11	0	0	9	1.7	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	2.8	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	4.9	
	Chloride (mg L^{-1})	50	11	0	0	10	7.0	
	Total dissolved solids (mg L^{-1})[3]	50	11	2	18	40	38	
E5 (Esopus Creek at Allaben)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	4	0	0	0.4	0.09	KM
	Ammonia (as N) (mg L^{-1})	0.25	4	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	4	0	0	NA	12.9	
	Dissolved Organic Carbon (mg L^{-1})	25	4	0	0	9	1.4	
	Sulfate (as SO4) (mg L^{-1})	15	1	0	0	10	2.8	
	Dissolved sodium (mg L^{-1})	10	1	0	0	5	3.1	
	Chloride (mg L^{-1})	50	4	0	0	10	5.2	
	Total dissolved solids (mg L^{-1})[3]	50	4	0	0	40	33	
Catskill System - Schoharie Basin								
S5I (Schoharie Creek at Prattsville)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.17	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	22.2	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	2.4	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.4	
	Dissolved sodium (mg L^{-1})	10	4	1	25	5	8.3	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Chloride (mg L^{-1})	50	12	0	0	10	10.5	
	Total dissolved solids (mg L^{-1})[3]	50	12	9	75	40	57	
S6I (Bear Kill at Hardenburgh Falls)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.31	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	28.2	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	3.0	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	4.3	
	Dissolved sodium (mg L^{-1})	10	4	2	50	5	14.6	
	Chloride (mg L^{-1})	50	12	0	0	10	16.4	
	Total dissolved solids (mg L^{-1})[3]	50	12	12	100	40	79	
S7I (Manor Kill)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.08	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	24.5	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	2.3	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.5	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	6.5	
	Chloride (mg L^{-1})	50	12	0	0	10	8.5	
	Total dissolved solids (mg L^{-1})[3]	50	12	8	67	40	55	
SRR2CM (Schoharie Reservoir Diversion)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	24	0	0	0.4	0.07	ROS
	Ammonia (as N) (mg L^{-1})	0.25	24	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	24	6	25	NA	16.2	
	Dissolved Organic Carbon (mg L^{-1})	25	22	0	0	9	2.0	
	Sulfate (as SO4) (mg L^{-1})	15	8	0	0	10	2.6	
	Dissolved sodium (mg L^{-1})	10	8	0	0	5	3.7	
	Chloride (mg L^{-1})	50	12	0	0	10	6.4	
	Total dissolved solids (mg L^{-1})[3]	50	24	4	17	40	45	
Delaware System - Cannonsville Basin								
C-7 (Trout Creek above Cannonsville Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.30	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	17.1	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.4	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	4.2	
	Dissolved sodium (mg L^{-1})	10	4	1	25	5	9.2	
	Chloride (mg L^{-1})	50	12	0	0	10	17.2	
	Total dissolved solids (mg L^{-1})[3]	50	12	12	100	40	72	
	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.27	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
C-8 (Loomis Brook above Cannonsville Reservoir)	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	16.0	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.4	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	4.5	
	Dissolved sodium (mg L^{-1})	10	4	1	25	5	8.3	
	Chloride (mg L^{-1})	50	12	1	8	10	16.0	
	Total dissolved solids (mg L^{-1})[3]	50	12	10	83	40	68	
CBS (formerly WDBN, West Branch Delaware River at Beerston Bridge)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.49	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	21.7	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.8	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	4.2	
	Dissolved sodium (mg L^{-1})	10	4	1	25	5	9.4	
	Chloride (mg L^{-1})	50	12	0	0	10	14.1	
	Total dissolved solids (mg L^{-1})[3]	50	12	12	100	40	73	
Delaware System - Neversink Basin								
NCG (Neversink River near Claryville)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.18	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	12	100	NA	3.7	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.8	
	Sulfate (as SO4) (mg L^{-1})	15	0			10		
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	1.9	
	Chloride (mg L^{-1})	50	12	0	0	10	3.0	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	19	
NK4 (Aden Brook above Neversink Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.16	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	12	100	NA	6.1	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.9	
	Sulfate (as SO4) (mg L^{-1})	15	0			10		
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.1	
	Chloride (mg L^{-1})	50	12	0	0	10	3.5	KM
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	24	
NK6 (Kramer Brook above Neversink Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.31	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	0.03	KM
	Alkalinity (mg L^{-1})	>=10.0	12	5	42	NA	11.5	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	3.5	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Sulfate (as SO4) (mg L^{-1})	15	0			10		
	Dissolved sodium (mg L^{-1})	10	4	4	100	5	17.1	
	Chloride (mg L^{-1})	50	12	1	8	10	28.1	
	Total dissolved solids (mg L^{-1})[3]	50	12	11	92	40	91	
Delaware System - Pepacton Basin								
P-13 (Tremper Kill above Pepacton Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.27	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	17.9	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.6	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.5	
	Dissolved sodium (mg L^{-1})	10	4	1	25	5	10.1	
	Chloride (mg L^{-1})	50	12	0	0	10	12.6	
	Total dissolved solids (mg L^{-1})[3]	50	12	8	67	40	61	
P-21 (Platte Kill at Dunraven)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.20	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	19.3	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.6	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.5	
	Dissolved sodium (mg L^{-1})	10	4	1	25	5	15.0	
	Chloride (mg L^{-1})	50	12	1	8	10	14.3	
	Total dissolved solids (mg L^{-1})[3]	50	12	7	58	40	66	
P-60 (Mill Brook near Dunraven)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.21	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	5	42	NA	11.2	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.2	
	Sulfate (as SO4) (mg L^{-1})	15	6	0	0	10	2.9	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.3	
	Chloride (mg L^{-1})	50	12	0	0	10	2.5	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	29	
P-7 (Terry Clove above Pepacton Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.29	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	1	8	NA	14.7	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.6	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.3	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	1.6	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Chloride (mg L^{-1})	50	12	0	0	10	1.3	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	31	
P-8 (Fall Clove above Pepacton Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.36	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	1	8	NA	14.2	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.5	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.6	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.1	
	Chloride (mg L^{-1})	50	12	0	0	10	2.2	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	34	
PMSB (East Branch Delaware River near Margaretville)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.26	
	Ammonia (as N) (mg L^{-1})	0.25	11	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	19.5	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.6	
	Sulfate (as SO4) (mg L^{-1})	15	6	0	0	10	3.2	
	Dissolved sodium (mg L^{-1})	10	4	2	50	5	10.2	
	Chloride (mg L^{-1})	50	12	0	0	10	12.5	
	Total dissolved solids (mg L^{-1})[3]	50	12	9	75	40	63	
Delaware System - Rondout Basin								
RD1 (Sugarloaf Brook near Lowes Corners)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.12	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	12	100	NA	4.8	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.5	
	Sulfate (as SO4) (mg L^{-1})	15	1	0	0	10	2.9	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	3.2	
	Chloride (mg L^{-1})	50	12	0	0	10	5.4	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	27	
RD4 (Sawkill Brook near Yagerville)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.08	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	12	100	NA	5.1	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	2.7	
	Sulfate (as SO4) (mg L^{-1})	15	1	0	0	10	3.4	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	3.3	
	Chloride (mg L^{-1})	50	12	0	0	10	5.0	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	27	
	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.16	KM

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
RDOA (Rondout Creek near Lowes Corners)	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	12	100	NA	3.8	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.5	
	Sulfate (as SO4) (mg L^{-1})	15	1	0	0	10	2.5	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.1	
	Chloride (mg L^{-1})	50	12	0	0	10	3.2	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	19	
RGB (Chestnut Creek below Grahamsville STP)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.23	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	11	92	NA	7.9	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	3.0	
	Sulfate (as SO4) (mg L^{-1})	15	0			10		
	Dissolved sodium (mg L^{-1})	10	4	2	50	5	8.6	
	Chloride (mg L^{-1})	50	12	0	0	10	11.3	KM
	Total dissolved solids (mg L^{-1})[3]	50	12	5	42	40	51	
Croton System - Croton Basin								
AMAWALKR (Amawalk Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	0			0.35		
	Ammonia (as N) (mg L^{-1})	0.2	0			0.1		
	Alkalinity (mg L^{-1})	>=40.0	0			NA		
	Dissolved Organic Carbon (mg L^{-1})	25	0			9		
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	100	0			35		
	Total dissolved solids (mg L^{-1})[3]	175	0			150		
BOGEASTBRR (Combined release for Bog Brook and East Branch Reservoirs)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	0			0.35		
	Ammonia (as N) (mg L^{-1})	0.2	0			0.1		
	Alkalinity (mg L^{-1})	>=40.0	0			NA		
	Dissolved Organic Carbon (mg L^{-1})	25	0			9		
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	100	0			35		
	Total dissolved solids (mg L^{-1})[3]	175	0			150		
BOYDR (Boyd Corners Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.35	0.09	KM
	Ammonia (as N) (mg L^{-1})	0.2	12	1	8	0.1	0.05	KM
	Alkalinity (mg L^{-1})	>=40.0	12	10	83	NA	37.4	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	4.7	
	Sulfate (as SO4) (mg L^{-1})	25	4	0	0	15	6.2	
	Dissolved sodium (mg L^{-1})	20	4	4	100	15	22.7	
	Chloride (mg L^{-1})	100	12	0	0	35	37.0	
	Total dissolved solids (mg L^{-1})[3]	175	12	0	0	150	138	
CROFALLSVC (Croton Falls Reservoir Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.35	0.32	
	Ammonia (as N) (mg L^{-1})	0.2	12	0	0	0.1	0.04	KM
	Alkalinity (mg L^{-1})	>=40.0	12	0	0	NA	63.4	
	Dissolved Organic Carbon (mg L^{-1})	25	11	0	0	9	3.5	
	Sulfate (as SO4) (mg L^{-1})	25	4	0	0	15	10.0	
	Dissolved sodium (mg L^{-1})	20	4	4	100	15	39.2	
	Chloride (mg L^{-1})	100	12	0	0	35	69.7	
	Total dissolved solids (mg L^{-1})[3]	175	11	11	100	150	249	
CROSS2 (Cross River above Cross River Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.35	0.17	KM
	Ammonia (as N) (mg L^{-1})	0.2	12	0	0	0.1	0.02	ROS
	Alkalinity (mg L^{-1})	>=40.0	12	0	0	NA	59.9	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	4.5	
	Sulfate (as SO4) (mg L^{-1})	25	3	0	0	15	7.5	
	Dissolved sodium (mg L^{-1})	20	3	3	100	15	21.1	
	Chloride (mg L^{-1})	100	12	0	0	35	39.1	
	Total dissolved solids (mg L^{-1})[3]	175	12	7	58	150	175	
CROSSRVVC (Cross River Reservoir Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.35	0.07	KM
	Ammonia (as N) (mg L^{-1})	0.2	12	0	0	0.1	0.06	KM
	Alkalinity (mg L^{-1})	>=40.0	12	1	8	NA	49.8	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	3.8	
	Sulfate (as SO4) (mg L^{-1})	25	4	0	0	15	7.7	
	Dissolved sodium (mg L^{-1})	20	4	3	75	15	20.6	
	Chloride (mg L^{-1})	100	12	0	0	35	39.0	
	Total dissolved solids (mg L^{-1})[3]	175	12	0	0	150	166	
DIVERTR (Diverting Reservoir Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	4	0	0	0.35	0.14	
	Ammonia (as N) (mg L^{-1})	0.2	4	1	25	0.1	0.08	
	Alkalinity (mg L^{-1})	>=40.0	4	0	0	NA	83.6	
	Dissolved Organic Carbon (mg L^{-1})	25	5	0	0	9	5.5	
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	Dissolved sodium (mg L^{-1})	20	0			15		

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
	Chloride (mg L^{-1})	100	4	0	0	35	50.6	
	Total dissolved solids (mg L^{-1})[3]	175	5	5	100	150	237	
EASTBR (East Branch Croton River above East Branch River)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	0			0.35		
	Ammonia (as N) (mg L^{-1})	0.2	0			0.1		
	Alkalinity (mg L^{-1})	>=40.0	0			NA		
	Dissolved Organic Carbon (mg L^{-1})	25	0			9		
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	100	0			35		
	Total dissolved solids (mg L^{-1})[3]	175	0			150		
GYPSYTRL1 (Gypsy Trail Brook above West Branch Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.35	0.05	KM
	Ammonia (as N) (mg L^{-1})	0.2	12	0	0	0.1	<0.02	>80%
	Alkalinity (mg L^{-1})	>=40.0	12	9	75	NA	32.1	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	5.2	KM
	Sulfate (as SO4) (mg L^{-1})	25	4	0	0	15	4.5	
	Dissolved sodium (mg L^{-1})	20	4	1	25	15	18.9	
	Chloride (mg L^{-1})	100	12	0	0	35	24.3	
	Total dissolved solids (mg L^{-1})[3]	175	12	1	8	150	108	
HORSEPD12 (Horse Pound Brook above West Branch Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.35	0.31	
	Ammonia (as N) (mg L^{-1})	0.2	12	0	0	0.1	<0.02	>80%
	Alkalinity (mg L^{-1})	>=40.0	12	4	33	NA	43.9	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	3.6	
	Sulfate (as SO4) (mg L^{-1})	25	4	0	0	15	7.6	
	Dissolved sodium (mg L^{-1})	20	4	4	100	15	25.0	
	Chloride (mg L^{-1})	100	12	0	0	35	44.3	
	Total dissolved solids (mg L^{-1})[3]	175	12	4	33	150	167	
KISCO3 Kisco River above New Croton Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	4	0	0	0.35	0.58	
	Ammonia (as N) (mg L^{-1})	0.2	4	0	0	0.1	<0.02	>80%
	Alkalinity (mg L^{-1})	>=40.0	4	0	0	NA	95.1	
	Dissolved Organic Carbon (mg L^{-1})	25	4	0	0	9	3.6	
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	100	4	2	50	35	96.0	
	Total dissolved solids (mg L^{-1})[3]	175	4	4	100	150	347	
	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.35	0.24	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
LONGPD1 (Long Pond outflow above West Branch Reservoir)	Ammonia (as N) (mg L^{-1})	0.2	12	0	0	0.1	0.02	ROS
	Alkalinity (mg L^{-1})	>=40.0	12	0	0	NA	59.9	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	4.8	
	Sulfate (as SO4) (mg L^{-1})	25	4	0	0	15	9.0	
	Dissolved sodium (mg L^{-1})	20	4	4	100	15	43.8	
	Chloride (mg L^{-1})	100	12	1	8	35	71.9	
	Total dissolved solids (mg L^{-1})[3]	175	12	12	100	150	249	
MIKE2 (Michael Brook above Croton Falls Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	9	75	0.35	3.55	
	Ammonia (as N) (mg L^{-1})	0.2	12	2	17	0.1	0.23	ROS
	Alkalinity (mg L^{-1})	>=40.0	12	0	0	NA	93.6	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	4.4	
	Sulfate (as SO4) (mg L^{-1})	25	4	0	0	15	17.6	
	Dissolved sodium (mg L^{-1})	20	4	4	100	15	127.1	
	Chloride (mg L^{-1})	100	12	11	92	35	175.5	
	Total dissolved solids (mg L^{-1})[3]	175	12	12	100	150	537	
MUSCOOT10 (Muscoot River above Amawalk Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	1	0	0	0.35	0.18	
	Ammonia (as N) (mg L^{-1})	0.2	1	0	0	0.1	0.02	
	Alkalinity (mg L^{-1})	>=40.0	1	0	0	NA	89.0	
	Dissolved Organic Carbon (mg L^{-1})	25	1	0	0	9	5.1	
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	100	1	1	100	35	139.0	
	Total dissolved solids (mg L^{-1})[3]	175	1	1	100	150	412	
TITICUSR (Titicus Reservoir Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	4	0	0	0.35	0.09	
	Ammonia (as N) (mg L^{-1})	0.2	4	0	0	0.1	0.07	
	Alkalinity (mg L^{-1})	>=40.0	4	0	0	NA	75.8	
	Dissolved Organic Carbon (mg L^{-1})	25	4	0	0	9	4.6	
	Sulfate (as SO4) (mg L^{-1})	25	0			15		
	Dissolved sodium (mg L^{-1})	20	0			15		
	Chloride (mg L^{-1})	100	4	0	0	35	39.3	
	Total dissolved solids (mg L^{-1})[3]	175	4	4	100	150	193	
WESTBR7 (West Branch Croton River above Boyd	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.35	0.05	KM
	Ammonia (as N) (mg L^{-1})	0.2	12	0	0	0.1	0.02	KM
	Alkalinity (mg L^{-1})	>=40.0	12	10	83	NA	33.0	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	6.2	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2021 Mean[1]	Note[2]
Corners Reservoir)	Sulfate (as SO4) (mg L^{-1})	25	4	0	0	15	4.9	
	Dissolved sodium (mg L^{-1})	20	4	3	75	15	22.3	
	Chloride (mg L^{-1})	100	12	0	0	35	35.4	
	Total dissolved solids (mg L^{-1})[3]	175	12	0	0	150	125	
WESTBRR (West Branch Reservoir Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.14	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	0.01	ROS
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	13.8	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	2.4	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	4.4	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	6.7	
	Chloride (mg L^{-1})	50	12	0	0	10	13.7	
	Total dissolved solids (mg L^{-1})[3]	50	12	9	75	40	57	

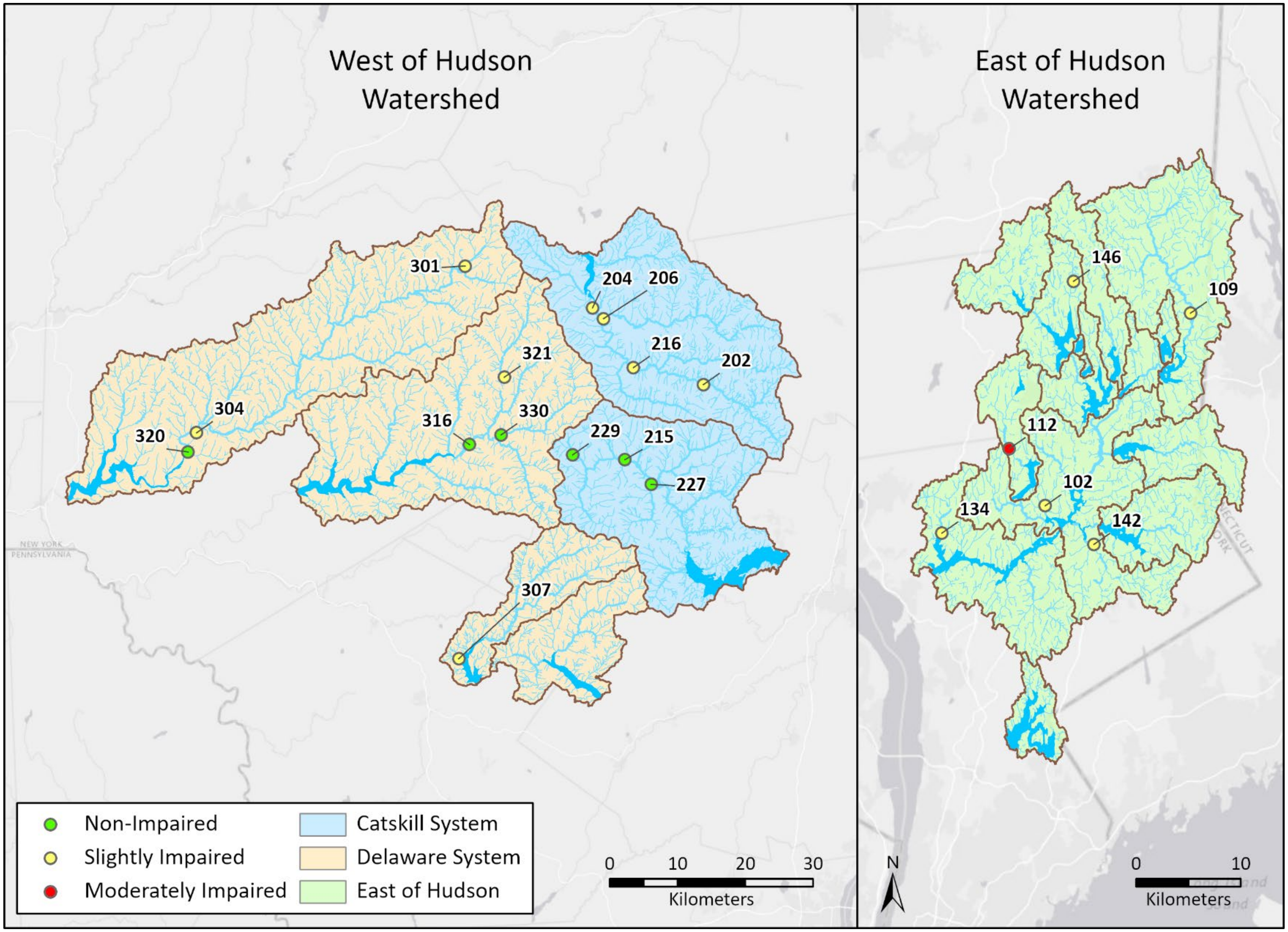
Streams included in this analysis are required by WWQMP as per 3.2.1. Status of Stream Water Quality and 5.8. Croton System Streams – Water Quality Status

[1]Means for data containing non-detects were estimated using techniques recommended in Helsel (2005) using an R program developed for U.S. Environmental Protection Agency (Bolks et al. 2014).

[2]Note indicates which analysis method was used to determine the statistics when there were censored data. KM indicates Kaplan-Meier, ROS indicates robust regression on order statistics, and >80% indicates that the mean could not be calculated for the following reasons: 1) the data contains greater than 80% censored data or 2) there are 5 or fewer samples with greater than 50% censored. In these cases, the detection limit, preceded by "<", is reported. A blank cell in the Note column indicates that the 2021 mean was calculated as the standard arithmetic average.

[3]Total dissolved solids estimated from specific conductivity according to the USGS in van der Leeden et al. (1990)

Appendix J. Biomonitoring Sampling Sites



Environmental Protection

2021 Biomonitoring Sites and their Water Quality (WQ) Status

SYSTEM	SITE	WQ STATUS	WQ SITE	STREAM
EOH	102	Slight	ANGLE3	Angle Fly Brook
EOH	109	Slight	EASTBR	East Br. Croton River
EOH	112	Moderate	MUSCOOT9	Muscoot River
EOH	134	Slight	HUNTER1	Hunter Brook
EOH	142	Slight	STONE5	Stone Hill River
EOH	146	Slight	HORSEPD12	Horse Pound Brook
Catskill	202	Slight	S3	Schoharie Creek
Catskill	204	Slight	S5I	Schoharie Creek
Catskill	206	Moderate	S10	Batavia Kill
Catskill	215	Non	E5	Esopus Creek
Catskill	216	Non	S4	Schoharie Creek
Catskill	227	Non	AEAWDL	Esopus Creek
Catskill	229	Non	BELLEGIG	Giggle Hollow
Delaware	301	Slight	WDHOA	W. Br. Delaware River
Delaware	304	Slight	WSPB	W. Br. Delaware River
Delaware	307	Slight	NK4	Aden Brook
Delaware	316	Non	PMSB	E. Br. Delaware River
Delaware	320	Non	WDBN	W. Br. Delaware River
Delaware	321	Slight	EDRB	E. Br. Delaware River
Delaware	330	Non	PBKG	Bush Kill

Appendix K. Semivolatile and Volatile Organic Compounds and Herbicides

EPA 525.2 – Semivolatiles

2,4-Dinitrotoluene, 2,6-Dinitrotoluene, 2,4 DDD, 2,4 DDE, 2,4-DDT 4, 4-DDD, 4,4-DDE, 4,4-DDT, Acenaphthene, Acenaphthylene, Acetochlor, Alachlor, Aldrin, Alpha-BHC, alpha-Chlordane, Anthracene, Atrazine, Benz(a)Anthracene, Benzo(a)pyrene, Benzo(b)Fluoranthene, Benzo(g,h,i)Perylene, Benzo(k)Fluoranthene, Beta-BHC, Bromacil, Butachlor, Butylbenzylphthalate, Caffeine, Chlorobenzilate, Chloroneb, Chlorothalonil (Draconil,Bravo), Chlorpyrifos (Dursban), Chrysene, Delta-BHC, Di-(2-Ethylhexyl)adipate, Di(2-Ethylhexyl)phthalate, Diazinon, Dibenz(a,h)Anthracene, Dichlorvos (DDVP), Dieldrin, Diethylphthalate, Dimethoate, Dimethylphthalate, Di-n-Butylphthalate, Di-N-octylphthalate, Endosulfan I (Alpha), Endosulfan II (Beta), Endosulfan Sulfate, Endrin, Endrin Aldehyde, EPTC, Fluoranthene, Fluorene, gamma-Chlordane, Heptachlor, Heptachlor Epoxide (isomer B), Hexachlorobenzene, Hexachlorocyclopentadiene, Indeno(1,2,3,c,d)Pyrene, Isophorone, Lindane, Malathion, Methoxychlor, Metolachlor, Metribuzin, Molinate, Naphthalene, Parathion, Pendimethalin, Permethrin (mixed isomers), Phenanthrene, Propachlor, Pyrene, Simazine, Terbacil, Terbuthylazine, Thiobencarb, trans-Nonachlor, Trifluralin

EPA 524.2 - Volatile Organics

1,1,1,2-Tetrachloroethane, 1,1,1-Trichloroethane, 1,1,2,2-Tetrachloroethane, 1,1,2-Trichloroethane, 1,1-Dichloroethane, 1,1-Dichloroethylene, 1,1-Dichloropropene, 1,2,3-Trichlorobenzene, 1,2,3-Trichloropropane, 1,2,4-Trichlorobenzene, 1,2,4-Trimethylbenzene, 1,2-Dichloroethane, 1,2-Dichloropropane, 1,3,5-Trimethylbenzene, 1,3-Dichloropropane, 2,2-Dichloropropane, 2-Butanone (MEK), 4-Methyl-2-Pentanone (MIBK), Benzene, Bromobenzene, Bromochloromethane, Bromodichloromethane, Bromoethane, Bromoform, Bromomethane (Methyl Bromide), Carbon disulfide, Carbon Tetrachloride, Chlorobenzene, Chlorodibromomethane, Chloroethane, Chloroform (Trichloromethane), Chloromethane(Methyl Chloride), cis^{-1},2-Dichloroethylene, cis^{-1},3-Dichloropropene, Dibromomethane, Dichlorodifluoromethane, Dichloromethane, Di-isopropyl ether, Ethyl benzene, Hexachlorobutadiene, Isopropylbenzene, m,p-Xylenes, m-Dichlorobenzene (1,3-DCB), Methyl Tert-butyl ether (MTBE), Naphthalene, n-Butylbenzene, n-Propylbenzene, o-Chlorotoluene, o-Dichlorobenzene (1,2-DCB), o-Xylene, p-Chlorotoluene, p-Dichlorobenzene (1,4-DCB), p-Isopropyltoluene, sec-Butylbenzene, Styrene, tert-amyl Methyl Ether, tert-Butyl Ethyl Ether, tert-Butylbenzene, Tetrachloroethylene (PCE), Toluene, Total 1,3-Dichloropropene, Total THM, Total xylenes, trans^{-1},2-Dichloroethylene, trans^{-1},3-Dichloropropene, Trichloroethylene (TCE), Trichlorofluoromethane, Trichlorotrifluoroethane (Freon 113), Vinyl chloride (VC)

Herbicides

Glyphosate

Appendix L. Emerging Contaminant PFAS Compounds

Samples were analyzed by Eurofins - Eaton Analytical, using USEPA Method 537 with a method reporting limit (MRL) of 0.0020 $\mu g L^{-1}$ which includes the following 14 compounds:

N-ethyl perfluorooctanesulfonamidoacetic acid (NEtFOSAA)

N-methyl perfluorooctanesulfonamidoacetic acid (NMeFOSSA)

Perfluorobutanesulfonic acid (PFBS)

Perfluorodecanoic acid (PFDA)

Perfluorododecanoic acid (PFDoA)

Perfluoroheptanoic acid (PFHpA)

Perfluorohexanesulfonic acid (PFHxS)

Perfluorohexanoic acid (PRHxA)

Perfluorononanoic acid (PFNA)

Perfluorooctanoic acid (PFOA)

Perfluoroctanesulfonic acid (PFOS)

Perfluorotetradecanoic acid (PFTA)

Perfluorotridecanoic acid (PFTrDA)

Perfluoroundecanoic acid (PFUnA)