NYC Department of Environmental Protection

2019 Watershed Water Quality Annual Report

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Bureau of Water Supply

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List of Acronyms

AEAP	Esopus Creek above Portal for Shandaken Tunnel
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
^{o}C	degree Celsius
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
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
GLEON	Global Lake Ecological Observatory Network
GWLF	Generalized Watershed Loading Function
HEV	Human Enteric Virus
IAR	Inactivation Ratio
LT2	Long Term 2 Enhanced Surface Water Treatment Rule
$\mu g\ L^{-1}$	microgram per liter
$\mu mhos\ cm^{-1}$	micromhos per centimeter
$mg\ L^{-1}$	milligram per liter
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
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
PR2	East Delaware Intake Chamber Tap 2; 1186 feet above sea level
ROS	Regression on order statistics
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
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 2019 to manage the water quality of the New York City water supply and to provide information for regulatory agencies and the general public. Department of Environmental Protection (DEP) Commissioner Vincent Sapienza, P.E., provided oversight of the Department throughout 2019. Paul Rush, P.E., Deputy Commissioner, and Mr. Steven Schindler, Director of Water Quality, continued to provide direction for the many activities of the Water Quality Directorate (WQD). Dr. Lorraine Janus, Chief of Water Quality Science and Research (WQSR) and her division were responsible for the data analysis, interpretation, and report production. Mr. Andrew Bader, Chief of Watershed Water Quality Operations (WWQO), provided oversight of Watershed Field Operations, Watershed Laboratory Operations, Wildlife Studies, and Systems Support, - the Divisions that provided the data which form the basis of this report.

Chapter 1 Introduction was co-authored by Dr. Lorraine Janus; Mr. James Mayfield, Section Chief of Program Evaluation and Planning; Mr. James Broderick, Deputy Chief, WQ Systems Support; Ms. Meredith Mathewson, Deputy Chief, East of Hudson Field Operations; and Mr. David Robinson, Deputy Chief, East of Hudson Laboratory Operations. Chapter 2 Water Quantity was written by Mr. James Mayfield and Mr. Rich Van Dreason. Mr. Ken DeRose, Section Chief for Data Management in Water System Operations provided the operations and rainfall data presented in this chapter. Chapter 3 Water Quality was written by Dr. Karen Moore and Mr. Rich Van Dreason with contributions from Mr. James Mayfield on streams and Mr. Don Kent on stream biomonitoring. The descriptions of Special Investigations were compiled and authored by Mr. David Quentin, with contributions from: EOH field and laboratory staff, authored by Ms. Meredith Mathewson and Mr. David Robinson; WOH field and laboratory staff, Water Quality Science and Research staff, BWS Water Quality Operations staff, and Watershed Protection Program staff, authored by Mr. Kurt Gabel, Mr. Robert Howe, Mr. Michael Spada, and Ms. Emily Pereira; and Water Innovation and Research and other BWS staff, authored by Ms. Allison Dewan and Mr. Jason Railing. Chapter 4 Kensico Reservoir was written by Mr. Dave Van Valkenburg, Mr. Chris Nadareski, Mr. Christian Pace, Mr. David Quentin, and Ms. Kerri Alderisio, with contributions for Special Investigations from Ms. Meredith Mathewson and Ms. Allison Dewan. Chapter 5 Pathogens was co-authored by Mr. Christian Pace and Ms. Kerri Alderisio. Chapter 6 Water Quality Modeling was written by Mr. Emmet Owens, P.E., Section Chief of Water Quality Modeling, Dr. Rakesh Gelda, Dr. Rajith Mukundan, Mr. Jordan Gass, Dr. Theo Kpodonu, and Dr. Myeong-Ho (Chris) Yeo. This chapter describes ongoing model development and applications conducted by the Modeling Section. Chapter 7 Further Research describes how WQD supplements its capabilities through contracts and participation in scientific organizations. The chapter was coordinated by Dr. Lorraine Janus with contributions from Mr. Andrew Bader, Mr. James Mayfield, Mr. Emmet Owens, P.E., Mr. Chris Nadareski, Mr. Jordan Gass, Mr. James Alair, Ms. Jennifer Farmwald, and Dr. Karen Moore. Other essential database expertise was provided by Mr. Brian O'Malley, Section Chief of Data Management. Maps were created by Mr. Jordan Gass. Mr. Rich VanDreason authored Appendices. Mr. James Mayfield, Dr. Karen Moore, Mr. Dave Van Valkenburg, and Mr. Rich VanDreason were responsible for bringing the chapters together as a single document and polishing the format to produce the final document. Mr. Michael Risinit, BWS Reporting and Publications Assistant, provided edits for the entire document, and Ms. Kristen Rendler provided the cover photo.

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.

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 2019, and compliance with regulatory standards. It is complementary to the New York City 2019 Drinking Water Supply and Quality Report, 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.

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 one 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 two billion cubic meters (570 billion gallons). A summary of the number of sites, samples, and analyses that were processed in 2019 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 2019 the NYC water supply watershed received 6.24 inches (158 mm) of precipitation above the historical calendar year average (1989-2018) of 46.19 inches (1,173 mm). The National Climatic Data Center's (NCDC) climatological rankings determined the 2019 rankings for New York. Overall total precipitation for New York State in 2019 was 48.18 inches (1,224 mm), which was 7.89 inches (200 mm) above the 20th-century mean (1901-2000) and the ninth wettest in the last 125 years (1895-2018). New York State also had well above-normal runoff (8th highest (93.3 percentile) out of the last 119 years) for the 2019 water year (October 1, 2018-September 30, 2019), as determined by the U.S. Geological Survey (USGS) (http://waterwatch.usgs.gov/index.php?r=ny&m=statesum). Usable storage capacity of the water supply was at or above normal storage except for September through mid-October, when dry conditions resulted in capacity at 5% below normal levels.

Chapter 3 Water Quality

Turbidity levels in most of the Catskill/Delaware and Croton systems' streams and reservoirs were generally close to or below their historic median levels, with some exceptions.

Turbidity in the east and west basins of Ashokan was well below historic levels in 2019, which was due in large part to the below-average flood hydrology in Esopus Creek. Data collected as part of an ongoing collaborative DEP-USGS study also indicated that the delivery of turbid water to Esopus Creek from the Stony Clove sub-basin (the largest tributary and historically a significant turbidity source) has been substantially reduced after the implementation of eight stream turbidity reduction projects between 2012 and 2016, although there have not been any high flow events since their construction, so attribution of turbidity reduction will require further study under a full range of flow conditions. Monitoring data indicate that East Branch Delaware River (PMSB) and Cross River (CROSS2) were slightly above their historic 10-year median turbidity, although still at relatively low levels (2.3 and 2.4 NTU, respectively). Reservoir turbidity was elevated to some degree for Boyd Corners, Titicus, Muscoot, and New Croton reservoirs, and associated either with runoff events or algal blooms.

Fecal coliform counts were close to historic levels in most streams and reservoirs in 2019. However, there were some elevated counts associated with rain events that were reflected in the medians for both WOH and EOH streams and reservoirs. Despite these occurrences, all terminal reservoir basins remained "non-restricted" for coliform-restricted assessments in 2019. Total coliform counts were lower in Catskill and Croton system reservoirs with some exceptions (Boyd Corners, Croton Falls, and Muscoot), but higher than the historical 10-year medians in all Delaware System reservoirs. The higher total coliform levels were associated with spring runoff and warmer temperatures during the second half of 2019.

In 2019, there were no changes in phosphorus-restricted status as compared to the previous five-year assessment period. Annual geometric mean total phosphorus (TP) concentrations declined in all reservoirs with the exception of Cannonsville, where a small increase was observed, and Neversink, which remain unchanged from the previous year. Total phosphorous (TP) levels in the Catskill/Delaware reservoirs, including West Branch and Kensico, were generally within their historic ranges, except Cannonsville exceeded its historic median TP by 1 $\mu g\ L^{-1}$ and Boyd Corners was also above its historic median. Streams had mixed results, with the 2019 median TP above the 10-year median concentration in four inflows to Croton System reservoirs and the West Branch Delaware River, the main inflow to Cannonsville.

Trophic state indices (TSI) are used to describe algal productivity of lakes and reservoirs. In 2019, TSI increased relative to historic levels in most reservoirs of the Catskill/Delaware System and in six reservoirs of the Croton System. Reasons for the relatively high TSI are not clear, as nutrient levels were generally normal to low for most reservoirs in 2019.

Evaluation of additional reservoir and stream analytes in 2019 included chloride and data are compared to benchmark values set in the NYC Watershed Rules and Regulations. All reservoirs and controlled lakes in the Croton System exceeded the annual mean chloride benchmark of 30 $mg\ L^{-1}$ with the exception of West Branch, and 14 of 16 streams exceeded the mean annual benchmark of 35 mg L^{-1}. This is consistent with previous years and reflects the population and road density for the region. For Catskill/Delaware System reservoirs, none exceeded the annual mean of 8 mg L^{-1} or single sample benchmark of 12.0 mg L^{-1} with the exception of Cannonsville Reservoir, while 13 of 24 streams exceeded the annual mean benchmark of 10 mg L^{-1}. All exceedances of benchmark values for chloride were well below the public health standard of 250 mg L^{-1}.

Sample collection for water quality assessments of watershed streams based on resident benthic macroinvertebrate assemblages continued in 2019, but no sample analysis was performed due to budget restrictions in early 2020. Samples were preserved and held for possible future analysis.

DEP has been monitoring all reservoirs for the presence of zebra mussel (*Dreissena polymorpha*) larvae (veligers), as well as settlement of juvenile and mature zebra mussels since the early 1990s. There have been no attached zebra mussels found to date in the reservoirs, but in 2019 veligers were present in low concentrations at the end of the culvert that conveys water from the Muscoot River into the Amawalk Reservoir. The source is likely from Lake Mahopac, which drains into Muscoot River. To date, attached zebra mussels have been found in the Muscoot River up to about 1 kilometer downstream of the Lake Mahopac outlet.

Routine annual surveillance monitoring for metals, a wide range of semivolatile and volatile organic compounds, and the herbicide glyphosate continued at several keypoint locations. Most metal sample results were well below state and federal benchmarks, with few exceptions. Occasional exceedances of benchmark values occurred for iron, aluminum, and manganese, but were not at levels considered to be a health risk. There were no detections of the monitored semivolatile and volatile compounds or glyphosate in 2019.

There were 20 water quality special investigations conducted throughout the system in 2019. Four of these occurred in the Kensico basin and are reported in Chapter 4, and one screening study on emergent contaminants included multiple keypoint sites both in Kensico and other parts of the system (reported in Chapter 3). The 15 remaining special investigations conducted outside of the Kensico basin included monitoring for algal toxins; continued study of Foamstream, a non-toxic alternative to pesticides such as glyphosate, for vegetation control; and evaluation of watershed protection programs for streambank stabilization and septic to sewer conversions. Other investigations were exploratory to inform water supply management, including ultrasonic treatment of algae in Croton Falls Reservoir; jar tests blending water with different UV absorbance characteristics to assess the potential to minimize disinfection byproduct formation; intern projects to explore DBP precursors, their formation potential, and proxy measurements; and an evaluation of mixing characteristics in the Ashokan Reservoir gatehouse. The remaining investigations were related to water quality operations or concerns arising from events, including increased monitoring for operational changes at the Cross River and Croton Falls pumping stations; water quality sampling at Moodna Shaft 7; monitoring a fuel spill that occurred in the Titicus basin; tracking elevated *Giardia* levels originating in the Rondout basin; evaluating conditions surrounding a taste and odor event in the Croton System; sampling an algal bloom in the west basin of Ashokan Reservoir; and sediment sampling on the lower Esopus Creek.

Chapter 4 Kensico Reservoir

Kensico Reservoir is the terminal reservoir for the unfiltered Catskill/Delaware water supply. Monitoring of the water discharged from Kensico takes place at DEL18DT. The City's high frequency monitoring ensures that every effort is taken at this keypoint location to meet strict requirements for turbidity and fecal coliform concentrations set forth in the federal Surface Water Treatment Rule (SWTR). During 2019, all of the DEL18DT turbidity and fecal coliform results were less than their respective limits (5 NTU and 20 fecal coliforms $100mL^{-1}$), 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 inspections of the turbidity curtains near the Catskill Upper Effluent Chamber cove continued to show they were intact. Overall, water quality from Kensico continued to be excellent during 2019.

In addition to DEP's routine monitoring, there were four special investigations/projects conducted in the Kensico watershed and annual video monitoring for Bryozoans continued at the Delaware Shaft 18 sluice gates. There was one storm event monitored in the Malcom Brook and Stream N5-1 watersheds resulting in a temporary increase in turbidity and fecal coliforms at the stream sites, but turbidity and fecal coliform levels remained in compliance at DEL18DT. Microbial source tracking (MST) with Bacteroidales were submitted for analysis for the storm event and contained trace to low-level detections for human markers. There were two special investigations, both involved catchment basins, where there was a detection of petroleum hydrocarbon in one and bacterial growth/sewage odor in the other. The results from both investigations indicated no potential threat to drinking water quality. There were two special projects: Kensico Shoreline Stabilization and a pilot study to detect human waste contamination using a specially trained canine. Results from the shoreline study indicated no turbidity impact to Shaft 18 from efforts to repair the nearby shoreline. Results from the canine study indicated limited agreement between the canine and analytical results for human waste and follow-up investigations are planned. Bryozoan inspections continued through 2019 and provided additional evidence that reduced flows through a sluice gate resulted in reduction of colonial growth.

Chapter 5 Pathogen Monitoring and Research

DEP collected 604 samples for protozoan analysis, 52 for *Cryptosporidium* infectivity testing, and 33 samples for human enteric virus (HEV) monitoring in 2019. Most samples were collected at watershed streams and reservoirs (34.3%) and source water keypoint locations (24.7%). Additional samples were collected at Hillview Reservoir, the CAT/DEL UV plant, upstate reservoir effluents, and wastewater treatment plants (WWTPs). As a reminder, a method variation - replacing acid dissociation with heat dissociation - was implemented by DEP in August 2017. Therefore, fluctuations in the sample data may be a result of a method change and not a variation of prevalence in the environment. Additional data gathered using the method adjustment are needed to confirm method changes as a cause of a potential shift in the data.

For the two-year period from January 1, 2018, to December 31, 2019, DEP unfiltered source water results continued to be below the Long Term 2 Enhanced Surface Water Treatment Rule (LT2) *Cryptosporidium* threshold for additional treatment. The Catskill/Delaware system was below the LT2 unfiltered water supply threshold (0.010 oocysts L^{-1}), with a mean of 0.0014 oocysts L^{-1} at the Delaware outflow – which is the same LT2 mean as the previous two-year period. Since the LT2 monitoring is complete, and the frequency of sample collection at New Croton Reservoir has been reduced to quarterly, assessments of the data for comparison to LT2 thresholds for DEP's filtered system are no longer conducted due to the small sample size.

As historical data have established, protozoan concentrations leaving the upstate reservoirs and Kensico Reservoir were lower than levels at the stream sites that feed these reservoirs, suggesting a continued reduction as water passes through the system. Elevated *Giardia* concentrations at Rondout Reservoir continued from fall 2018 into spring 2019. Cyst concentrations declined in the summer and increased again in November 2019; however not to the levels seen in the fall of the previous year. Several actions were taken to investigate this increase and these steps, as well as results, have been discussed in a special investigation report issued by DEP in December 2019. There were five samples positive for *Giardia* cysts at WWTPs this year, and no samples were positive for *Cryptosporidium*. As per the Hillview Consent Decree and Judgement, DEP continued weekly protozoan monitoring at the Hillview Reservoir outflow (Site 3) through 2019, with 52 routine samples collected. Of the 52, there were 22 samples positive for *Giardia* and two samples positive for *Cryptosporidium*. All 52 Hillview samples tested for infectious *Cryptosporidium* by cell-culture immunofluorescent assay were negative.

Chapter 6 Water Quality Modeling

The staff of the Water Quality Modeling section 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 also 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 2019, the development of a model to estimate historical precipitation for areas of the West of Hudson watersheds where no rainfall gages are located was completed. Also, identification of the characteristics or magnitude of extreme hydrologic events (floods and droughts) under both current and future climate conditions is an important component of the modeling program. In 2019, a new project was initiated to estimate, or reconstruct, the time series of historical streamflows for hundreds of years prior to the beginning of actual streamflow measurements. This reconstruction is based on analysis of tree rings. Development of a model to conduct this reconstruction began in 2019. In addition, a data analysis project was initiated in 2019 to analyze historical meteorological, hydrologic, water quality, and operations data to identify long-term trends that may be associated with the changing climate.

The Soil and Water Assessment Tool (SWAT) model was used to quantify stream nutrient loading to Cannonsville Reservoir. Future climate scenarios that were developed earlier were used to forecast the impact of climate change on nitrogen and phosphorus loading. Testing and validation of SWAT for other West of Hudson watersheds was also completed in 2019. Testing and validation of SWAT for streamflow (runoff quantity) was completed for the watersheds of Ashokan, Neversink, Pepacton, Rondout, and Schoharie. Climate change scenarios were also used together with DEP's Operations Support Tool (OST) to estimate how the operation of the entire water supply system may change in the future in response to climate change. The impact of climate change on shifts in diversion from the various reservoirs, turbidity of diverted water, and measures of system resilience, reliability, and the number of days of alum addition to manage elevated turbidity are forecast using OST.

The testing and validation of the W2 turbidity model for Pepacton Reservoir was completed in 2019. This model has now been tested and validated for all West of Hudson reservoirs except Cannonsville, which will be undertaken in 2020. The testing of a new reservoir hydrothermal and eutrophication model, GLM-AED, for Cannonsville Reservoir was completed in 2019. Testing features the simulation (hindcasting) of water quality for the period 1995-2015. The initial testing of a model to simulate UV_{254} in the water column of Cannonsville is also described.

The Water Quality Modeling section continued its involvement and interaction with outside scientific groups. Section staff made presentations at meetings of the National Academy of Sciences, Engineering and Medicine (NASEM) Expert Panel reviewing DEP's Watershed Protection Program. A meeting was held in October 2019 to describe water quality modeling progress and findings to representatives of state and federal regulatory agencies. Modeling section staff and associates were authors on nine technical papers published in peer reviewed journals.

Chapter 7 Further Research

The analytical, monitoring, and research activities of DEP are supported through a variety of contracts, participation in 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 Observation Network (GLEON). In 2019, DEP managed five contracts for laboratory services and five for other support services, including bathymetric surveys and operation of a stream gage network by the USGS, modeling support by CUNY, waterfowl management, and software support for Water Information System KISTERS (WISKI) software. DEP participated in six 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. In 2019, DEP continued as one of 12 members of the Water Utility Climate Alliance (WUCA) where use of models to evaluate the impact of climate change was shared. DEP's participation in the Global Lake Ecological Observatory Network (GLEON) also continued. A study on the effects of climate on dissolved oxygen concentrations (DO) in lakes and reservoirs around the globe was initiated in 2016 and DEP contributed Cannonsville and Neversink reservoir temperature, DO, nutrient, and chlorophyll data and expertise. A second project "Before the Pipe: Monitoring and Modeling DBP Precursors in Drinking Water Sources" will identify important questions and research gaps on disinfection byproduct (DBP) precursors and water supply concerns. Participation with external groups is an efficient way for DEP to bring specialized expertise into the work of the Water Quality Directorate and to remain aware of the most recent developments in the water supply industry.

1. Introduction

1.1 Water Quality Monitoring of the Watershed

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 the public, regulators, and other stakeholders with a detailed description of the City's water resources, their condition during 2019, and compliance with regulatory standards. It also provides an overview of operations and the use of water quality models for management of the water supply. It is complementary to the New York City 2019 Drinking Water Supply and Quality Report (https://www1.nyc.gov/assets/dep/downloads/pdf/water/drinking-water/drinking-water-supply-quality-report/2019-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.

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 one 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 two 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, 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

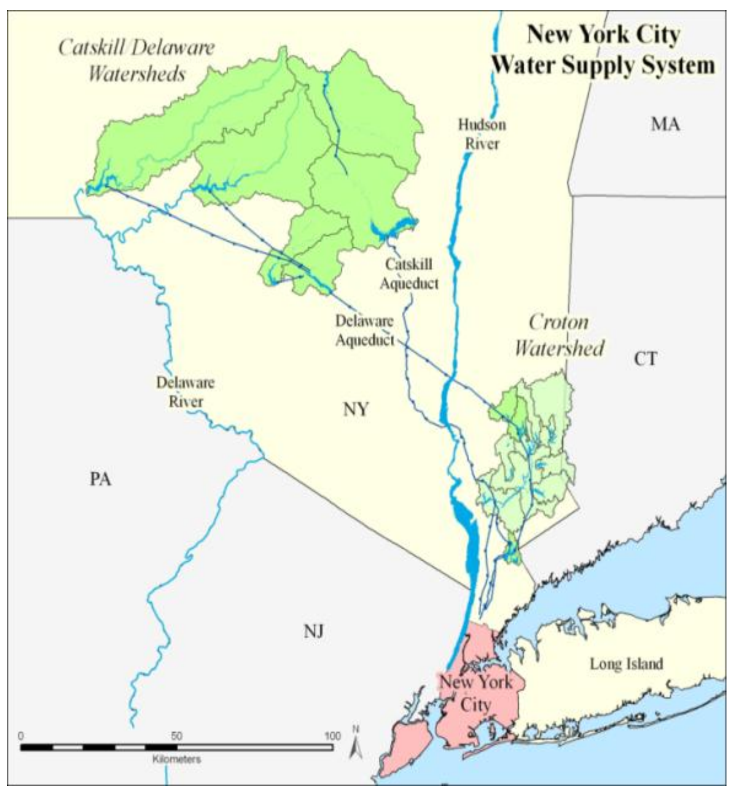


Figure 1.1. The New York City water supply system.

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 Watershed Water Quality Operations based primarily at three upstate New York locations: Grahamsville, Kingston, and Hawthorne. Manual and automated monitoring systems are used for database development. The Water Quality Science and Research Division uses these data to perform data and modeling analyses. The results of these activities guide operational responses to changing water quality conditions of the reservoirs. The information generated by field, laboratory, and data analysis activities are presented here to provide an overview of watershed water quality in 2019, and to show how high quality source water is reliably maintained through constant vigilance and operational changes. In addition to the work of the Water Quality Directorate, DEP extends its capabilities through contracts and interactions with other organizations (see Chapter 7, Further 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. Results are used for several purposes: to ensure regulatory compliance, to guide operations, to demonstrate the effectiveness of watershed protection measures, and to provide data for modeling applications. 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 carefully tailored to meet specific objectives of DEP.

A summary of the number of sites, samples, and analyses that were processed in 2019 by the three upstate laboratories is provided below in Table 1.1. The samples included in the table were collected from streams, reservoirs, reservoir releases, wastewater treatment plants (WWTPs), and keypoints (i.e., water supply intakes, reservoir elevation taps, and aqueduct sites) as described in the WWQMP (DEP 2018). Samples taken as the result of special investigations (SIs) and from the free residential lead test kits, performed at the DEP Kingston Laboratory, are also included. The sample numbers for the City's distribution system are listed simply to demonstrate the comprehensive sampling from source to tap, however, this report is devoted to discussion of results from watershed samples that relate to untreated source water.

Table 1.1. Summary of grab samples collected, water quality analyses performed, and sites visited by WQD in 2019.

System	Number of Samples	Number of Analyses	Number of Sites
Watershed	15,000	262,500	495
Distribution	36,300	456,500	~1,000
Total	51,300	682,000	~1,495

In addition to grab sampling, data are recorded by continuous monitoring equipment at keypoints on the aqueducts, by data loggers at stream sites, and by robotic monitoring buoys deployed at reservoirs as described in the sections that follow.

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 for water quality modeling. The data are of particular importance when conditions are changing rapidly and operational responses may be required. In addition to surveillance, these data are used to run the Operations Support Tool (OST), reservoir models, and terrestrial models. The data generated by the RoboMon network have proven to be invaluable for protection of the water supply, particularly during storm events, special investigations, and construction of water supply infrastructure projects that potentially affect water quality. In 2019, approximately two million measurements were recorded from more than 20 sites. These automated systems contribute significantly to manage the water supply for the safety and reliability of high quality drinking water.

The RoboMon network began in 2012 with four reservoir sites (three at Ashokan and one at Kensico). The network has continued to grow to its current configuration (Figure 1.2) with sites located in both reservoirs and streams. There has also been enhancement of some sites with additional sensors to obtain data essential for model development.

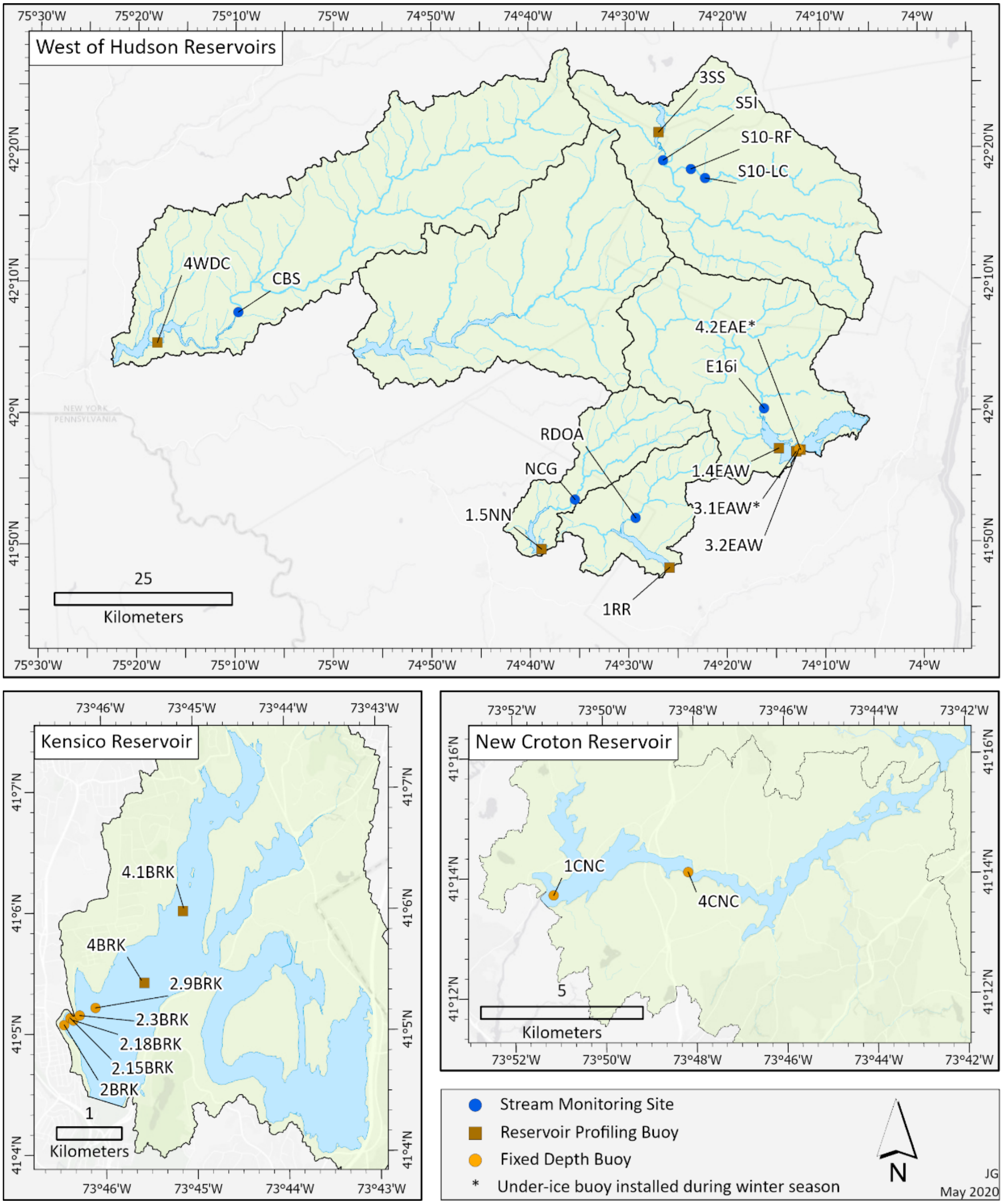


Figure 1.2. Robotic monitoring sites and types in the Catskill and Delaware Systems in 2019.

Three types of site installations comprise the RoboMon network: (1) profiling buoys in reservoirs, (2) fixed-depth sensors in reservoirs, including under-ice buoys, and (3) sensors in streams. Profiling buoys record and transmit full water column profiles for reservoir sites every six hours. These buoys are typically equipped with sensors that measure temperature, turbidity, and specific conductivity. Fixed depth buoys consist of turbidity sensors suspended in the water column at specific depths (e.g., 5, 10, and 15 meters) to provide near-real-time turbidity data recorded in 15-minute intervals. Stream sensors also typically record temperature and turbidity at 15-minute intervals. Sites with fixed-depth buoys are on Kensico Reservoir (at sites 2BRK and 2.9BRK) and on Ashokan (at site 3.2EAW). The Ashokan fixed depth buoy, deployed in 2018, is located at the site of the Ashokan dividing weir. It collects temperature, turbidity, and specific conductivity at approximately 1 meter from the surface and 2 meters from the bottom. The objective of this buoy is to help guide operations at the Ashokan Reservoir. Specifically, these data help mangers decide whether the reservoir should spill (from the west to the east) or should be transferred through the dividing weir gates. Fixed depth buoys have also been deployed on a short-term basis to monitor specific issues.

Each site is designed to contribute data for specific objectives. In an effort to develop reservoir carbon budgets to ultimately improve DEP's understanding of disinfection by-product formation potential (DBPfp), sensors for chlorophyll, phycocyanin (a blue-green algae pigment), dissolved oxygen, and fluorescent dissolved organic matter (fDOM) were added at the Cannonsville and Neversink reservoirs' buoys in 2015. In addition, fDOM probes were installed in 2017 at two stream monitoring huts to record data for the main inflows to Cannonsville and Neversink reservoirs.

To monitor water quality conditions during times of ice-over, two under-ice buoys were deployed on Ashokan Reservoir in December 2019. These units consisted of fixed depth underwater enclosures attached to stick buoys with turbidity sensors positioned at two discrete depths at approximately 5 and 15 meters below the water surface. The units were placed in front of the east and west basin gatehouses.

In addition to the reservoir buoy network, there are seven automated stream monitoring stations (RoboHuts) operated and maintained year-round. Two RoboHuts continuously monitor water temperature, specific conductivity, and turbidity at 15-minute intervals. One is located at Esopus Creek, near Coldbrook (installed 2012) and the other station is located on the Schoharie Creek near Prattsville (installed 2017). Five additional stream monitoring stations—Rondout Creek, near Lowes Corners (installed 2012), Neversink River (installed 2014), West Branch Delaware River (installed 2011), and two sites on the Batavia Kill in the Schoharie watershed (installed 2016 and 2017) —continuously monitor for turbidity and temperature only.

Changes in the robotic monitoring program during 2019 include the following:

- In spring 2019, three additional fixed depth buoys were deployed in Kensico to allow BWS staff ensure that the intake at Shaft 18 would not be impacted by elevated turbidity during shoreline stabilization construction activities near Shaft 18. These buoys provide turbidity data on 15-minute intervals. Sensors are deployed on these buoys at specific depths, generally one in the middle of the water column and one about 1m off the bottom of the reservoir.

- Two new profiling buoys were deployed on New Croton reservoir at sites 1CNC and 4CNC. This deployment began in August 2019 in support of using New Croton water during the Catskill Aqueduct shutdowns. Each buoy was outfitted with sensors for temperature, pH, dissolved oxygen (DO), and turbidity. These buoys were deployed adjacent to the Croton intake buildings to give operating staff at the Croton Filtration Plant current reservoir water quality data that is used to guide operational decisions.

Each robotic monitoring location contains data logging and communications equipment. At regular intervals each day, the most recent data are uploaded to a database at the DEP Kingston facility. These data can be viewed on the DEP intranet through a custom web application. In some cases, data are available within three minutes of the field measurement being taken. A standard operating procedure was developed for the program’s data management and quality control procedures.

As a result of failing equipment, some RoboMon data was not recorded in 2019. The profiling buoy in Kensico Reservoir (site 4.1BRK) was not deployed in 2019 due to extensive issues with the equipment. In the Catskill System, the Ashokan Reservoir site 1.4EAW buoy platform became compromised and the equipment was removed from the reservoir at the end of October. Ashokan Reservoir site 4.2EAE also had some technical difficulties resulting in data loss. Capital orders were being prepared in fiscal year 2020 for the replacement of the original four profiling buoys deployed in 2012.

1.1.3 Early Warning Remote Monitoring

The Early Warning Remote Monitoring (EWRM) team operates a network of real-time, continuous, water quality monitoring stations at strategic locations known as keypoints. These include aqueduct shafts, pumping stations, treatment facilities, and Esopus Creek. Instrumentation and sensors vary by site (Appendix A) and typical parameters include turbidity, temperature, pH, conductivity, free and/or total chlorine residual, fluoride residual, dissolved oxygen, elevation, and flow. The EWRM team follows a quality assurance program to ensure stations operate continuously and generate defensible data. The data are used by BWS staff for operation of the water supply.

Keypoint monitoring also includes sites needed for regulatory compliance. The Surface Water Treatment Rule (SWTR) requires calculation of the inactivation ratio (IAR). The daily IAR report utilizes data from the sites DEL18DT and DEL19LAB (or its alternate site DELSFBLAB). Fluoride residual is monitored at DEL19LAB and CCCLAB for compliance with treatment targets and limits. The Shandaken Portal (SRR2CM) and the upstream sampling station (AEAP) are both monitored for compliance with SPDES permits. For the Croton System, data collected from the Croton Gatehouse (CROGH) and the five potential withdrawal taps are of utmost importance to process control at the Croton Water Filtration Plant.

In addition to the instrumentation and parameters listed above, ToxProtect 64 fish biomonitoring systems were installed at DEL18DT and CROGH sites in 2019 for rapid detection of water quality impairments, including contamination events not detectable by the standard array of continuous monitoring instruments. Compared to the prior system, the new system has reduced false alarms and maintenance requirements.

Other 2019 enhancements completed by the EWRM team include the following:

- Design and installation of a new instrumentation panel at Ashokan.
- Reconfiguration of instruments at the Shaft 4 interconnection to support future treatment of the Catskill aqueduct.
- Reconstruction of the EARCM station.
- Addition of wireless data telemetry at the Cross River and Croton Falls pump stations.
- Reconstruction of three stations at the Croton Lake Gatehouse.
- Reconstruction of two stations at the Cornell Dam.
- Configuration of a buoy for real-time algae monitoring in Croton Falls Reservoir.

1.2 Operations in 2019 to Control Turbidity and Fecal Coliforms

In 2019, Water Quality staff developed a new weekly report, 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. The calculation uses the most recent data available for turbidity, fecal coliform, UV_{254}, and phytoplankton ASU to calculate an index number for nine reservoirs in the Catskill and Delaware systems so they can be ranked according to their water quality. Normally the four parameters are given equal weight in the index number, but the report can be modified as concerns change throughout the year. For example, after a storm event the report could be modified to give turbidity a greater weight in the calculation. The report is issued weekly to those involved in making operational decisions about reservoir diversions.

In 2019, monitoring for the potential formation of disinfection by-products (DBPfp) continued to guide selective withdrawal in order to deliver the highest quality water to the distribution system. As surrogates for DBPfp, UV_{254} (absorbance at 254 nm) and dissolved organic carbon (DOC), are indicators of aromatic organic compounds found in natural organic matter. Each were monitored weekly at the reservoir effluents and elevation taps and the data helped guide decision making when selecting which reservoirs to utilize. This proved most useful in the Delaware District, where there can be significant differences between the three headwater reservoirs. Utilizing reservoirs with lower UV_{254} and DOC help minimize DBP formation in the distribution system.

In the Catskill System, the elevation and location (east and/or west basin) of withdrawal at Ashokan Reservoir can be adjusted as needed throughout the year to draw 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). In 2019, the main water quality component driving operational changes was turbidity, as DBPfp surrogates were relatively low throughout the year.

In 2019, water was diverted from middle elevations in the East and West basins. For most of the year, the water was diverted from the East Basin, because an abundant supply minimized opportunity to create a void in the West Basin. In mid-June, the diversion was switched to a West Basin draw in an attempt to create a void, but rising turbidity curtailed that operation and the supply was switched back to East Basin at the end of the summer. The dividing weir was opened as needed to equalize the two basin elevations and closed in autumn to isolate the East Basin from turbidity in the West Basin. The Ashokan Release Channel helped control the storage elevation by sending water from West Basin into the lower Esopus Creek.

In the Delaware System, intake chambers at the four reservoirs were configured for diversion through the mid- or lower-level intakes. The only change in the elevation of withdrawal was at Rondout Effluent Chamber. Following an autumn rainstorm, the elevation was raised from the bottom (RR1) to a surface draw (RR4) to seek lower turbidity levels, where the draw remained for the remainder of the year. As mentioned above, UV_{254} and DOC data, with UV_{254} being the main driver, helped guide decisions on diversions into Rondout from the three upstream reservoirs.

Weather forecasts at Kensico Reservoir are watched closely to minimize the potential for elevated turbidity from entering the intake. If there are predictions of sustained easterly or northeasterly winds in excess of 15 mph, the operating mode at Delaware Aqueduct Shaft 18 is often changed from reservoir-only withdrawal to float mode withdrawal. This proactive change is made due to the potential for wave action to resuspend adjacent shoreline sediments. Float mode operation brings water from the Delaware Aqueduct directly to the downtake at Delaware Aqueduct Shaft 18, supplemented by water drawn from Kensico Reservoir. This operational change minimizes turbidity from Kensico Reservoir that could otherwise enter the Delaware Aqueduct. Float operation in anticipation of strong winds occurred four times (for all or part of 15 days) in 2019. The shoreline stabilization project mentioned above is expected to substantially reduce sediment resuspension.

The Croton Water Filtration Plant was operating at the start of 2019 and continued to operate until March 20, when it was shut down for maintenance. The plant was then restarted April 29 and operated until June 3, when it was again shut down for maintenance. The plant operated again on October 16 and remained on until December 23, when it was shut down due to taste and odor concerns.

2. Water Quantity

2.1 Introduction

The New York City water supply system is dependent on precipitation (rainfall and snowmelt) 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 2019 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 2019 monthly precipitation total for each watershed is plotted along with the historical monthly average (1989-2018) (Figure 2.1).

The total monthly precipitation (Figure 2.1) shows that precipitation was above the previous 30-year historical average (1989-2018) for January, and generally near the historical average in February, with March below average in several watersheds. Most watersheds in both April and May had amounts well above the historical average. The precipitation totals in June, July, and August were variable, with most watersheds showing fairly typical values, while others had below-average precipitation during this period e.g., Neversink and Rondout in July and Rondout and Pepacton in August. September was very dry in all watersheds, while October was a very wet month. Precipitation totals in November and December were variable, with some watersheds showing below average totals in November, e.g. Cannonsville and Pepacton, and some showing above average totals in December e.g., Neversink, Ashokan, and New Croton. In 2019, overall the NYC water supply watershed received 6.24 inches (158 mm) of precipitation above the historical calendar year average (1989-2018) of 46.19 inches (1,173 mm).

The National Climatic Data Center's (NCDC) climatological rankings (https://www.ncdc.noaa.gov/cag/) were queried to determine the 2019 rankings for New York. Overall total precipitation for New York State in 2019 was 48.18 inches (1,224 mm), which was 7.89 inches (200 mm) above the 20th-century mean (1901-2000) and the ninth wettest in the last 125 years (1895-2018). In New York's Climate Division 2, which includes the WOH reservoirs, the 2019 precipitation total was 7.37 inches (187 mm) above the 20th-century mean. October was the seventh wettest October on record for the division with 7.27 inches (185 mm) of precipitation. In New York's Climate Division 5, which includes the EOH reservoirs, precipitation was 5.91 inches (150 mm) above the 20th-century mean (1901-2000). October was the sixth wettest October in this division since 1895 with 7.06 inches (179 mm) of precipitation during the month. Also, the average temperature for New York State in 2019 was 45.3°F (7.4°C), which was 0.8°F (0.5°C) above normal (1901-2000) and the thirty-sixth warmest in the last 125 (1895-2019) years for New York.

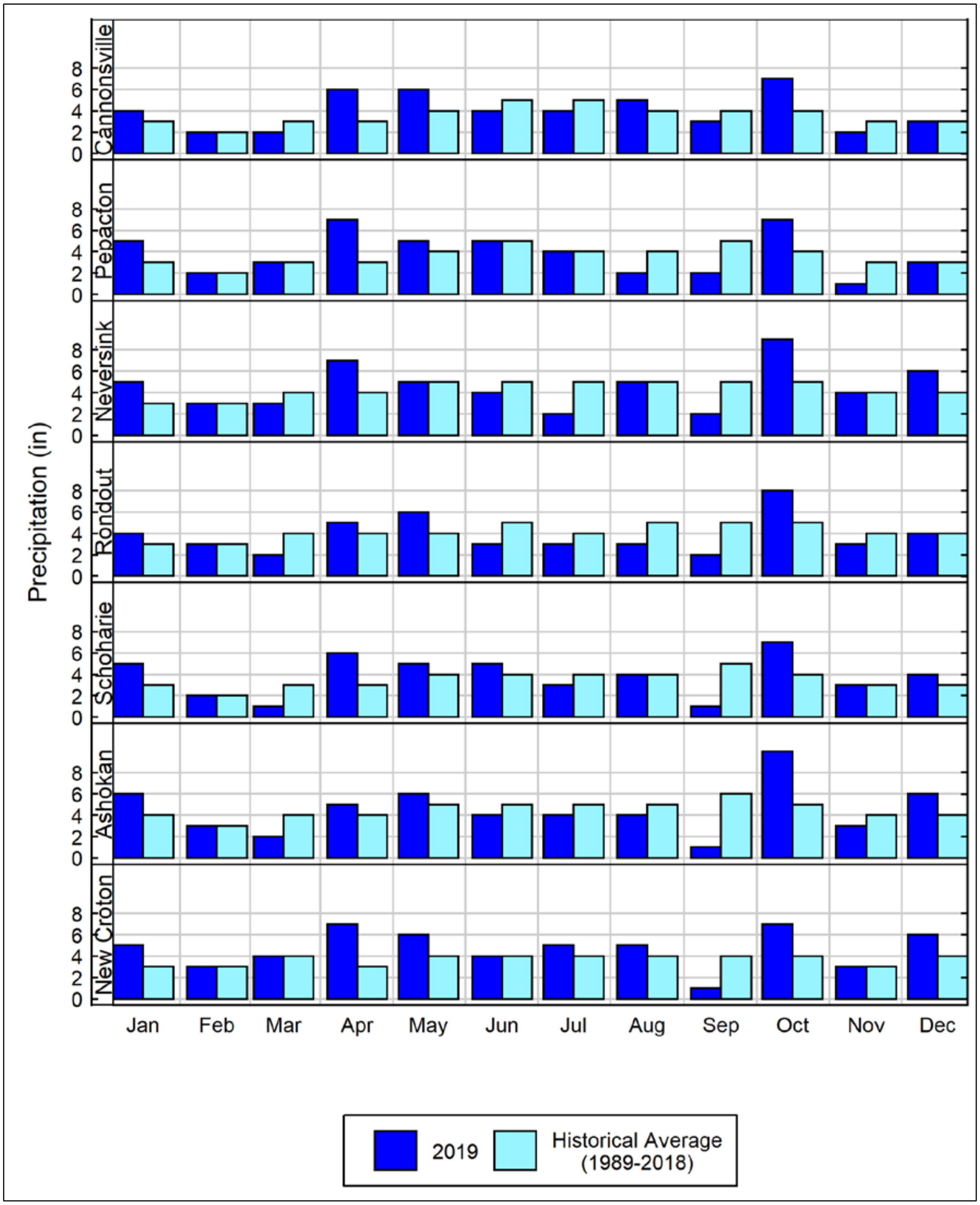


Figure 2.1 Monthly precipitation totals for New York City watersheds, 2019 and historical values (1989-2018).

2.3 2019 Watershed Runoff

Runoff is defined as the portion of the total rainfall and snowmelt that flows from the ground surface to a stream channel or directly into a basin. The runoff from 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 precipitation and resulting soil moisture, and temperature.

The physical characteristics of the watersheds also affect runoff. 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, which store or alter runoff. The annual runoff is a useful statistic to compare the runoff between watersheds. It is calculated by dividing the annual flow volume by the drainage basin area, yielding a depth that would cover the drainage area if all the runoff for the year were uniformly distributed over the basin. This statistic allows comparisons of the hydrologic conditions in watersheds of varying sizes.

Selected United States Geological Survey (USGS) stations (Figure 3.7) were used to characterize annual runoff in the different NYC watersheds (Figure 2.2). The time period with a complete record to calculate annual statistics for the WOH USGS stations ranges from 56 years at the Esopus Creek Allaben station to 113 years at the Schoharie Creek Prattsville gage. The EOH USGS stations have a 24-year period of record, except for the Wappinger Creek site (91-year period of record). Wappinger Creek is not located in the EOH System, but is included here because it is located in nearby Dutchess County and its longer period of record is more comparable to those found in the WOH System. Due to the above average precipitation (see sec. 2.2), annual runoff in calendar year 2019 was above the median annual runoff for the period of record for all sites, with the East Branch Delaware River, West Branch Delaware River, Neversink River, and Rondout Creek all exceeding the 75th percentile. Overall, New York State had well above normal runoff (8th highest (93.3 percentile) out of the last 119 years) for the 2019 water year (October 1, 2018-September 30, 2019), as determined by the USGS (http://waterwatch.usgs.gov/index.php?r=ny&m=statesum).

Figure 2.3 shows the 2019 mean daily discharge, along with the minimum, maximum, and median daily discharge for the period of record, for the same USGS stations used to characterize annual runoff. The stream discharge reflects the precipitation patterns. Of particular note are the low flows in September followed by storm peaks in October due to two large storms, with flows returning to normal conditions thereafter.

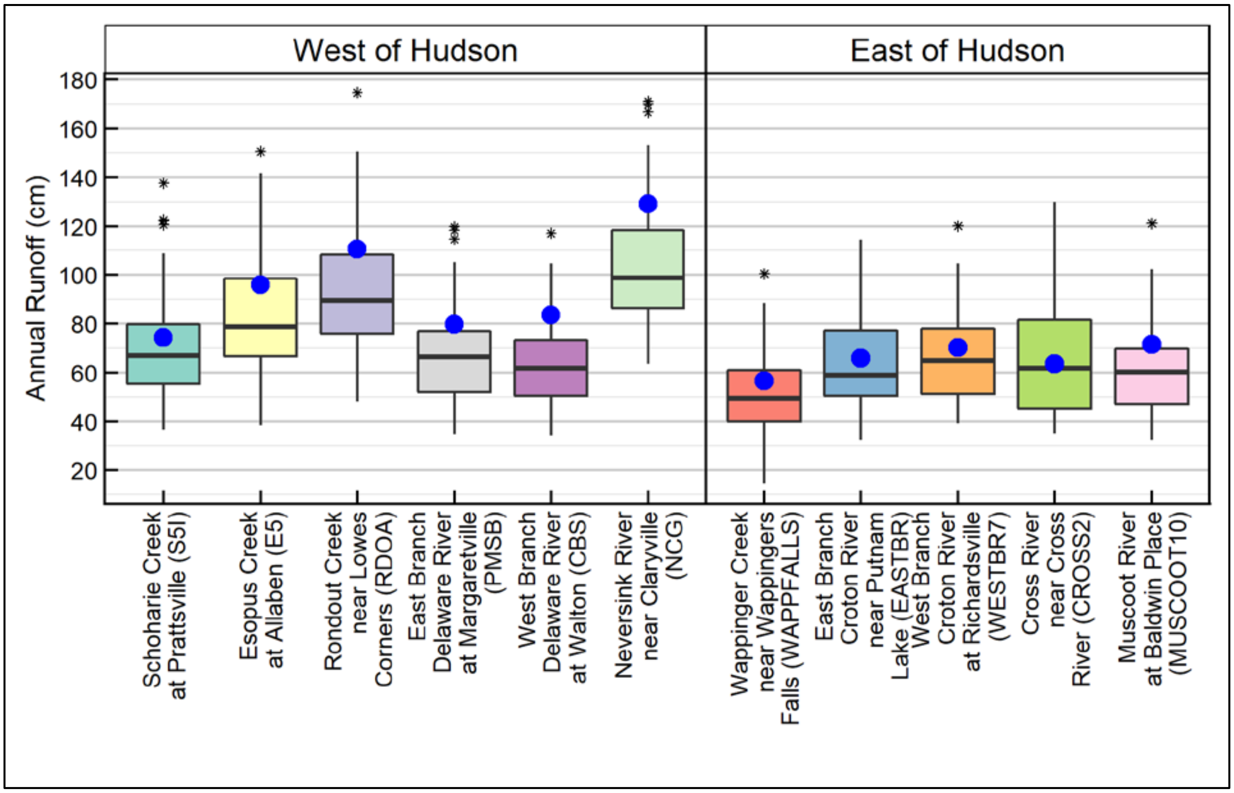


Figure 2.2 Historical annual runoff as boxplots for the WOH and EOH watersheds, with the values for 2019 displayed as a solid blue dot. The asterisks indicate outliers (see Appendix C for a key to the boxplot).

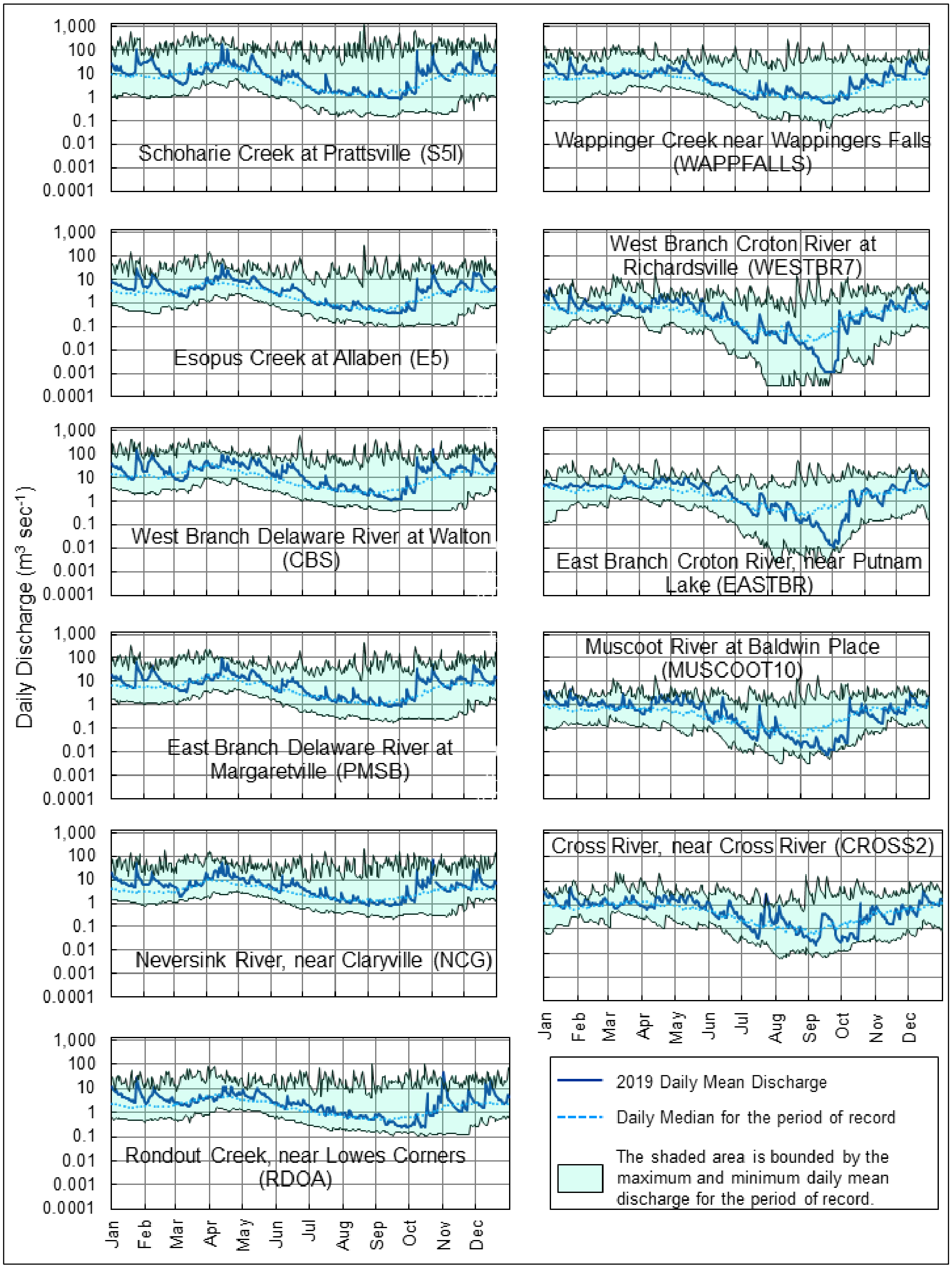


Figure 2.3 Daily mean discharge for 2019 at selected USGS stations. Daily data from October 1-December 31, 2019 are provisional and subject to revision until final approval from the USGS.

2.4 Reservoir Usable Storage Capacity in 2019

Ongo10ing daily monitoring of reservoir storage allows DEP to compare the systemwide storage in 2019 (including Kensico Reservoir) against average historical values for 1991-2018 for any given day of the year (Figure 2.4). Storage capacity fluctuated between 91% and 97% through February, ranging from 5% to 20%above normal capacity. Capacity remained slightly higher than normal through spring and early summer and then matched normal storage levels from mid-July to late August. Dry conditions from September through mid-October caused capacity to decrease to about 5% below normal levels during this period. The downward capacity trend was reversed in mid-October when a large storm produced 2-3 inches of rain throughout the water supply region. Numerous small events through the end of the year allowed storage to increase almost continually, resulting in capacity well above normal in November and December.

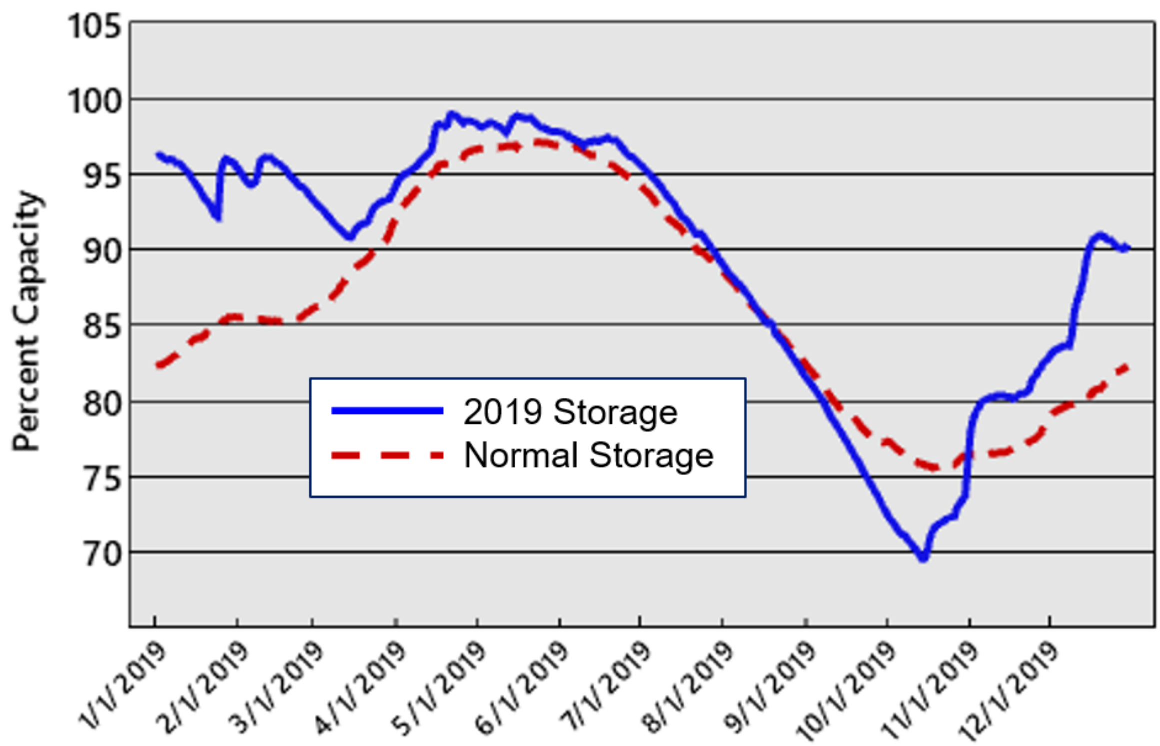


Figure 2.4 Systemwide usable storage in 2019 compared to the average historical value (1991-2018). Storage greater than 100% occurs when the water surface elevation is greater than the spillway elevation and reservoirs are spilling.

3. Water Quality

3.1 Monitoring Overview

Water quality samples are collected from designated sites (Appendix B) at streams, reservoirs, and aqueduct locations throughout the NYC water supply. Routine stream samples used in this report are collected on a fixed frequency, typically monthly schedule. Unless otherwise indicated, reservoir samples are obtained from multiple sites and multiple depths with routine sampling frequencies of once per month from April through November. Aqueduct keypoint samples are collected year-round at frequencies that vary from daily to weekly. Note that although Kensico Reservoir is usually operated as a source water, the reservoir can be bypassed so that any or all of 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 Surface Water Treatment Rule (SWTR).

3.2 Reservoir Turbidity Patterns in 2019

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 2019, turbidity levels in the Catskill/Delaware System reservoirs were close to their median historic levels or well below in the case of the east and west basins of Ashokan (Figure 3.1). (A key to boxplots is provided in Appendix C). Although lower compared to historic medians on an annual basis, turbidity levels in Schoharie Reservoir did experience some seasonal increases tied to rain events ranging from 1.7 to 2.2 inches in April, May, and October. Rain events greater than 2 inches did not occur in the Ashokan basin and precipitation levels were generally low within seven days prior to sampling. Preliminary results indicate that streambank stabilization projects within the Ashokan basin may have also contributed to the lower turbidity levels observed in Ashokan Reservoir in 2019, but further study under a full range of flows will be required to assess their impact.

As previously reported, past turbidity and suspended-sediment monitoring in the Ashokan basin found that the Stony Clove sub-basin was the highest yielding suspended-sediment contributor in the Ashokan basin prior to 2013 (McHale and Siemion 2014). Since 2012, DEP and the U.S. Department of Agriculture Natural Resource Conservation Service have sponsored eight stream sediment and turbidity reduction projects (STRPs) totaling approximately 2 kilometers in length in the Stony Clove sub-basin to help reduce turbidity at the sub-basin scale within the Ashokan basin. DEP and USGS began a 10-year suspended-sediment and turbidity monitoring study in 2016 to (1) track sub-basin trends in suspended-sediment yield and turbidity-discharge relationships in the upper Esopus Creek basin, and (2) evaluate the turbidity reduction efficacy of STRPs in the Stony Clove sub-basin. A biennial status report submitted as a FAD deliverable in March 2019 (DEP 2019a) presented the findings of the monitoring study through 2018. At that time, Woodland Creek was ranked as the highest yielding suspended-sediment and turbidity source in the Ashokan basin, followed by Broadstreet Hollow, Birch Creek, Beaver Kill, and Stony Clove Creek. Incorporating the 2019 turbidity monitoring data into the previous data set shows that Birch Creek and Woodland Creek have a similar range and median value as the highest ranking mean daily turbidity sub-basin sources. Birch Creek turbidity increased notably in 2019, while Stony Clove Creek continued to have lower median and maximum mean daily turbidity values, although both sub-basins experienced similar hydrologic conditions that drive turbidity production. This observation provides further support to the conclusion presented

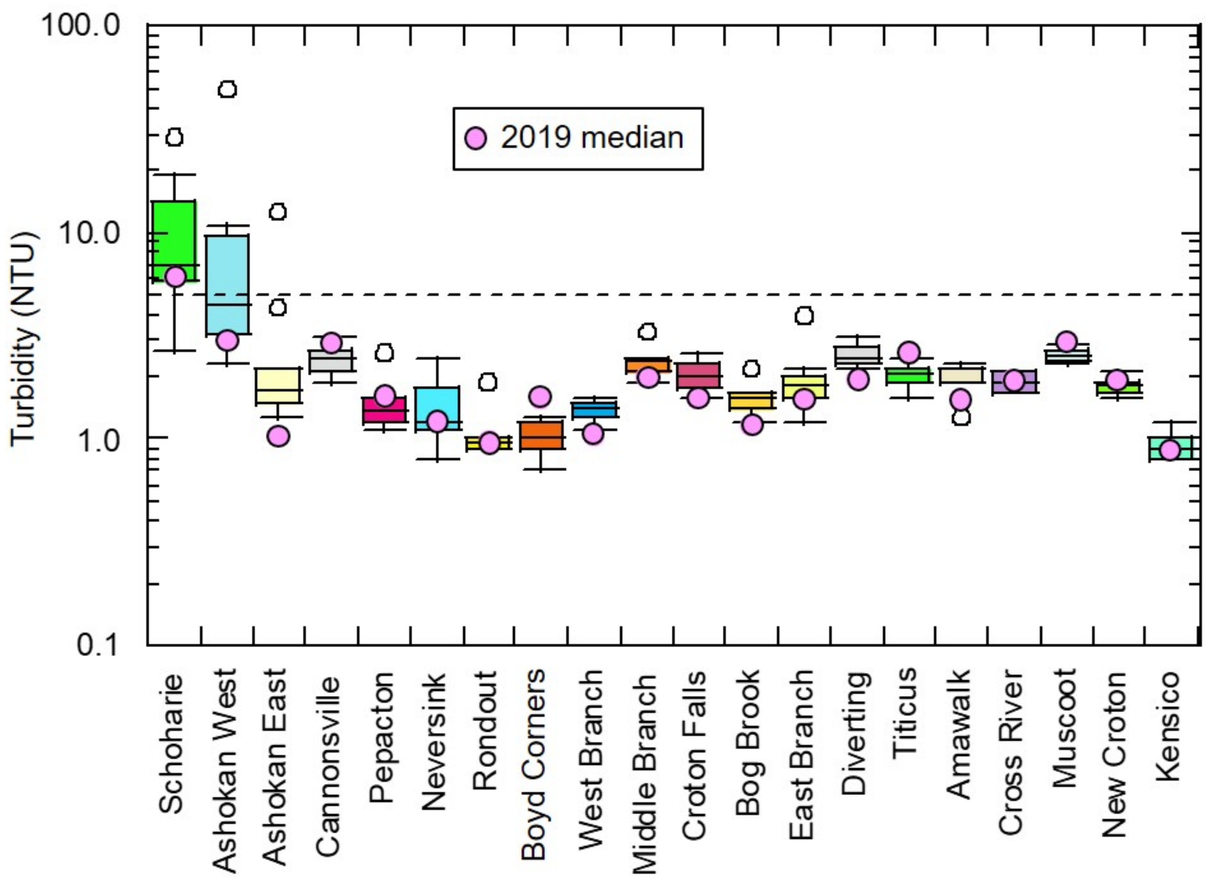


Figure 3.1 Annual median turbidity in NYC water supply reservoirs (2019 vs. 2009-2018), with the 2019 values displayed as a solid dot and outliers as open circles. The dashed line represents the SWTR standard for source water as a reference.

in the 2019 biennial status report that there is growing evidence that the STRPs in the Stony Clove sub-basin are continuing to be effective in reducing turbidity for the range of observed flows. As noted last year, the study area has still not experienced a high magnitude flood event that would test STRP efficacy for the high turbidity levels that can impact Ashokan Reservoir operations.

West Branch Reservoir, which receives inputs from both the Delaware (i.e., Rondout Reservoir) and the Croton System (i.e. local West Branch streams and Boyd Corners release), also had low turbidity levels in 2019. Much higher inputs of low turbidity water from Rondout dominated the total inputs into West Branch in 2019, which helped lower turbidity below historic levels. The slightly higher historic turbidity of West Branch Reservoir compared to its main inputs, Rondout Reservoir and Boyd Corners Reservoir, is largely due to higher summer-fall turbidity associated with low oxygen conditions in the hypolimnion of West Branch. Within Kensico Reservoir, the terminal reservoir for the Catskill/Delaware System, turbidity was low, corresponding to the high clarity of water received from both systems in 2019.

Similar to the Catskill/Delaware System, turbidity in the Croton System was generally normal to well below normal in 2019 (reservoirs shown in Figure 3.1, controlled lakes in Table 3.1). Note that due to inadequate resources and to accommodate the samples from numerous special investigations, turbidity samples were not collected after August at the following reservoirs: Amawalk, Bog Brook, Diverting, East Branch, Middle Branch, Titicus, Muscoot, or the controlled lakes. To ensure a fair comparison, only data from April to August was used to represent historic data for these reservoirs in Figure 3.1. Compared to historic levels, turbidity was elevated at Boyd Corners and Titicus, and slightly elevated at Muscoot and New Croton. Higher turbidity at these reservoirs was associated with algal blooms and various runoff events.

Table 3.1 Turbidity summary statistics for NYC controlled lakes (NTU).

Lake	Median Turbidity (2009-18)	Median Turbidity (2019)
Gilead	1.4	1.1
Gleneida	1.4	1.0
Kirk	4.5	4.5

3.3 Coliform-Restricted Basin Assessments in 2019

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) restrict 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 NYS ambient water quality standard limits on total coliform bacteria (6 NYCRR Parts 701 and 703).

3.3.1 Terminal Basin Assessments

Table 3.2 provides coliform-restricted assessments for the five terminal reservoir basins. The results are based on 2019 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 $100mL^{-1}$ 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 2019.

Table 3.2 Coliform-restricted basin status as per Section18-48(c)(1) for terminal reservoirs in 2019.

Reservoir basin	Effluent keypoint	2019 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 3.3 provides a summary of the 2019 coliform-restricted calculation results for the non-terminal reservoirs and Appendix D includes the details for coliform monthly medians and the percentage of values exceeding the relevant standard.

In 2019, there was a decrease in exceedances from the previous year for the Part 703 total coliform standard for seven reservoirs. The highest number of exceedances occurred in Cannonsville Reservoir for seven out of eight months sampled, an increase from four months with exceedances the previous year. Five reservoirs and three controlled lakes had no exceedances.

Total coliform bacteria originate from a variety of natural and anthropogenic (human-related) sources. However, Section 18-48(d)(1) states that 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 3.3 Coliform-restricted calculations for total coliform counts on non-terminal reservoirs in 2019.

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

3.4 Reservoir Fecal and Total Coliform Patterns in 2019

Total coliform and fecal coliform bacteria are important as indicators of potential pathogen contamination. Fecal coliform bacteria are more specific 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 3.3 and reservoir total coliform results in Figure 3.4. Coliform results for the controlled lakes of the Croton System are summarized in Table 3.4. According to the Filtration Avoidance Criteria of the Surface Water

Treatment Rule (SWTR), fecal coliform concentrations must be ≤ 20 fecal coliforms 100 mL^{-1} or total coliform concentrations must be ≤ 100 total coliforms 100 mL^{-1} in at least 90% of the measurements from the last 6 months. The rule only applies to source waters immediately prior to the first point of disinfectant application and so does not apply to the reservoirs and controlled lakes of the NYC water supply. Nonetheless, lines at 20 fecal coliforms 100 mL^{-1} and 100 total coliform 100 $mL^{-1}$are provided on the plots in this section as a point of reference. Also, note that data used to construct the boxplots are based on the distribution of the annual 75th percentiles. The center line in the boxplot represents the median of the 75^{th} percentile values rather than the 50^{th} percentile or median of annual values. Using the 75th percentile makes it is easier to discern differences among reservoirs because a large percentage of coliform data are generally below the detection limit. If a calculated annual 75^{th} percentile results in a censored value or zero, it was estimated using the robust regression on statistics method (ROS) of Helsel and Cohn (1988).

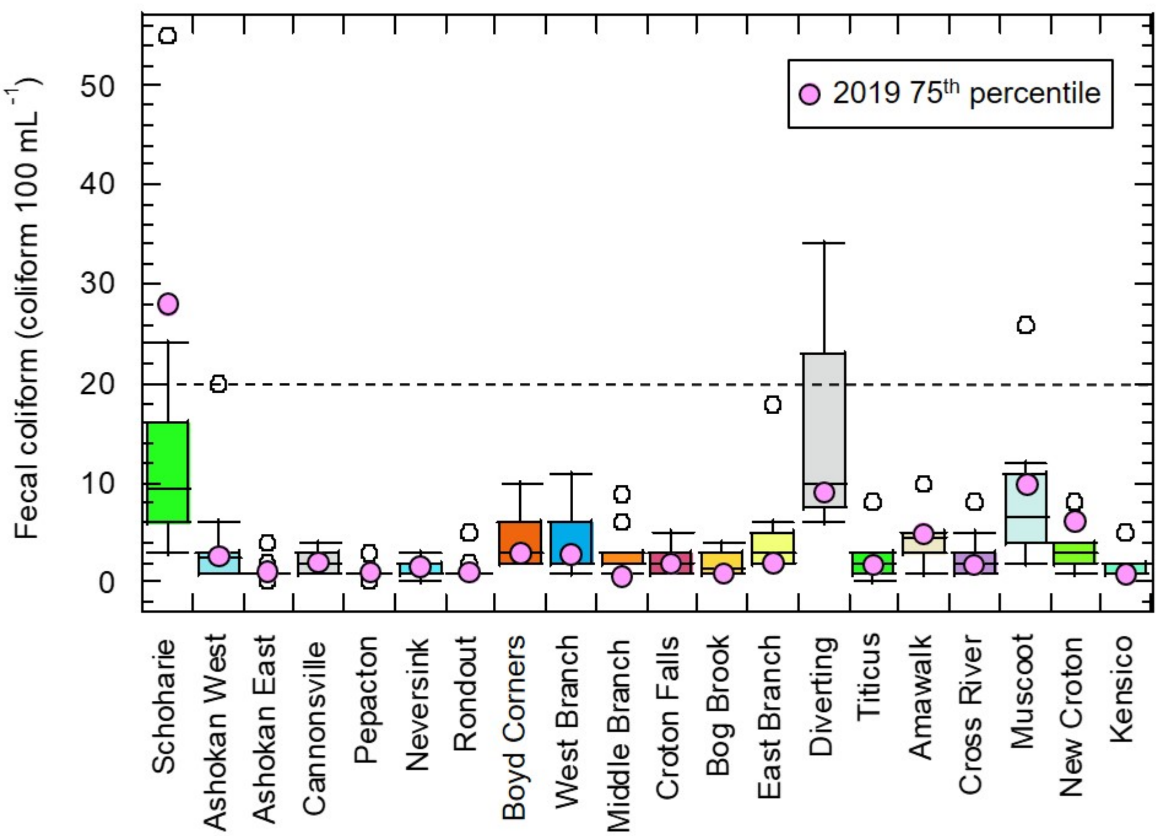


Figure 3.2 Annual 75th percentile of fecal coliforms in NYC water supply reservoirs (2019 vs. 2009-2018), with the 2019 values displayed as a solid dot and outliers as open circles. The dashed line represents the SWTR standard for source water as a reference.

In 2019, fecal coliform counts were generally within normal levels in most of the Catskill/Delaware reservoirs, including West Branch and Kensico (Figure 3.3). Elevated fecal counts were observed at Schoharie, however, with the highest counts preceded by rain ranging from 1.2 to 2.1 inches within eight days of sampling in April, June, and October. Fecal coliform counts were in the normal to low range for most of the Croton System reservoirs and controlled lakes (Table 3.4) with only elevated annual medians occurring at Boyd Corners, Croton Falls, and Muscoot. Elevated fecal coliform counts at these reservoirs were generally preceded by rain events in excess of 1 inch within nine days of sampling.

Similar to 2018, total coliform counts were lower than normal in the Catskill System reservoirs but were higher than normal in all reservoirs of the Delaware System (Figure 3.4). The elevated total coliform counts occurred throughout the water column and were probably introduced to the reservoirs via higher than usual runoff in April and May. Diversions from headwater reservoirs Cannonsville and Pepacton into Rondout were likely the primary factor for the higher total coliform counts observed at Rondout. Daily keypoint results from Cannonsville were elevated starting in late June and from Pepacton in mid-August and both stayed high for much of the remaining year.

Total coliform counts generally decreased from the previous year in the Croton System following the same pattern observed for fecal coliform counts; only Boyd Corners, Croton Falls, and Muscoot exhibited somewhat higher counts in 2019. High total coliform counts were typically preceded by rain events and, in the case of Croton Falls and Muscoot, perhaps enhanced by higher than historic water temperatures from April to July.

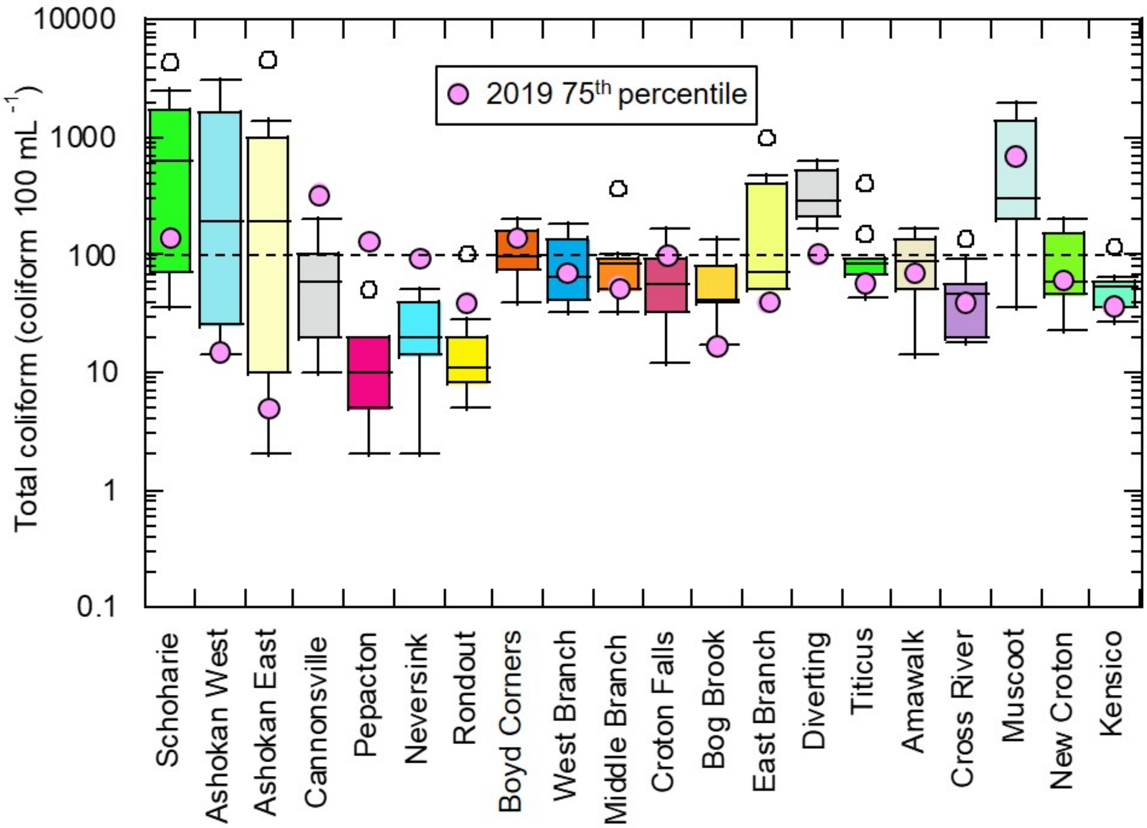


Figure 3.3 Annual 75th percentile of total coliforms in NYC water supply reservoirs (2019 vs. 2009-2018), with the 2019 75th percentile values displayed as a solid dot and outliers as open circles. The dashed line represents the SWTR standard for source water as a reference."

Table 3.4 Summary statistics for coliforms in NYC controlled lakes (coliforms 100 mL^{-1}).

Lake	Historical total coliforms (75th percentile 2009-18)	Current total coliforms (75th percentile 2019)	Historical fecal coliforms (75th percentile 2009-18)	Current fecal coliforms (75th percentile 2019)
Gilead	15	20	1	<1
Gleneida	10	10	<1	<1
Kirk	97	33	3	3

3.5 Phosphorus-Restricted Basin Assessments in 2019

The phosphorus-restricted basin status determination for 2019 is presented in Table 3.5. Status is determined from two consecutive assessments (2014-2018 and 2015-2019) using the methodology described in Appendix E. 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.

In 2019, there were no changes in phosphorus-restricted status from the previous assessment period. Figure 3.4 graphically shows the phosphorus-restricted basin status of the City's reservoirs for the five-year assessment period compared with the previous assessment period. Geometric means for individual years that contributed to the assessments are shown in Appendix E. For 2019, annual geometric mean phosphorus concentrations declined in all reservoirs and controlled lakes, with the exception of Cannonsville, with an increase of 1.3 µg L^{-1} and Neversink, which remain unchanged (Appendix E). The greatest declines from the previous year's annual geometric mean TP concentration were in Lake Gilead (12.2 µg L^{-1} decrease), Middle Branch (11.1 µg L^{-1} decrease), and Amawalk (8.1 µg L^{-1} decrease) (Appendix E). In a comparison of the five-year assessment periods (Table 3.5), changes are small in magnitude. None of the Delaware or Catskill reservoirs were phosphorus-restricted and all of the reservoirs and lakes in the Croton System were phosphorus-restricted, with the exception of Boyd Corners Reservoir. Among the source water reservoirs and potential source water (i.e., terminal) reservoirs, New Croton, Cross River, and Croton Falls reservoirs were classified as phosphorus-restricted. West Branch Reservoir was non-restricted, reflecting the influence of Delaware System water on its water quality status.

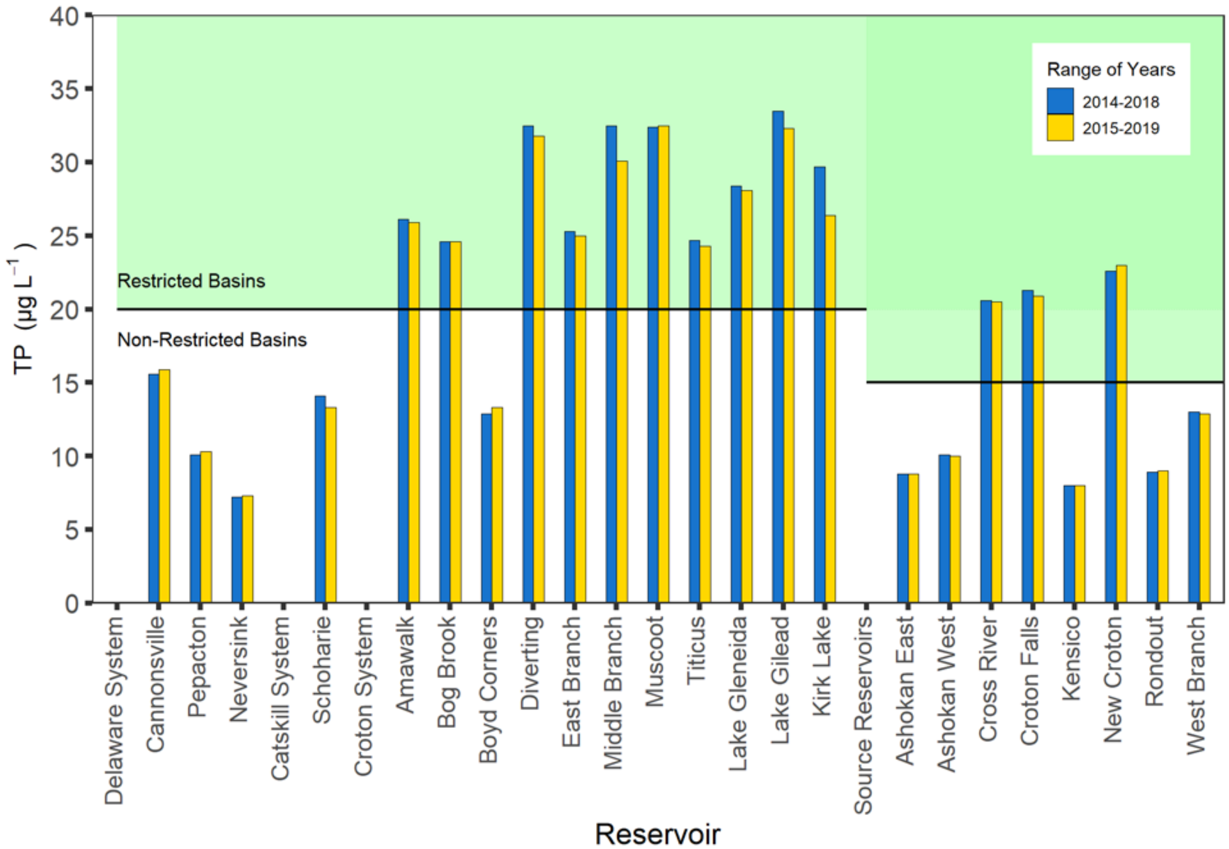


Figure 3.4 Phosphorus-restricted basin assessments. The horizontal solid lines at 20 µg L^{-1} and 15 µg L^{-1} represent the trophic guidance value for non-source and source waters, respectively.

Table 3.5 Phosphorus-restricted basin status for 2019.

Reservoir basin	2014-2018 Assessment[1] (μg L^{-1})	2015-2019 Assessment[1] (μg L^{-1})	Phosphorus restricted status[2]
Non-Source Waters (Delaware System)			
Cannonsville	15.6	15.9	Non-restricted
Pepacton	10.1	10.3	Non-restricted
Neversink	7.2	7.3	Non-restricted
Non-Source Waters (Catskill System)			
Schoharie	14.1	13.3	Non-restricted
Non-Source Waters (Croton System)			
Amawalk	26.1	25.9	Restricted
Bog Brook	24.6	24.6	Restricted
Boyd Corners	12.9	13.3	Non-restricted
Diverting	32.5	31.8	Restricted
East Branch	25.3	25.0	Restricted
Middle Branch	32.5	30.1	Restricted
Muscoot	32.4	32.5	Restricted
Titicus	24.7	24.3	Restricted
Lake Gleneida	28.4	28.1	Restricted
Lake Gilead	33.5	32.3	Restricted
Kirk Lake	29.7	26.4	Restricted
Source Waters (all systems)			
Ashokan East	8.8	8.8	Non-restricted
Ashokan West	10.1	10.0	Non-restricted
Cross River	20.6	20.5	Restricted
Croton Falls	21.3	20.9	Restricted
Kensico	8.0	8.0	Non-restricted
New Croton	22.6	23.0	Restricted
Rondout	8.9	9.0	Non-restricted
West Branch	13.0	12.9	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]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 2019

Total phosphorous (TP) levels in the Catskill/Delaware reservoirs, including West Branch and Kensico, were generally within their historic ranges (Figure 3.6,). Only Cannonsville was elevated but only exceeded its historic median TP by 1 µg L^{-1}. In the Croton System, only Boyd Corners Reservoir showed a TP increase in 2019 (Figure 3.6, Table 3.6). The increase is likely the result of inputs from the West Branch of the Croton River. Although annual TP was close to its historic median concentration (Figure 3.8b), monthly TP concentrations were higher than their historic levels in the river from May-August, coinciding with multiple runoff events that occurred throughout this period.

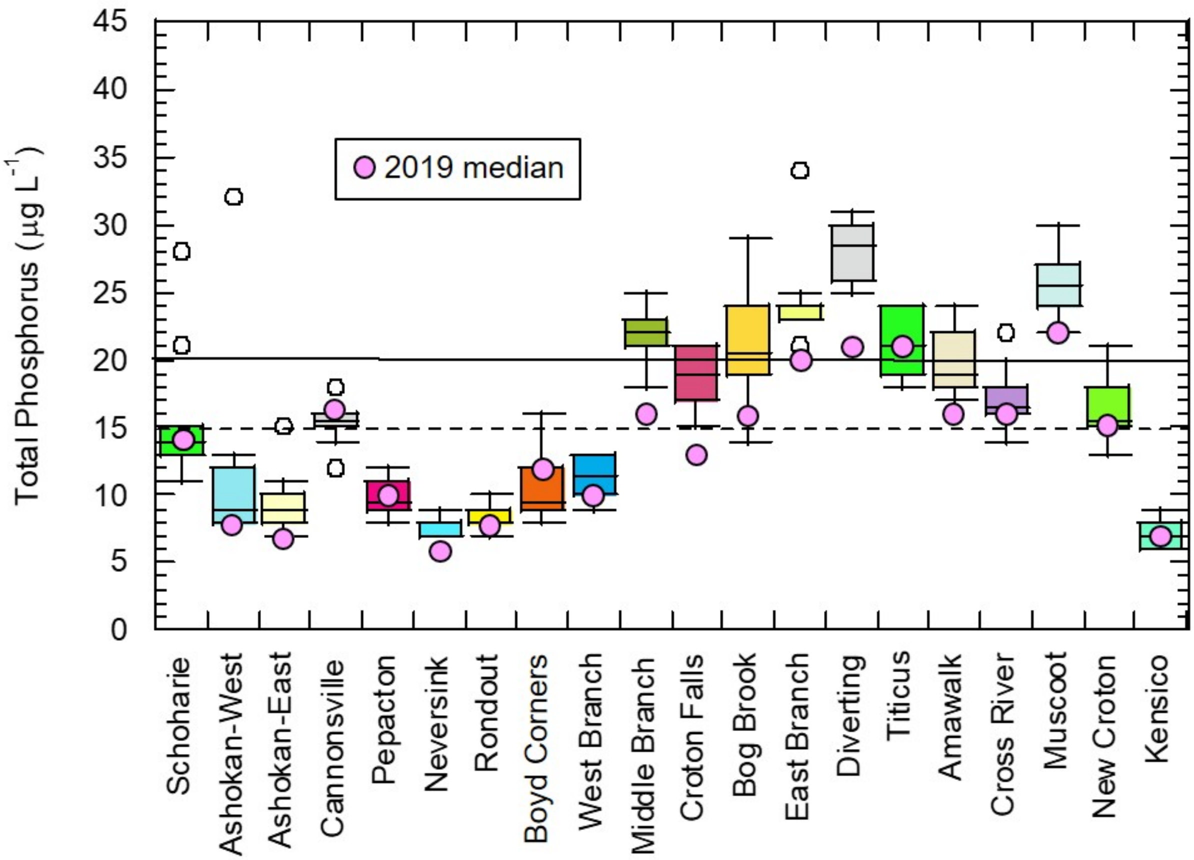


Figure 3.5 Annual median total phosphorus in NYC water supply reservoirs (2019 vs. 2009-2018), with the 2019 75th percentile values displayed as a solid dot and outliers as open circles. The horizontal dashed line at 15 µg L^{-1} refers to the NYC Total Maximum Daily Load (TMDL) guidance value for source 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 3.6 Total phosphorus summary statistics for NYC controlled lakes (µg L^{-1}).

Lake	Median Total Phosphorus (2009-2018)	Median Total Phosphorus (2019)
Gilead	20	14
Gleneida	16	9
Kirk	30	19

3.7 Reservoir Comparisons to Benchmarks in 2019

The New York City reservoirs and water supply system are subject to the federal SWTR standards, NYS ambient water quality standards, and DEP's own guidelines. In this section, the results for 2019 water quality sampling, including a variety of physical, biological, and chemical analytes for the terminal reservoirs, are evaluated by comparing the results to the water quality benchmarks listed in Table 3.7. These benchmarks are based on applicable federal, state, and DEP standards or guidelines. Note that the standards 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 reservoirs. Placing the data in the context of these benchmarks assists in understanding the robustness of the water system and helps in identifying water quality issues.

Comparisons of 2019 reservoir sample results to benchmark values are provided in Appendix F. Data represent samples collected monthly from April to November for multiple reservoir and controlled lake sites and depths as part of the fixed-frequency water quality monitoring program. Highlights of the benchmark comparisons for terminal reservoirs from 2019 include the following:

pH

In 2019, reservoir samples were generally in the circumneutral pH range (6.5-8.5). The majority of pH values outside the circumneutral range for Kensico and West of Hudson reservoirs, with lower alkalinities than Croton System reservoirs, were below a pH of 6.5, with some exceptions when algal blooms elevated pH. The pH exceeded 8.5 during summer phytoplankton blooms, particularly in Cannonsville Reservoir for over half of the cases of pH outside the circumneutral range. The greatest number of pH values below 6.5 were in Neversink Reservoir, with 70% of all samples below this benchmark. In the Croton System, all exceedances were from values above pH 8.5, with the exception of three samples in West Branch Reservoir below pH 6.5, a reflection of water transferred from the Delaware System. The number of high values of pH was greatest in Croton Falls Reservoir, with 29% of samples exceeding pH 8.5. Boyd Corners and Diverting had no pH values outside the circumneutral range.

Table 3.7 Reservoir and controlled lake benchmarks as listed in the WR&R (DEP 2019b).

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 100 mL^{-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 counts exceeded the single sample maximum of 2,000 ASU mL^{-1} for total phytoplankton for 24 out of 467 samples evaluated across both EOH and WOH reservoirs and controlled lakes. These exceedances occurred in seven EOH reservoirs, with the highest number of exceedances in Croton Falls (27%) and New Croton (25%). The only WOH reservoirs with exceedances of the single sample maximum were Cannonsville (11%) and Pepacton (6%). Phytoplankton samples are collected at a discrete depth of 3 m. Some additional surface samples were collected as part of screening for algal toxins (see section 3.13.7). Six NYC reservoirs and one controlled lake were included on the NYSDEC Harmful Algal Blooms (HABs) Program notifications (NYSDEC 2019) (http://www.dec.ny.gov/docs/water_pdf/habsextentsummary.pdf). As in the preceding year, Kirk Lake was listed as having a confirmed bloom in 2019. NYSDEC categorizes confirmed blooms for water sampling results as those with confirmed presence of cyanobacteria that may produce toxins or other harmful compounds. Ashokan, Croton Falls, New Croton, West Branch, Neversink, and Cannonsville reservoirs were listed as having a "suspicious bloom" based on visual observation and/or digital photographs.

Chlorophyll a, Color, and Dissolved Organic Carbon

Chlorophyll *a* concentration is a surrogate measure of algal biomass. Among the WOH reservoirs, Cannonsville had five samples (14%) that exceeded the single sample maximum and also slightly exceeded the annual mean standard. Neversink and Ashokan East had no chlorophyll single sample exceedances, while the remaining WOH reservoirs were below the annual mean standard with few exceedances of the single sample maximum. In the Croton System, 10 reservoirs and one controlled lake (Kirk Lake) exceeded the single sample maximum and four of these reservoirs and Kirk Lake exceeded the annual mean benchmark for chlorophyll *a*. There were no chlorophyll *a* exceedances in Kensico.

Color is an indicator of organic matter both from reservoir and watershed sources. For reservoir samples in 2019, only New Croton was evaluated for color. All 10 samples collected exceeded the 15 Pt-Co unit color benchmark value for single sample maximum.

There were no exceedances of the annual mean standard for dissolved organic carbon (DOC) in NYC reservoirs in 2019. Ashokan East had one exceedance of the single sample maximum, the only exceedance for DOC in the entire system.

Chloride

In 2019, there were no exceedances for chloride in the WOH reservoirs with the exception of Cannonsville, which exceeded both the single sample maximum (20 of 24 samples or 83%) and mean annual benchmark value of 8 mg L^{-1} (annual mean 11.5 mg L^{-1}). All Croton System reservoirs and three controlled lakes sampled in 2019 exceeded the single sample maximum of 40 mg L^{-1} and annual mean benchmark of 30 mg L^{-1}, with the exception of West Branch, with 80% exceedances of the single sample maximum and an annual mean chloride concentration below the benchmark value. Five Croton System reservoirs were not sampled for chloride (Amawalk, Diverting, Middle Branch, Muscoot and Titicus). Kensico Reservoir had no exceedances for chloride. All chloride samples were well below the health secondary standard of 250 mg L^{-1}.

Turbidity

The Catskill/Delaware reservoirs had a higher number of exceedances for turbidity than those in the Croton System in 2019. For the Catskill System, the highest number of exceedances were for Schoharie Reservoir (69%), fewer than in the previous year, and the number of exceedances was much lower in the receiving waters Ashokan West (29%) and Ashokan East (6%). In the Delaware System, Cannonsville had 24 out of 102 samples (24%) that exceeded the 5 NTU benchmark, with fewer exceedances in the other three Delaware reservoirs. Rondout had only 2 out of 80 samples (3%) above 5 NTU. Turbidity levels in Kensico, and the majority of Croton System reservoirs did not exceed the single sample maximum of 5 NTU in 2019. The highest number of exceedances in the Croton System for turbidity was in Croton Falls, where 15 of 64 samples collected (23%) exceeded the 5 NTU benchmark.

Nutrients

In the Delaware System, Cannonsville had the greatest number of single sample maximum exceedances (61%), Pepacton had fewer exceedances (17%), and Neversink and Rondout had one sample that exceeded the benchmark value for total phosphorus (TP) in 2019. For the Catskill System, Schoharie had the greatest number of exceedances for TP (43%), with fewer in Ashokan West (8%) and Ashokan East (5%). In the Croton System, TP exceeded the 15 µg L^{-1} benchmark in all reservoirs and controlled lakes, and Muscoot (98%), Diverting (94%), and Titicus (83%) were among the highest in number of exceedances for TP. West Branch, with influences from the Catskill/Delaware systems, had fewer exceedances (17%). Kensico Reservoir had a single sample that exceeded the benchmark value for TP.

There were few exceedances for nitrate/nitrite throughout the system in 2019. The only exceedances of the single sample maximum for the WOH reservoirs was in Cannonsville (24%) with a slight exceedance of the annual benchmark value. Three Croton System reservoirs exceeded the single sample maximum value: Croton Falls (8%), Muscoot (17%), and New Croton (2%). Only Muscoot exceeded the annual mean benchmark of 0.30 mg L^{-1} in 2019, with an annual mean of 0.49 mg L^{-1}.

Fecal Coliform Bacteria

In 2019, fecal coliform bacteria were low in reservoirs throughout the system. Fecal coliform counts exceeded the single sample maximum of 20 fecal coliforms $100mL^{-1}$ for one sample in Kensico, West Branch, Pepacton, and Neversink, representing 1% of samples. Rondout had two samples that exceeded the benchmark (3%). The highest percentage of values greater than the benchmark in the Catskill System was in Schoharie (29%). There were no exceedances in Ashokan East. The highest number of exceedances for the Croton System was in Muscoot (22%). There were no exceedances in the Croton System in East Branch and Middle Branch, and the three controlled lakes.

3.8 Reservoir Trophic Status in 2019

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:

$$TSI = 9.81 \times (\ln (CHLA)) + 30.6$$

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. Trophic state indices are generally calculated from data collected in the photic zone of the reservoir during the growing season (May through October). A low trophic state is desirable because such reservoirs produce better water quality at the tap.

Historical (2009-2018) annual median TSI based on chlorophyll *a* concentration is presented in boxplots for all reservoirs in Figure 3.6. Results for the East of Hudson controlled lakes are provided in Table 3.8. This analysis generally indicates that all West of Hudson reservoirs (including Kensico and West Branch) and only three East of Hudson reservoirs/lakes (Boyd Corners, Gilead, and Gleneida) usually fall into the mesotrophic category. The remaining East of Hudson reservoirs tend to fall into the meso-eutrophic to eutrophic range.

In 2019, TSI was elevated in most reservoirs of the Catskill/Delaware System and in six of 11 reservoirs of the Croton System. Note that due to inadequate resources and to accommodate the samples from numerous special investigations, TSI samples were not collected after August at the following reservoirs: Amawalk, Bog Brook, Diverting, East Branch, Middle Branch, Titicus, Muscoot, and the controlled lakes. To ensure a fair comparison, only data from May to August was used to represent historic data for these reservoirs (Figure 3.6). Reasons for the productivity increase are not clear. Annual median TP from incoming streams was generally high for the Croton System but low for the Catskill/Delaware System, with the exception of the main inflow to Cannonsville (Figure 3.8). Annual median total nitrogen (TN) was normal to low (data not shown) for incoming streams in all systems. With the exception of Boyd Corners and Cannonsville, reservoir annual median TP concentrations were generally in the normal to low range when including samples from all depths (Figure 3.5) and were in discordance with the elevated TSI. Additional factors were examined in an attempt to explain the increase in TSI.

Surface water temperatures were warmer than normal in various months during the year but did not necessarily coincide with the months displaying elevated productivity. An increase in residence time may allow algae more opportunity to access available nutrients, but with the exception of Ashokan, residence times were similar to the past. While residence time increased at Ashokan, only the West Basin experienced elevated TSI in 2019. To a limited extent, water clarity could be a factor accounting for increased productivity. In the past, high turbidity levels that could prevent algal growth have occurred in Schoharie and in the west basin of Ashokan. In 2019, turbidity levels were relatively low (Figure 3.1) and water clarity was probably sufficient to support algal growth in these reservoirs. Water transfer is an additional factor that influences TSI levels in cascading reservoir systems. Rondout water quality is largely a product of the inputs it receives from its headwater reservoirs. In 2019, Rondout's elevated TSI was a reflection of water transfers from reservoirs with higher TSI values, especially from Cannonsville and Pepacton. Likewise, TSI in West Branch and Kensico is largely influenced by inputs from its sources. Inputs to West Branch are dominated by diversions from Rondout with lesser contributions from water released from Boyd Corners and from streams located within the West Branch watershed. Median TP from these streams was high in 2019 and also may have contributed to the elevated TSI observed at West Branch in 2019. Kensico's TSI largely reflects the mixture of water it receives from Rondout and Ashokan reservoirs with some variation due to in-reservoir algal production and losses through senescence and sedimentation.

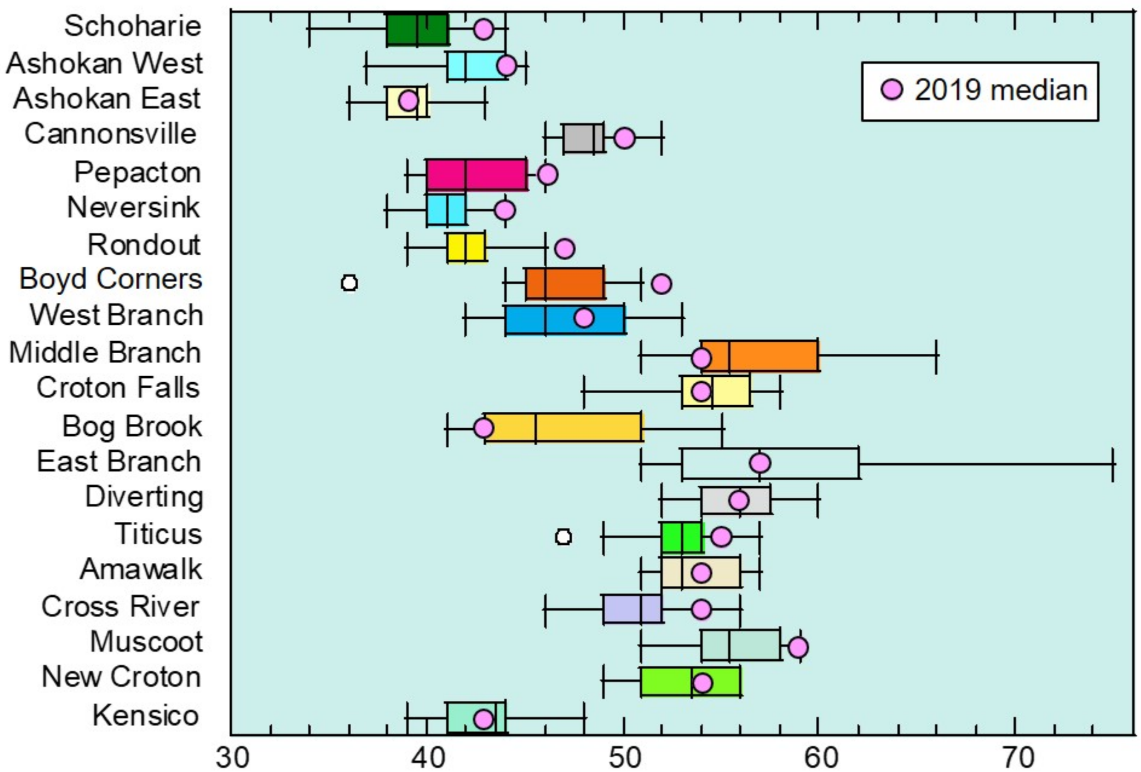


Figure 3.6 Annual median Trophic State Index (TSI) in NYC water supply reservoirs (2019 vs. 2009-2018), with the median displayed as a solid dot and outliers as open circles. In general, data were obtained from epilimnetic depths at multiple sites, at routine sampling frequencies once per month from May through October. TSI is based on chlorophyll *a* concentration.

Table 3.8 Trophic State Index (TSI) summary statistics for NYC controlled lakes.

Lake	Median TSI (2009-2018)	Median TSI (2019)
Gilead	45	42
Gleneida	41	39
Kirk	61	62

3.9 Water Quality in the Major Inflow Streams in 2019

The stream sites discussed in this section are listed in Table 3.9, with locations shown in Figure 3.7. These stream sites were chosen because they are immediately upstream from the six Catskill/Delaware reservoirs and six of the Croton reservoirs. They represent the bulk of the water entering the reservoirs from their respective watershed. 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 2019 results presented in Figure 3.8 are based on routine grab samples generally collected once a month. Figure 3.8 compares the 2019 median values against historical median annual values for the previous 10 years (2009-2018).

Table 3.9 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

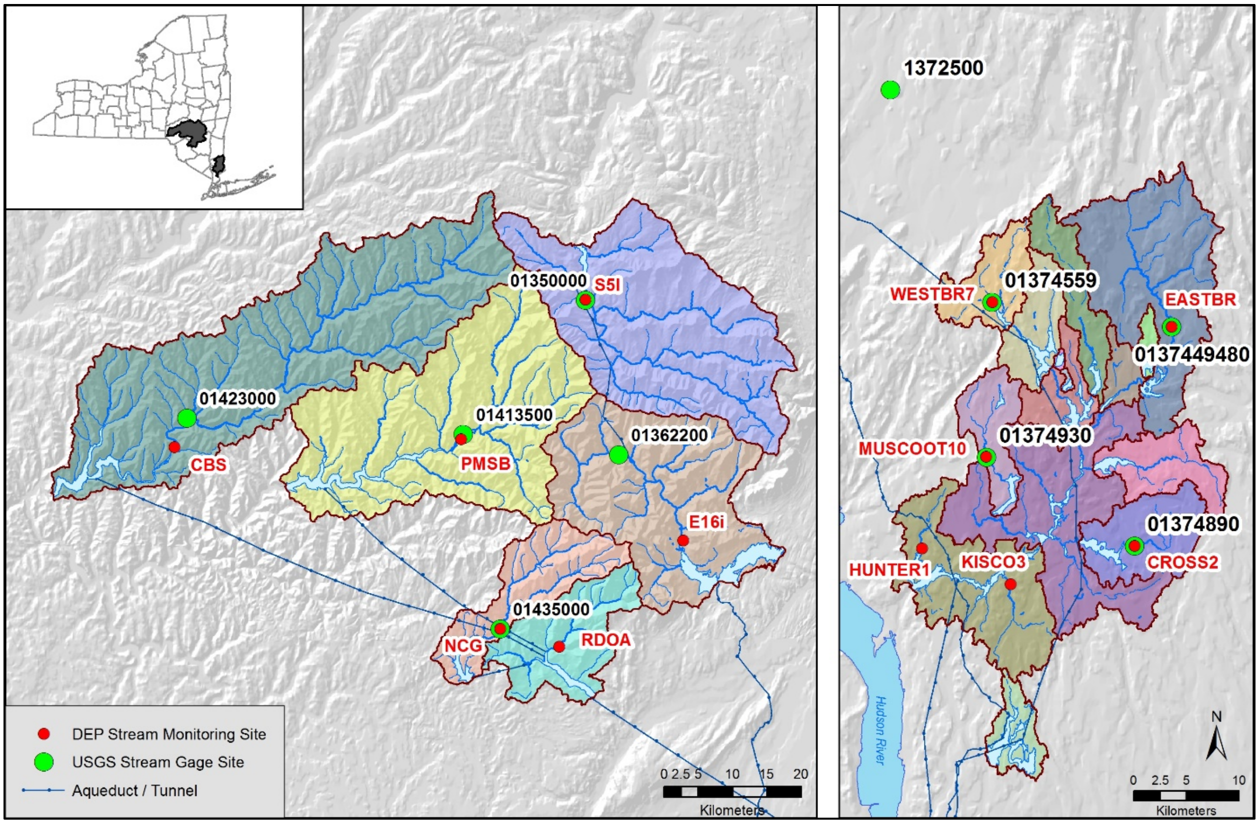


Figure 3.7 Locations of major inflow stream water quality sampling sites and USGS gage stations used to calculate runoff values (see Section 2.3).

Turbidity

The turbidity levels for 2019 were generally within the range of the annual medians observed over the previous 10 years (2009-2018) (Figure 3.8a), with the exception of East Branch Delaware River (PMSB) and Cross River (CROSS2). PMSB and CROSS2 had their highest annual median turbidity values, although they were only 2.3 and 2.4 NTU, respectively, compared to the last 10 years. East Branch Croton River, above East Branch Reservoir (EASTBR) had its lowest annual median (1.3 NTU) in 2019 compared to the last 10 years.

Total Phosphorus

The 2019 median TP concentrations (Figure 3.8b) exhibited mixed results among the major inflows. For example, three of the EOH inflows (Cross River (CROSS2), the Kisco River input to New Croton Reservoir (KISCO3), and Hunter Brook, a tributary to New Croton (HUNTER1)) had their highest medians (42, 43, 34.5 µg L^{-1}), respectively, in 2019. Muscoot River, above Amawalk Reservoir (MUSCOOT10) had its second highest annual median (53 µg L^{-1}) compared to the previous ten years. In WOH West Branch Delaware River (CBS) also had had its second highest annual median (20.5 µg L^{-1}) compared to the previous ten years.

Fecal Coliform Bacteria

The fecal coliform bacteria levels for 2019 (Figure 3.8c) also exhibited mixed results when compared to the previous 10 years. For WOH sites, Rondout Creek at Lowes Corners (RDOA) had it highest annual median for fecal coliform (7.5 coliforms $100ml^{-1}$) when compared to 2009-2018, while the other WOH sites were generally within the range of the annual medians observed over the previous 10 years (2009-2018). For EOH, several of the sites showed somewhat elevated annual medians for 2019. Cross River (CROSS2) had it highest annual fecal coliform median (83 coliforms $100mL^{-1}$) over the last 10 years while West Branch Croton River, above Boyd Corners Reservoir (WESTBR7) had its second highest annual median (51 $100mL^{-1}$). East Branch Croton River above East Branch Reservoir (EASTBR), and two inputs to the Croton Reservoir, Kisco River (KISCO3) and Hunter Brook (HUNTER1), had their third highest annual fecal coliform median (59.5, 135, and 87.5 coliforms $100mL^{-1}$, respectively)

A fecal coliform benchmark of 200 coliforms $100mL^{-1}$ is shown as a solid red line in Figure 3.9c. This benchmark relates to the NYSDEC water quality standard for fecal coliforms (which is a monthly geometric mean of five samples) (6NYCRR §703.4b). The 2019 median values for all streams shown here are below this benchmark value. There were 20 individual samples with a result greater than or equal to 200 coliforms $100mL^{-1}$, with three occurrences at WOH sites (two at East Branch Delaware River (PMSB) and one at West Branch Delaware River (CBS)). The other 17 occurrences were at EOH sites. These elevated fecal coliform counts were generally associated with rain events.

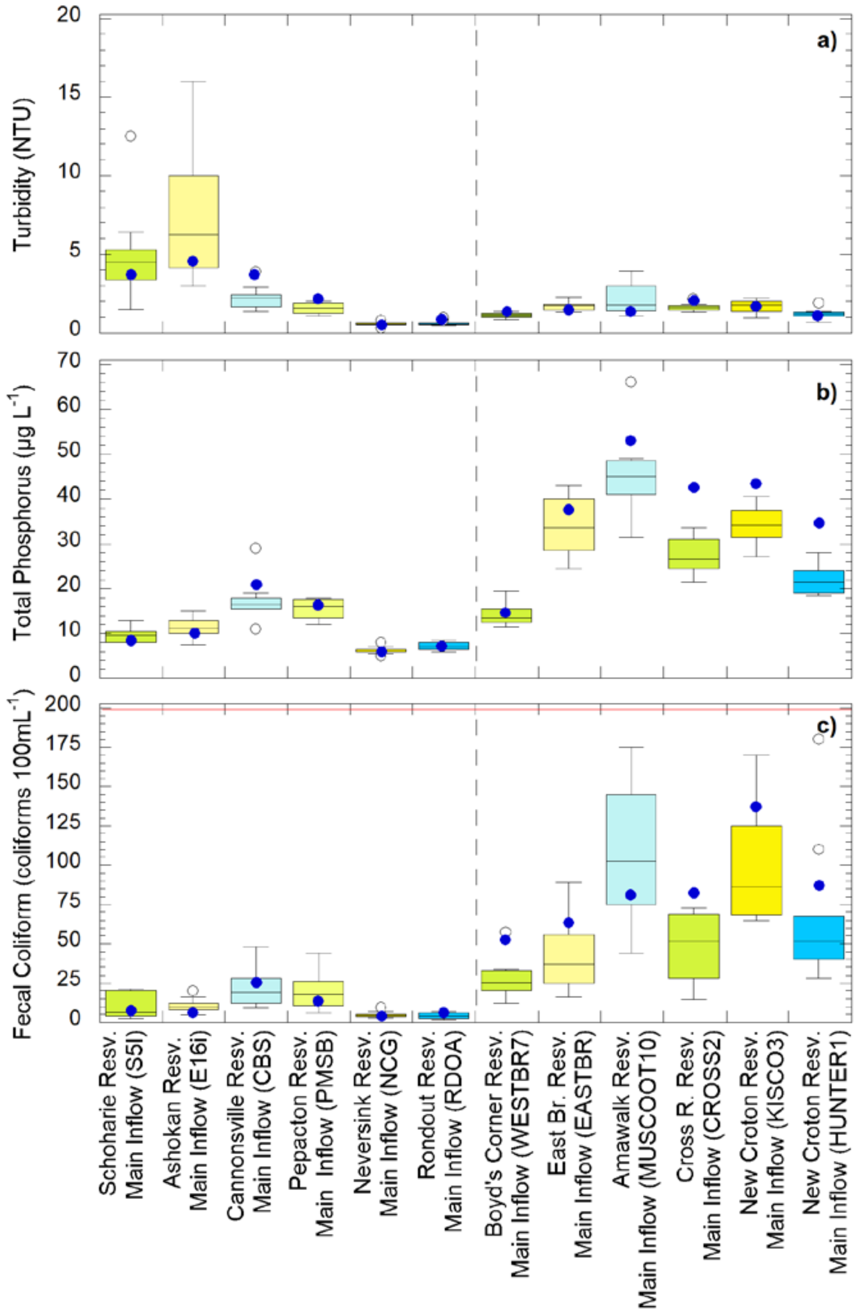


Figure 3.8 Boxplot of annual medians (2009-2018) for a) turbidity, b) total phosphorus, and c) fecal coliforms for selected stream (reservoir inflow) sites, with the 2019 values displayed as a solid dot. The dotted line separates WOH streams (left) from EOH streams (right). The solid red line indicates the fecal coliform benchmark of 200 coliforms $100mL^{-1}$.

3.10 Stream Comparisons to Benchmarks in 2019

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 2019b). In this section, the application of these benchmarks has been extended to 40 streams and reservoir releases to evaluate stream status in 2019 (DEP 2018). The benchmarks are provided in Table 3.10.

Table 3.10 Stream water quality benchmarks as listed in the WR&R (DEP 2019b). The benchmarks are based on 1990 water quality results.

	Croton System		**Catskill/Delaware Systems**	
	Annual Mean	**Single Sample Maximum**	**Annual Mean**	**Single Sample Maximum**
Alkalinity (mg $CaCO_3 L^{-1}$)	N/A	>40.00	N/A	>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 G 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.

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. 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 excursions below the alkalinity single sample benchmark of 10 mg L^{-1} were common much of the year in most streams from these watersheds. In contrast, only occasional excursions below 10 mg L^{-1} were observed in streams of the Cannonsville and Pepacton basins. These excursions occurred mostly in the winter-spring period and were likely caused by rain and melting snow, which are naturally acidic, moving over frozen or semi-frozen ground into the streams. Streams of the Schoharie basin did not go below 10 mg L^{-1} in 2019. 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 with stream sites GYPSYTRL1, HORSEPD12, WESTBR7, and BOYDR often below 40 mg L^{-1}, with mean alkalinities ranging from 34.2 to 44.3 mg L^{-1} in 2019.

Chloride

The Catskill/Delaware System annual mean benchmark of 10 mg L^{-1} was exceeded in 13 of the 24 streams monitored in the Catskill/Delaware System with the highest mean, 36.0 mg L^{-1}, occurring at site NK6 on Kramer Brook in the Neversink watershed. The single sample Catskill/Delaware chloride benchmark of 50 mg L^{-1} was also exceeded at Kramer Brook with a result of 50.5 mg L^{-1} in September. 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 4.0 and 3.8 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.

Other Catskill/Delaware System streams with high annual mean chloride included Bear Kill at S6I (22.0 mg L^{-1}), Schoharie Creek at S5I (12.2 mg L^{-1}) , Manor Kill at S7I (11.0 mg L^{-1}), and the Schoharie release at SRR2CM (10.6 mg L^{-1}) all located within the Schoharie watershed; Trout Creek at C-7 (16.9 mg L^{-1}), Loomis Brook at C-8 (15.2 mg L^{-1}), and the West Branch of the Delaware River at CBS (14.5 mg L^{-1}), all tributaries to Cannonsville Reservoir; and Chestnut Creek at RGB (17.2 mg L^{-1}), a tributary to Rondout Reservoir. Two Pepacton streams: Tremper Kill at P-13 (11.5 mg L^{-1}) and the East Branch of the Delaware River at PMSB (12.4 mg L^{-1}) exceeded the average annual benchmark in 2019. 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). Average annual chloride was also high (16.8 mg L^{-1}) at the outflow from the West Branch Reservoir release (WESTBRR) but still much lower than its 2018 average of 32.9 mg L^{-1}. In 2019, more Rondout water with its lower chloride concentration was diverted to West Branch than in recent years thus offsetting the higher chloride concentrations from local West Branch streams.

The Croton System annual mean benchmark of 35 mg L^{-1} was exceeded in 14 of 16 monitored Croton streams. Only the release from Boyd Corners Reservoir at BOYDR and the West Branch of the Croton River at WESTBR7 were below the annual mean benchmark in 2019. Annual means exceeding the benchmark ranged from 37.3 mg L^{-1} in Gypsy Trail Brook at GYPSYTRL1 to 217.8 mg L^{-1} in Michael Brook at MIKE2. The mean 2019 chloride concentration for all 16 Croton streams was 74.9 mg L^{-1}, substantially higher than the streams of the Catskill/Delaware System, which together averaged 10.8 mg L^{-1}. The single sample chloride benchmark is 100 mg L^{-1} for streams of the Croton System. This benchmark was commonly exceeded on the Muscoot River at MUSCOOT10, at the Amawalk Reservoir Release at AMAWALKR, at the Croton Falls Release at CROFALLSVC, on Michael Brook at MIKE2, and on the Kisco River at KISCO3. Occasional exceedances occurred at the Long Pond outflow at LONGPD1, the Diverting Reservoir release at DIVERTR, and at BOGEASTBRR, the combined release for Bog Brook and East Branch reservoirs. Road salt is 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 G).

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 2019, 15 of 24 Catskill/Delaware streams had at least one value greater than the TDS single sample maximum of 50 mg L^{-1}. With the exception of the Schoharie Creek diversion at SRR2CM, these same streams also exceeded the TDS annual mean benchmark of 40 mg L^{-1}. All excursions of the single sample maximum were associated with chloride concentrations that exceeded 9.8 mg L^{-1} (Figure 3.9).

TDS (and chloride) levels were not only high in winter but were often high in the summer and fall, presumably due to the concentration effect of low flow conditions and to greater contributions from salt-impacted groundwater. Only streams with very low average chloride concentrations (6.4 mg L^{-1}) consistently met both TDS benchmarks.

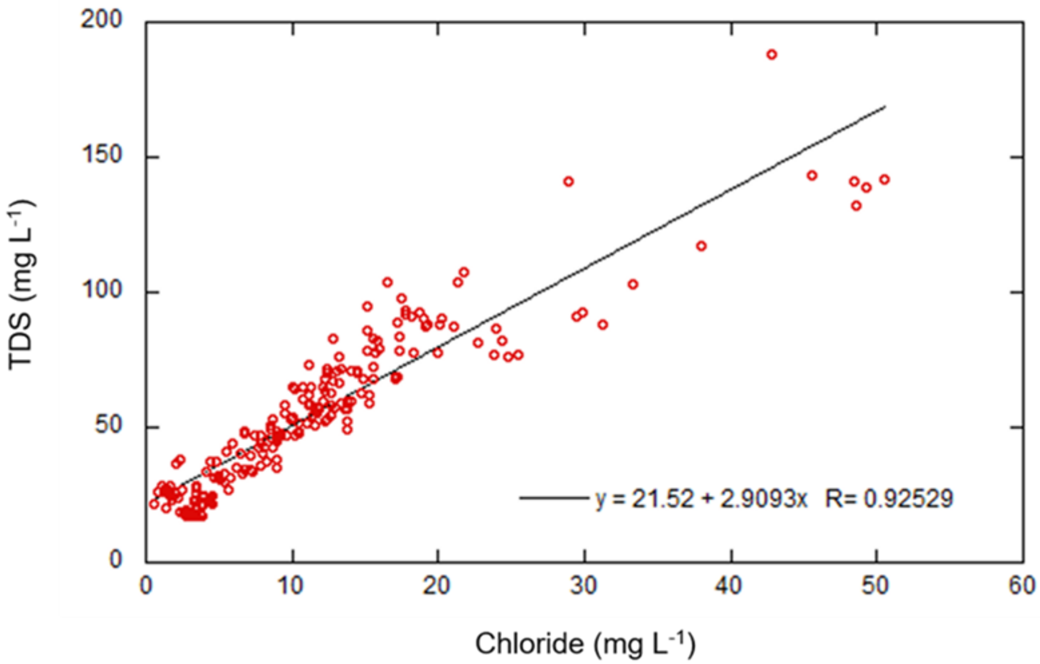


Figure 3.9 Total Dissolved Solids (TDS) versus chloride for Catskill/Delaware System streams in 2019.

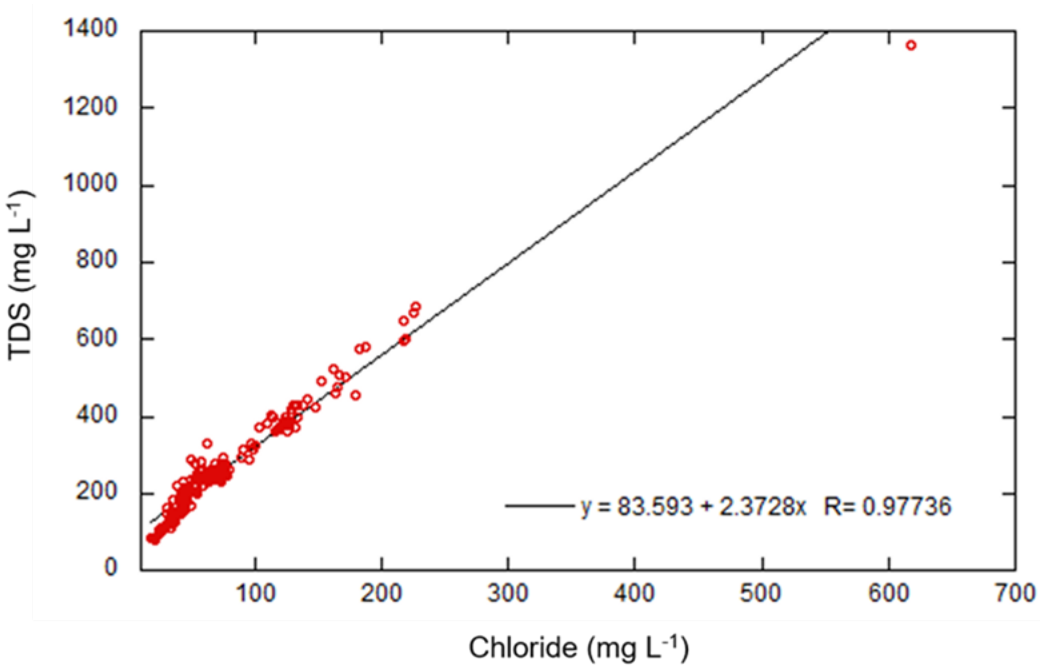


Figure 3.10 Total Dissolved Solids (TDS) versus chloride for Croton System streams in 2019.

TDS excursions in the Croton streams were also strongly associated with elevated chloride concentrations with chloride accounting for about 98 percent of the variation in TDS (Figure 3.10). In 2019, Gypsy Trail Brook (GYPSYTRL1), the West Branch of the Croton River

(WESTBR7) and the release from Boyd Corners Reservoir (BOYDR) were the only streams in the Croton System that met the annual benchmark of 150 mg L^{-1} and mostly met the single sample maximum criterion of 175 mg L^{-1}.

Nitrogen

Nitrogen results were generally in compliance with benchmarks in the Catskill/Delaware System in 2019. 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 exceeded in three streams: the West Branch of the Delaware River at CBS (0.61 mg L^{-1}), Fall Clove at P-8 (0.47 mg L^{-1}), and at Bear Kill at S6I (0.41 mg L^{-1}). Likely sources for nitrate are fertilizers associated with the relatively high agricultural activity in these basins, and wastewater treatment plants that discharge to the West Branch of the Delaware River and to the Bear Kill.

Three Croton streams exceeded the annual average benchmark of 0.35 mg L^{-1} for 2019: the Kisco River at KISCO3 (0.57 mg L^{-1}), the Muscoot River at MUSCOOT10 (0.54 mg L^{-1}) and Michael Brook at MIKE2 (3.66 mg L^{-1}). The single sample nitrate benchmark of 1.5 mg L^{-1} was also exceeded at Michael Brook in six of 12 monthly samples and was especially high in June (3.8 mg L^{-1}) and also from August to November when nitrate ranged from 2.68 to 12.86 mg L^{-1}.

All ammonia results were in compliance 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 2019. Four Croton System streams exceeded the ammonia single sample maximum of 0.20 mg L^{-1} in 2019. The Boyd Corners Reservoir release (BOYDR) exceeded it once, reaching 0.22 mg L^{-1} in September. The Cross River release (CROSS2RVVC) and the Titicus Reservoir release (TITICUSR) both exceeded the benchmark each month from August to November with concentrations ranging from 0.24 to 0.60 mg L^{-1}. Michael Brook (MIKE2) exceeded the benchmark in March with a result of 0.73 mg L^{-1}. All elevated ammonia results from the reservoir release sites were associated with the release of ammonia from upstream anoxic reservoir sediments in late summer/fall. The likely ammonia source at MIKE2 is an upstream wastewater treatment plant where SPDES sampling indicated an elevated 30-day average outfall ammonia concentration of 6.68 mg L^{-1} for March.

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 2019. The collective average for the Catskill/Delaware streams was 3.6 mg L^{-1}. With the exception of Michael Brook, Croton stream results were below the Croton System single sample maximum of 25 mg L^{-1} and the annual mean benchmark of 15 mg L^{-1}. Michael Brook (MIKE2) exceeded the single sample maximum with a result of 28.4 mg L^{-1} in August as well as the annual mean benchmark with an average of 19.7 mg L^{-1}. Sulfate was consistently high in all four quarterly samples, ranging from

10.3-28.4 mg L^{-1} at MIKE2. The Michael Brook watershed has 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 DEP's monitoring program. Previous work has shown that DOC constitutes the majority of the organic carbon in stream and reservoir samples. The DOC single sample benchmarks of 25 mg L^{-1} and annual mean of 9.0 mg L^{-1} were not surpassed by any stream in the Catskill/Delaware or Croton systems in 2019. In the Catskill/Delaware System, the highest single sample DOC result occurred in the Rondout watershed's Chestnut Creek at RGB (4.2 mg L^{-1}) while the annual mean DOC in the Catskill/Delaware System ranged from 0.9 to 2.6 mg L^{-1}; well below the annual mean benchmark. 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 2.9 to 4.9 mg L^{-1} in 2019, and the highest single sample DOC, 7.0 mg L^{-1}, occurred on both the east (EASTBR) and west (WESTBR7) branches of the Croton River.

3.11 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 and mature zebra mussels. This monitoring began in the early 1990s, via contract with a series of laboratories that have professional experience in identifying zebra mussels. All East of Hudson reservoirs are monitored on a monthly basis between May and October with the exception of Amawalk Reservoir, which was surveyed twice monthly in 2019. West of Hudson reservoirs are monitored less frequently (July and September) due to lower calcium levels and less chance of colonization. In 2018, this work was taken in-house and is no longer done by a contract lab. To date, no attached zebra mussels have been found in DEP's reservoirs; however, veligers were found at the end of the culvert that conveys water from the Muscoot River into the Amawalk Reservoir at low concentrations on one date in May. These apparently originate from zebra mussels in Lake Mahopac, which drains into Muscoot River. To date, attached zebra mussels have been found in the Muscoot River up to about 1 km downstream of Lake Mahopac.

3.12 Stream Biomonitoring

DEP has been performing water quality assessments of watershed streams based on resident benthic macroinvertebrate assemblages since 1994. Assessments are made following protocols developed by the New York State Stream Biomonitoring Unit (SBU) (NYSDEC

2014). In brief, 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 2019, DEP collected samples from 37 stations in 20 streams throughout New York City's watershed. 11 sites were surveyed on seven streams in the Croton System, 11 sites were surveyed on four streams in the Catskill System, and 15 sites were surveyed on nine streams in the Delaware System (for site locations, see Appendix G). After the surveys, the samples were sent to a contract laboratory for analysis but were not analyzed as of early 2020 due budget constraints. Samples were preserved and held for possible future analysis.

East of Hudson – Croton System

No data are available (see explanation above).

West of Hudson - Catskill/Delaware System

No data are available (see explanation above).

3.13 Supplemental Contaminant Monitoring

3.13.1 Volatile (VOC) and Semivolatile Organic (SVOC) Compounds

To supplement required distribution system monitoring, DEP collects one sample at key sites throughout the upstate watersheds each October to test for a large number of volatile and semivolatile organic compounds and the herbicide glyphosate. The list of compounds is provided in Appendix I and the sites sampled are provided below in Table 3.11. Because Cannonsville Reservoir was off-line at the time of sampling, reservoir elevation tap CR2 was sampled in place of its keypoint WDTOCM. All samples were shipped to a contract lab for analysis. In 2019, no detections were observed in West of Hudson or East of Hudson samples for any of the compounds monitored. Note that results for the compound pentachlorophenol were not available because the contract lab no longer includes this compound as part of EPA 525.2 but rather as part of EPA 515.4. The necessity of reporting on this compound going forward is currently under review.

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	Ashokan Intake	Represents Ashokan water
NRR2CM	Neversink Intake	Represents Neversink water
PRR2CM	Pepacton Intake	Represents Pepacton water
SRR2CM	Schoharie Intake monitoring site	Schoharie water entering Esopus
RDRRCM	Rondout Intake	Represents Rondout water
WDTOCM	West Delaware Tunnel Outlet	Represents Cannonsville water

In the event that one of these diversions 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.

3.13.2 Metals Monitoring

Supplemental (non-required) sampling of the Catskill, Delaware, and East of Hudson Systems is conducted in order to determine background concentrations for a variety of metals. The following metals (total concentrations in all cases) were analyzed on a quarterly basis: silver (Ag), aluminum (Al), arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), thallium (Tl), and zinc (Zn). These metals are monitored at the keypoint sites listed in Table 3.12.

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

Reservoir Basin	Site(s)
Catskill System	
Ashokan	EARCM[1]
Schoharie	SRR2CM[1]
Delaware System	
Cannonsville	WDTO[1]
Pepacton	PRR2CM[1]
Neversink	NRR2CM[1]
Rondout	RDRR2CM[1]
East of Hudson	
Kensico	CATALUM, DEL17, DEL18DT, DEL19LAB
Croton	CROGH, CROGH1CM[2], CROGHC, CRO9
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)	2000	
Beryllium (Be)	4	
Cadmium (Cd)	5	
Chromium (Cr)	100	
Copper (Cu)	1300	1000
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)		5000

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)	1000
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 2019, most metal sample results were well below state and federal benchmarks. Arsenic, lead, antimony, beryllium, cadmium, silver, and thallium were not detected above the detection limit of 1.0 µg L^{-1} for any sample. Selenium was detected once at its detection limit of 1.0 µg L^{-1}. No samples were detected for mercury or chromium at their detection limits of 0.10 µg L^{-1} and 5 µg L^{-1}, respectively.

Three samples were positive for zinc (10.0, 10.4 and 47.7 µg L^{-1}) but were well below the USEPA secondary standard of 5000 µg L^{-1}. Nickel was detected on three occasions at CROGH with concentrations ranging from 1.0 to 1.4 µg L^{-1}. All results were well below the NYSDEC regulation (Title 6, Chapter X, Part 703.5) of 100 µg L^{-1}. Barium was detected in all samples, ranging from 6.1 µg L^{-1} at SRR2CM and CATALUM to 35.4 µg L^{-1} at CROGH. Copper concentrations ranged from 1.0 µg L^{-1} at DEL10 and DEL18DT to 71.5 µg L^{-1} at PR2. No detections were recorded for 26 of 55 copper samples in 2019. All detected barium and copper results were well below their respective benchmarks.

Benchmarks for iron, aluminum, and manganese were occasionally surpassed in 2019. The iron benchmark of 300 µg L^{-1} was exceeded in one sample at SRR2CM (652 µg L^{-1}). The manganese benchmark of 50 µg L^{-1} was exceeded on nine occasions, while the aluminum benchmark of 50 µg L^{-1} was surpassed in eight samples. Manganese exceedances occurred at SRR2CM (54 and 71 µg L^{-1}), EARCM (83 µg L^{-1}), CATALUM (70 µg L^{-1}), NR2 (51 µg L^{-1}), DEL17 (118 µg L^{-1}), CROGH (51 µg L^{-1} and 71 µg L^{-1}), and PR2 (75 µg L^{-1}). Aluminum exceedances occurred in one sample at DEL9 (75.0 µg L^{-1}), in two samples at NR2 (58.4 and 114 µg L^{-1}), and CR2 (59.2 and 115 µg L^{-1}), and in three samples at SRR2CM (123, 142 and 925 µg L^{-1}). Note that these iron, aluminum, and manganese exceedances may pose aesthetic concerns (e.g., taste, staining) but are not considered a risk to health. Moreover, most of these excursions occurred 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 10.4 to 16.1 µg L^{-1} for aluminum, <30 to 45 µg L^{-1} for iron, and 10 to 25 µg L^{-1} for manganese (the "<" designates the analytical detection limit). The Croton keypoint closest to the distribution system, CROGH (or CRO1B), was also below most benchmarks, ranging from <10 to 21 µg L^{-1} for aluminum and from <30 to 100 µg L^{-1} for iron. However, the benchmark for manganese was exceeded in two samples, each with a concentration of 71 µg L^{-1}.

3.14 Special Studies

There were 20 special studies conducted throughout the watershed during 2019. Among these, four investigations occurred in the Kensico basin and are reported in Chapter 4. Studies were initiated when a water quality concern was raised or to better understand monitoring and management alternatives.

3.14.1 Foamstream: An Alternative to Common Herbicides

The purpose of this study titled "*A Comparison Study between Foamstream® and Conventional Herbicides: A Study on Efficacy*" was to investigate a viable alternative to glyphosate, a commonly used herbicide in the NYC watershed system. Glyphosate has been determined to be a probable carcinogen, and DEP has sought to discover a replacement with less toxic properties. Foamstream's mode of operation is to use super-heated water surrounded by a proprietary foam to scald plant tissue. Foamstream efficacy was compared to glyphosate and another herbicide, Finale® (a non-synthetic herbicide) at selected East of Hudson and West of Hudson test sites. The East of Hudson test sites were located on DEP property around DEL18DT and the UV Plant. The West of Hudson test sites were located at Gate # 19 (near the Schoharie Reservoir), the Shandaken Tunnel Outlet property and Route 28A, and near Whispell Hollow Road (Ashokan Reservoir basin). The study demonstrated that Foamstream was effective in scalding a variety of plant tissues. Regrowth occurred at all study sites after approximately one month, with rate of regrowth dependent upon the plant species at each plot and local environmental conditions. Glyphosate and Finale® were slower to act in eradicating plants, but were more effective at reducing regrowth at each plot over the long term. A follow-up observation of each site was conducted during spring, 2019. Observations showed sites were back to pre-study conditions with no lingering effects of the herbicides (DEP 2019c).

3.14.2 Emerging Contaminant Monitoring Project

Emerging contaminants, including per- and polyfluoroalkyl substances (PFAS) and pharmaceuticals and personal care products (PPCPs), were investigated within the New York City (NYC) watershed during 2019 as a quarterly sampling synoptic survey. Sampling sites included Kensico Reservoir aqueduct inflows and outflow, Kensico streams, the outflow of New Croton Reservoir, and the keypoints of three other upstate reservoirs. Analytes selected for the investigation included those from the Unregulated Contaminant Monitoring Rule (UCMR), specifically the UCMR3 and UCMR4, as well as those from the USEPA radionuclide suite. In addition to PFAS and PPCPs, analyses included individual regulated metals, 1, 4-dioxane, chlorate, pesticides, semivolatile compounds, alcohols, and algal toxins. Of the 148 analytes tested, 42 were detected. Kensico Reservoir inflows were positive for seven compounds and the outflow was positive for 7 of the 148 compounds tested. New Croton outflow had 16 compounds detected while the three upstate reservoir keypoint samples were positive for seven compounds. The New Croton outflow was the only keypoint positive for PFAS (PFOS, PFOA, PRHxA). The most commonly detected PPCPs at keypoint inflows and outflows were acesulfame-K (artificial sweetener), metformin (Type II diabetes medication) and TCPP (flame retardant in polyurethane foam). The eight Kensico streams ranged between 16 and 25 compounds detected, and were all positive for at least one PFAS detection with the ultra-low level detection method (ngL^{-1}) employed in this study. The most commonly detected PPCPs in Kensico streams were acesulfame-K, sucralose (artificial sweetener), caffeine (stimulant) and TCPP. No algal toxins (not tested in streams), alcohols, or semivolatile compounds were detected at any site. There were no exceedances of state or federal drinking water quality standards. The results from this study are posted on DEP's public website. The most recent quarterly report can be found at: https://www1.nyc.gov/assets/dep/downloads/pdf/water/water-monitoring/monitoring-for-contaminants/2019-q4-emerging-contaminants-monitoring-project.pdf. Other reports for 2019 are available on the website also. The final report summarizing all of the data will be available in July 2020.

3.14.3 Croton System Taste and Odor Event

In autumn 2019, the Bureau of Water Supply (BWS) began rehabilitation of the Catskill Aqueduct (CA) in preparation for the Rondout to West Branch Tunnel shutdown. To complete that rehabilitation work, the CA needed to be off-line for a period of approximately 10 weeks. The CA supplies on average 40% of the demand to the City, so additional water sources were needed to support the rehabilitation work. As a result, DEP utilized pump stations from Croton Falls and Cross River reservoirs and maximized production from the Croton Water Filtration Plant (CWFP) in the Bronx.

Maximized production from CWFP delivers water into the low and high service areas of the distribution system (DS). The areas in the DS that receive water from CWFP can be determined by monitoring conductivity due to the difference in conductivity between the Catskill/Delaware and Croton systems. BWS uses these data to determine the influence from CWFP, which generally services the boroughs of Manhattan and the Bronx.

BWS implemented start up and monitoring procedures that had been updated following the 2018 taste and odor event, prior to bringing CWFP online and delivering water into the DS. However, approximately four weeks after startup of CWFP, customer complaint calls from Manhattan and the Bronx began to increase. The majority of the calls described a musty odor. Complaint calls continued to rise over the next several weeks, until the CWFP was taken off-line.

BWS continued to monitor New Croton Reservoir for selection of the highest quality water to divert to CWFP. During the 2019 event, managers and operators held daily calls to discuss consumer complaints, monitoring results, and possible operational changes. During the course of the event, it became apparent the taste and odor complaints may have been associated with the taste and odor compound 2-Methylisoborneol (MIB). Analyses detected MIB in all water quality sample taps and effluent from the New Croton Reservoir, as well as the entry point into the distribution system serviced by CWFP. Analyses detected MIB in all water quality sample taps and effluent from the New Croton Reservoir, as well as the entry point into the distribution system serviced by CWFP. After CWFP was shut down, there were no detections of MIB at the entry point. Levels continued to rise and did not begin to decrease at New Croton Reservoir sample tap locations for several months after plant shutdown.

The specific source of MIB could not be determined. Despite the extensive amount of data captured during the event, BWS was unable to determine a direct correlation between MIB concentrations and an operational or environmental cause. However, multiple possible causes are listed below:

- MIB-producing phytoplankton
- MIB-producing Actinobacteria
- MIB development in New Croton Reservoir
- *Hydrilla* treatment
- Nutrient ratio changes

3.14.4 Titicus Fuel Spill

In February 2019, a tractor trailer carrying approximately 5,000 gallons of gasoline and diesel oil overturned on the side of Titicus Rd. opposite Titicus Reservoir in the town of North Salem. Product spilled into an area along the road about one-quarter of a mile upstream of the Titicus Dam, began passing through rip rap used on the road under construction and entered the reservoir. Remediation efforts began immediately. A monitoring plan was designed to monitor the potential movement of gasoline/diesel as it moved from the spill site upstream of the Titicus Dam, through the Muscoot Reservoir, and into the New Croton Reservoir to ensure the intakes were not compromised.

The following keypoint, release, and specific sites related to capturing and tracking the spill were collected at varying intervals for contract lab analyses, total petroleum hydrocarbons (TPH), gasoline range organics (GRO), and diesel range organics (DRO).

- TiticusR - Titicus Reservoir combined release and spill
- CT Impacted Shoreline - Impacted shoreline along Titicus Reservoir
- CT-Dam Release – Titicus Dam release point
- CT-Dam Spillway - Titicus Dam spillway
- CTDamNRipRap - Titicus Reservoir earthen dam rip rap
- CM Route 138 - Muscoot Reservoir, Route 138 overpass
- CM Weir - Muscoot Weir
- CROGH – Raw (untreated) effluent from Croton Reservoir selective withdrawal blend

Samples from the Titicus Reservoir release were collected at varying intervals throughout the entire year. To consistently monitor for any release from the reservoir, samples were collected immediately following the spill, daily into May, three times per week through June and weekly thereafter. DRO results were generally non-detect, < 0.1 mg/L over the course of the year. Eighteen results ranged from 0.1 to 0.3 mg/L, however they were qualified as “does not display a fuel pattern, contains several discreet [sic] peaks”, by the contract lab performing the analyses. Further description in the qualifiers provided by the contract lab explained that, “when random peaks in the range of where the TPH is quantitated and calculated, the small peaks in and of themselves do not represent a fuel pattern to call it fuel.” There was one distinct DRO result of 95 mg/L sampled on the day of the spill. However, other samples from the Titicus Dam release, spillway and impacted shoreline collected the same day were non-detect. All GRO results for the Titicus Reservoir release were non-detect, <0.05 or <0.8 mg/L, depending on the contract lab utilized. Only a positive GRO result of 280,000 mg/L was seen for the sample collected along the impacted shoreline of Titicus the day of the spill.

Samples from Muscoot Reservoir at Route 138 were also collected daily into March. DRO and GRO results were non-detect, except for one DRO result of 0.1 mg/L near the end of March. In addition, the Muscoot weir and the Titicus Reservoir earthen dam rip rap samples were collected one time within a week of the spill. The DRO and GRO results for each sample were non-detect. CROGH was collected in the month following the spill. The DRO and GRO results were non-detect, confirming that no evidence of the spill was detected entering the New Croton aqueduct.

Samples were collected from the three trenches at the excavation site along the reservoir, one of diesel, one of mixed product and one of gasoline in order to obtain a “fingerprint” of the product spilled.

All samples were also analyzed for scent analysis during the year. Scents were predominantly of a musty, moldy, or earthy nature. Only TiticusR, CT Dam Release, Spillway and Impacted Shoreline samples on the first day were described as having a hydrocarbon scent.

Monitoring and remediation efforts continued through the end of the year.

3.14.5 Cross River and Croton Falls Pump Stations

Due to the shutdown of the Catskill Aqueduct, the use of the Cross River and Croton Falls Pump Stations were needed to supplement the water supply in 2019. The activation of these pump stations requires preliminary sampling to determine water quality and subsequent approval by NYSDOH. This sampling is performed a minimum of two weeks prior to the actual activation of the pump station and consists of daily grab sampling, and weekly pathogen and limnology samplings. Additionally, wastewater treatment plant inspection sampling increased during the preliminary monitoring and throughout the use of the pump station. For the Croton Falls Pump

Station in 2019, this sampling was performed for a total of nine weeks to provide water quality data prior to pump station activation and during pump station use. The Croton Falls Pump Station was activated on June 26 and from June 28 to July 1 for equipment testing and then again November 11 - 15, November 18 - December 1, and December 3 - 31 in support of the Catskill Aqueduct shutdown. The Cross River Pump Station was operated from November 19 - 20, and was not needed again in 2019. An after-action report presenting all water quality results and describing the detailed operation of these pump stations has been issued (DEP 2020).

3.14.6 Ultrasonic Treatment for Algal Control Pilot Project

The Bureau of Water Supply is studying the effectiveness of ultrasound to reduce or eliminate algal blooms in NYC reservoirs in response to increased concern over regional harmful algal blooms. Several studies have proven that ultrasound can cause algal die off in laboratory settings, however, this technology has not been used widely in drinking water reservoirs. This technology could be applied in other NYC reservoirs as a non-chemical treatment alternative to harmful algal blooms if proven effective.

In 2018, two ultrasonic platforms were deployed on Croton Falls Reservoir and New Croton Reservoir. In 2019, a single ultrasonic platform was deployed on Croton Falls Reservoir. BWS monitored for multiple water quality parameters during the deployment periods to assess effectiveness of the units.

Results from 2018 and 2019 field deployments were inconclusive due to equipment malfunctions, and the study is expected to continue in 2020 using upgraded equipment.

3.14.7 Algal Toxins

In May 2015, the U.S. Environmental Protection Agency (USEPA) issued 10-Day Drinking Water Health Advisories (HAs) for the cyanobacterial toxins microcystin and cylindrospermopsin. USEPA has also listed cyanotoxins on their Contaminant Candidate Lists (CCLs) and will be requiring monitoring within distribution systems under the fourth Unregulated Contaminant Monitoring Rule (UCMR4). As a result, DEP initiated baseline sampling of keypoint and routine reservoir sites in 2015 that is ongoing.

In 2019, algal toxins were detected in three upstate watershed reservoirs. Samples were intentionally taken in search of toxins and were analyzed for total microcystins at DEP’s Hawthorne Laboratory with an Abraxis® test kit, which utilizes the ELISA method. Selected samples were also sent to a contract laboratory and were processed through LC/MS/MS analysis for anatoxin-a, cylindrospermopsin, nodularian, and six variants of microcystin (*-LA, -LF, -LR, -LY, -RR, -YR*). Enhanced algal toxin sampling took place at site 5 in Croton Falls in support of the ultrasonic algal control pilot project (see section 3.14.6). All sites with detections were distant from intakes. No algal toxins were detected in the reservoir keypoint (outflow) sites.

The three reservoirs that were found to have detectable total microcystins by the ELISA method in 2019 were New Croton, Cannonsville, and Croton Falls. New Croton algal toxin samples in 2019 were above the 0.3 µg L^{-1} detection limit but below 1 µg L^{-1} with a maximum of 0.52 µg L^{-1} on August 20. Values for Cannonsville were found to be 1.4 µg L^{-1} on August 13 and >5 µg L^{-1} on October 8. Croton Falls had the greatest frequency of sampling and also the highest results. The maximum value was 13.4 µg L^{-1} recorded at site 5.5CCF on November 14.

Further analysis by the contract laboratory was done for samples with elevated total microcystins. Cannonsville was sampled for two distinct blooms in 2019, one in mid-August and the other in early-October. In addition to the total microcystin results above, the August bloom was characterized by anatoxin-a (0.054 µg L^{-1}) and 3 variants of microcystin (-LA, -LR, and –LY) with concentrations all below 0.2 µg L^{-1}. The later season bloom showed a similar concentration of anatoxin-a (0.047 µg L^{-1}) and greater presence of microcystin variants (-LA, -LF, - LR, - LY, and –RR) with the highest concentrations belonging to –LR (2.7 µg L^{-1}) and –LA (1.3 µg L^{-1}).

Similarly, New Croton had two distinct blooms in mid-August and late-September but also had a small-scale bloom in late June. The small bloom was characterized by microcystin variant –YR (0.12 µg L^{-1}). The other two blooms were of similar compositions of anatoxin-a and microcystin-LA. The highest anatoxin-a concentration was 0.74 µg L^{-1} in late September, while the maximum concentration of –LA was 0.24 µg L^{-1} in late August.

Due to the presence of the ultrasonic algal control buoys on Croton Falls site 5, this basin was sampled regularly and routinely for algal toxins through the 2019 season from the end of May to the middle of November. Algal toxin compositions observed were variants –LR, -RR, and –YR. Maximum values of these variants through the growing season were as follows: -LR: 9.2 µg L^{-1} (October 31), -RR: 16 µg L^{-1} (November 14), -YR: 1.8 µg L^{-1} (November 14). Anatoxin-a showed up in one sample from late-September at a concentration of 0.022 µg L^{-1}.

To put these cyanotoxin results in perspective, NYSDEC criteria for a harmful algal bloom ("confirmed with high toxin bloom") is 10 µg L^{-1} microcystin in open water. There are no guidelines for anatoxin-a. Blooms were observed and sampled in the Croton System as well as the Delaware System. Operational flexibility throughout the upstate watersheds and the Croton Water Filtration Plant allow DEP to manage issues associated with algal blooms.

3.14.8 Water Quality Improvements in Catskill Mountain Streams for Stream Management Plans

The objective of this sampling program is to assist in determining the effectiveness of best management practices (BMPs) used by DEP's Stream Management Program to stabilize and reduce the natural turbidity and suspended sediment observed in Catskill Mountain streams. This study is attempting to quantify any change in turbidity that may occur due to the installation of BMPs on a project site on the Batavia Kill in the Schoharie watershed. To accomplish this, turbidity data are being collected at two sites: one located upstream (on Batavia Kill above Lewis Creek, site code S10-LC) and the other located downstream (Batavia Kill immediately upstream from Red Falls, site code S10-RF) of the BMP site. Data are being collected before and after BMP installation. Project construction is scheduled to begin in 2020. Turbidity sensors have been installed at each of the sites and are programed to collect a turbidity reading and a simultaneous temperature reading every 15 minutes, enabling data collection over a wide range of flow and environmental conditions. Sensors at the upstream site (S10-LC) began recording data on November 8, 2017, and sensors at the downstream site (S10-RF) began collecting data on October 21, 2016. In 2019 at S10-LC, 35,033 turbidity readings and 35,033 temperature readings were made. At S10-LF, 33,063 turbidity readings and 33,063 temperature readings were made. Upon completion of the sampling program, the data will be analyzed to determine if the BMP had a measurable impact on turbidity in the stream. The results of these analyses will be reported in the 2021 FAD Program Summary and Assessment Report.

3.14.9 Conversion of Septic to Sewer Evaluation

The objective of this sampling effort is to measure the potential water quality benefits of providing new or improved wastewater treatment to areas previously served by septic systems. Two areas were targeted for monitoring. The first area was in the Town of Hunter in the Schoharie watershed. The new extension conveys sewage to the Tannersville WWTP. Monitoring sites were located on Sawmill Creek above (site code SSMA) and below (site code SSMB) the area to be connected to the wastewater treatment plant. Sawmill Creek is a tributary to Gooseberry Creek, which flows into Schoharie Creek. The second area was in the Town of Middletown in the Pepacton watershed, with new construction conveying sewage from Bull Run Road residences to the Margaretville WWTP. Bull Run is a tributary to the East Branch of the Delaware River. Monitoring sites were located on Bull Run above and below the project area (site code PBRA and PBRB, respectively).

The monitoring plan specifies that samples are to be collected at these sites before the projects were installed and continue for at least two years after completion of the projects. Monthly sampling of these sites commenced in March 2009. The connections for the Sawmill Creek project were completed in June 2016 and those for the Bull Run Project were completed in May 2019. The two year post construction monitoring was accomplished for Sawmill Creek in 2019 and monitoring was terminated for SSMA and SSMB in October.

During 2019, monthly samples collected at the four sites for this project resulted in 488 analyses. Upon completion of the monitoring for the projects, the data will be analyzed and documented in a report to determine if any effects from the conversion are apparent.

3.14.10 Investigation of *Giardia* in the Rondout Basin

In January 2019, special investigation sampling was performed on Rondout Reservoir as a continuation of sampling events initiated by increased counts of *Giardia* cysts at keypoint sites

RDRRCM, DEL17 and DEL18DT in 2018. In January, beaver trapping was performed at lodges on the north shore of Rondout Reservoir and upstream on Rondout Creek. After trapping, follow-up pathogen sampling and analysis included sites at the beaver lodges, Rondout Reservoir transects sampled by airboat, upstream sites, and streams and ponds on adjacent private property. A series of high-volume samples were collected at RDRRCM in March and sent to the Centers for Disease Control for genotyping. Weekly pathogen sampling at RDRRCM continued through October 2019 when the number of cysts detected declined. Sampling returned to weekly in December when there was a recurrence of the seasonal spike in *Giardia* detections. A special investigation report was issued containing details of the monitoring efforts and results (DEP 2019d).

3.14.11 Lower Esopus Sediment Sampling

DEP's Catskill field staff collected 1-L grab samples from Lower Esopus Creek at mid-depth and mid-channel for suspended sediment analysis to support the CATALUM environmental impact statement that Hazen and Sawyer was preparing.

3.14.12 Moodna Shaft 7 Investigation

The DEP Kingston Field group on June 21 collected five samples from Shaft 7, a Catskill Aqueduct structure south of Moodna Creek. Staff from the CAT-399 project (rehabilitation of the Catskill Aqueduct Hudson River Drainage Chamber [HRDC]) initiated this investigation to determine the viability of releasing the water inside the shaft to the Hudson River while the aqueduct is dewatered as part of a partial pressure tunnel unwatering required to replace the aged blow off valves at the HRDC facility. Access to the shaft was through an eight-inch PVC pipe approximately thirty-two meters above the water's surface. A Kemmerer sampler was used to collect samples with corresponding in situ EXO multiparameter sonde measurements at a depth of 10 meters or 52 meters below the surface of the shaft. Samples were sent to EnviroTest Laboratories, Inc. in Newburgh, NY for total dissolved solids analysis, redox potential, and salinity. Additional analyses for pH, dissolved oxygen, chlorine residual, and total suspended solids were performed by DEP's Kingston Laboratory. Based on high pH values, the project team determined that water will not be released as raw water when the pressure tunnel is unwatered.

3.14.13 Ashokan West Basin Algal Bloom

DEP's Operations staff reported a small algal bloom along the dividing weir near the Upper Ashokan Gatehouse on the southeast shore of Ashokan Reservoir's West Basin. DEP's Kingston field staff used a pole sampler to collect phytoplankton samples from shore. A small *Anabaena* bloom was found on and around detritus along the shoreline.

3.14.14 Ashokan East Elevation Mixing Profiles

In an effort to better understand how thermal stratification affects water quality on its passage through the Upper Ashokan Gatehouse, DEP's water quality managers requested EXO temperature profiles. One set of profiles was taken outside of the gatehouse windows and another at the same elevations inside the building through the floor plates and in front of the sluice gates. These measurements were used to determine if the water leaving the reservoir remained stratified and, if not, determine to what degree mixing occurs as the water is drawn through the intake structure. This investigation confirmed that the basin samples and their inside surrogates were comparable.

3.14.15 UV_{254} Absorbance Jar Tests

One-liter samples were collected at keypoint sites RDRRCM, PRR2CM, PR2, NRR2CM, WDTOCM, and EARCM and submitted to Hawthorne Laboratory for jar testing. These samples were mixed in one-to-one ratios to test the proposition that blending waters from different reservoirs could result in lower UV_{254} absorbance, which is used as an indicator of disinfection byproduct formation potential. The jar tests also helped to determine if there were synergistic or antagonistic effects of blending. In the tests performed, UV_{254} behaved conservatively and blending reduced UV_{254} absorbance when waters with higher absorbance values were mixed with those with lower absorbance values.

3.14.16 Disinfection Byproduct Precursor Studies

In 2019, three interns conducted special projects to complement studies on disinfection byproduct (DBP) sources in the Cannonsville and Neversink basins under the supervision of DEP staff. In spring 2019, an intern explored the changes in DBP formation potential (DBPfp) and organic matter during a spring storm event with sampling and analysis support from DEP's Grahamsville field and laboratory staff. Some samples were taken for DBPfp analysis in the Reckhow Laboratory at University of Massachusetts-Amherst, while others were analyzed by a contract laboratory. Additionally, samples were analyzed for absorbance at 254 nm (UV_{254}), an indicator of aromatics that are probable DBP precursors, and absorbance at 440 nm, a surrogate measure of water color. In summer 2019, two interns in DEP's 10-week summer internship program collaborated on a project that examined spatial variability in fluorescent dissolved organic matter (fDOM) and the effects of temperature on quenching fDOM measured with two different models of hand-held fluorometer. These projects gave insights into sample variability and sample analysis practices that contribute to DEP's studies of the sources and variability in organic matter and DBP precursors near their points of origin.

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). These sampling site locations are shown in Figure 4.1. The WWQMP prescribes monitoring to achieve 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 2019. For all sample analyte groups except "Other Analyses", the number of Kensico samples collected were similar to 2018 totals. Increases in "Other Analyses" sample counts at keypoint effluent, keypoint influent, and stream sites were related to the Emerging Contaminants Monitoring Project to assess the presence of potential contaminants; see Section 3.14.2 for additional details.

Table 4.1 Summary of Kensico watershed water quality samples collected in 2019.

Kensico sampling programs	Turbidity	Bacteria	*Giardia/ Crypto-sporidium*	Virus	Phyto-plankton	Other Analyses
SWTR Turbidity compliance	2183					
Keypoint effluent	365	365	52	10	163	3111
Keypoint influent	471	471	93	20	95	4510
Reservoir	621	370			102	2640
Streams	109	118	113			6270

Compliance with the Safe Drinking Water Act Surface Water Treatment Rule (SWTR) (USEPA 1989) is of paramount importance to DEP to maintain the Filtration Avoidance Determination. Fecal coliforms and turbidity are focal points when discussing Kensico water quality. The results of this monitoring are representative of the excellent quality of water leaving Kensico Reservoir during 2019. Additionally, DEP data continue to demonstrate that the

Waterfowl Management Program is instrumental in keeping coliform bacteria concentrations well below the limits set by the SWTR.

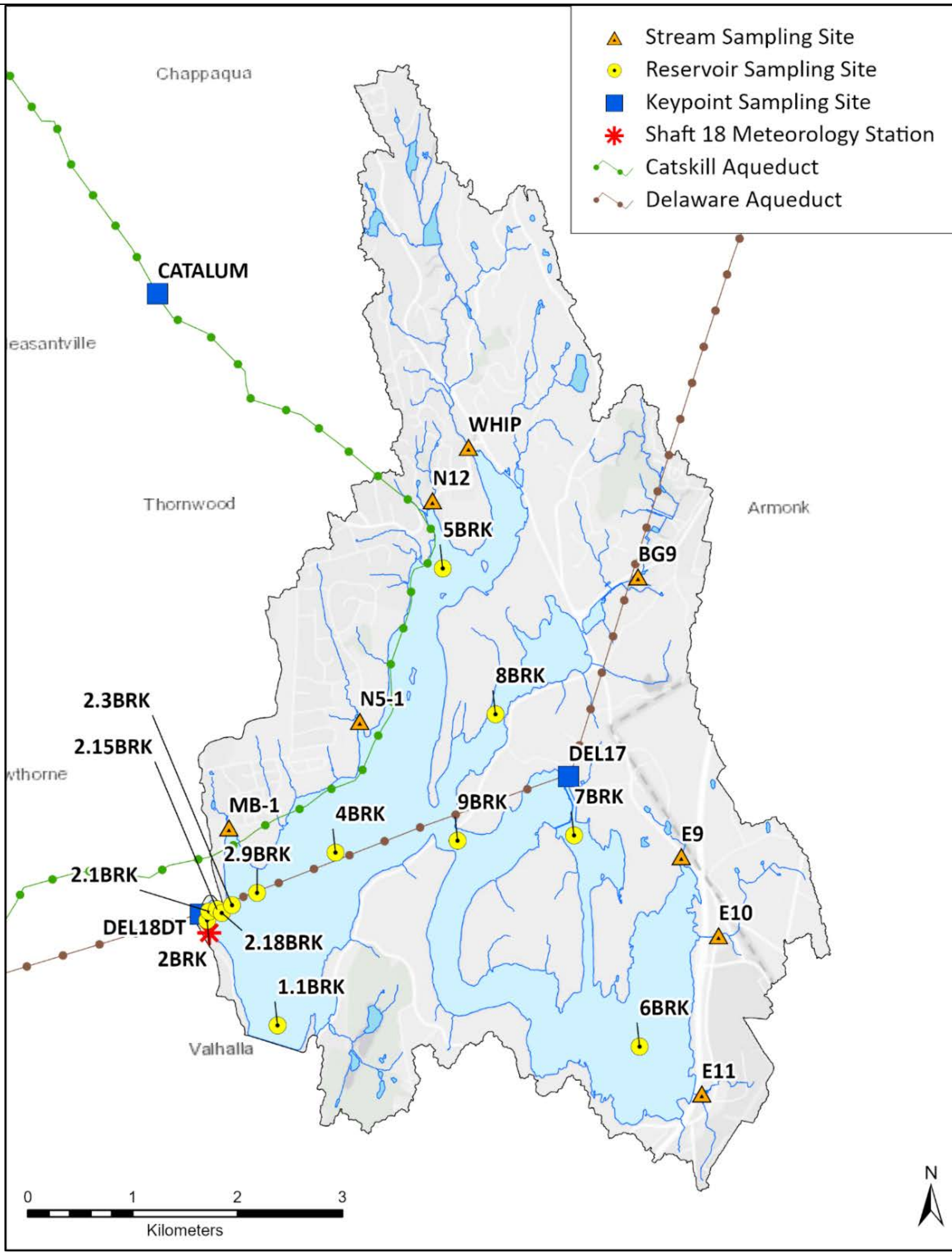


Figure 4.1 Kensico Reservoir showing limnological, hydrological, and keypoint sampling sites, meteorology stations, and aqueducts.

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 NYC upstate reservoirs via the Catskill and Delaware Aqueducts, respectively. The monitoring for CATALUM and DEL17 include 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 Building 18 at a point just prior to disinfection; this water ultimately travels down to distribution. Table 4.2 outlines the grab sample monitoring that took place at three active aqueduct keypoint locations during 2019. CATALUM and DEL17 keypoint monitoring was increased in July 2019 to begin collecting VIS-440, chlorophyll α, total dissolved nitrogen, and total nitrogen on a weekly basis for bench scale testing as part of the CAT/DEL filtration plant design project.

The analytes for all three keypoints are used as an indicator of water quality entering and discharging from Kensico Reservoir, which is used to optimize operational strategies to provide the best possible quality of water leaving the reservoir. In addition to the routine grab sample monitoring, these three sites were continuously monitored for temperature, pH, conductivity, and turbidity. The exceptional importance of the influent keypoints for optimal operations and the effluent keypoint as the source water compliance monitoring site warrants this high intensity monitoring.

Table 4.2 Water quality compliance monitoring for Kensico Reservoir aqueduct keypoints via routine grab samples for 2019.

Site	Fecal and Total Coliforms, Turbidity, Specific Conductivity, Scent, and Apparent Color	Field pH and Temperature	Turbidity (SWTR)	Phytoplankton	UV_{254}	VIS-440	TP, TN, TDN, Chlorophyll *a*	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	W	M	Q
DEL17	5D	5D		W	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
M – Sampled Monthly
Q – Sampled Quarterly

Table 4.3 shows the median and single sample maximum for Kensico Reservoir influent and effluent turbidity and fecal coliform samples collected during 2019. The 2019 turbidity and fecal coliform values were similar to or less than the 2018 values.

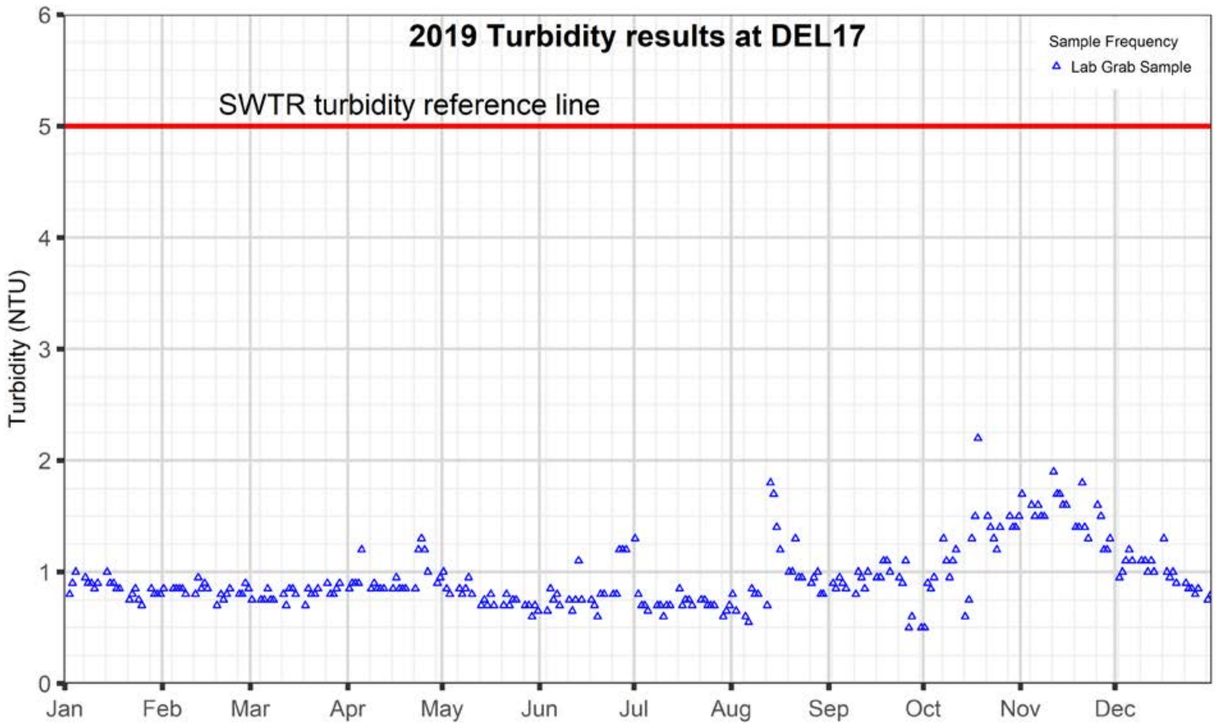
Table 4.3 Kensico keypoint fecal coliform and turbidity results from January 1, 2019, to December 31, 2019.

Analyte	Kensico Sampling Location	Median	Single Sample Maximum
Fecal Coliform (coliforms $100mL^{-1}$)	CATALUM	<1	E7
	DEL17	1	30
	DEL18DT	1	E9
Turbidity (NTU)	CATALUM	1.5	4.5
	DEL17	0.8	2.2
	DEL18DT	0.7	1.4

"E" indicates that the coliform plate count is estimated based on a non-ideal plate.

For most of 2019, short term increases in turbidity or fecal coliforms could be attributed to changes in reservoir operations and/or rainfall/runoff events. Turbidity values were well below the SWTR turbidity limit at DEL18DT and the influent locations were less than 5 NTU for the entire year. The highest turbidity values were at CATALUM at the beginning of September 2019 and decreased due to the operational change of switching the draw from the Ashokan West Basin to the Ashokan East Basin. Fecal coliform analyses resulted in no results greater than 20 fecal coliforms $100mL^{-1}$ at DEL18DT and one result greater than 20 fecal coliforms $100mL^{-1}$ at DEL17 during 2019. Overall, water quality in 2019 was excellent, with the source water at Kensico meeting the SWTR requirements for both fecal coliforms and turbidity.

The routine grab sample results at CATALUM, DEL17, and DEL18DT for the 2019 turbidity and fecal coliform results are shown in Figure 4.2, Figure 4.3, and Figure 4.4. For the two influent sites, DEL17 and CATALUM, the SWTR limit line is shown only as a reference line because the influent sites are not subject to the SWTR. Results greater than turbidity and fecal coliform y-axis scales were replaced with a value and an arrow pointing toward the top of the chart. Results below the detection limit include a "drop line" connecting the result to the x-axis and the length of the drop line goes to the top of the censored range. A drop line that goes to one indicates that the result was less than one.



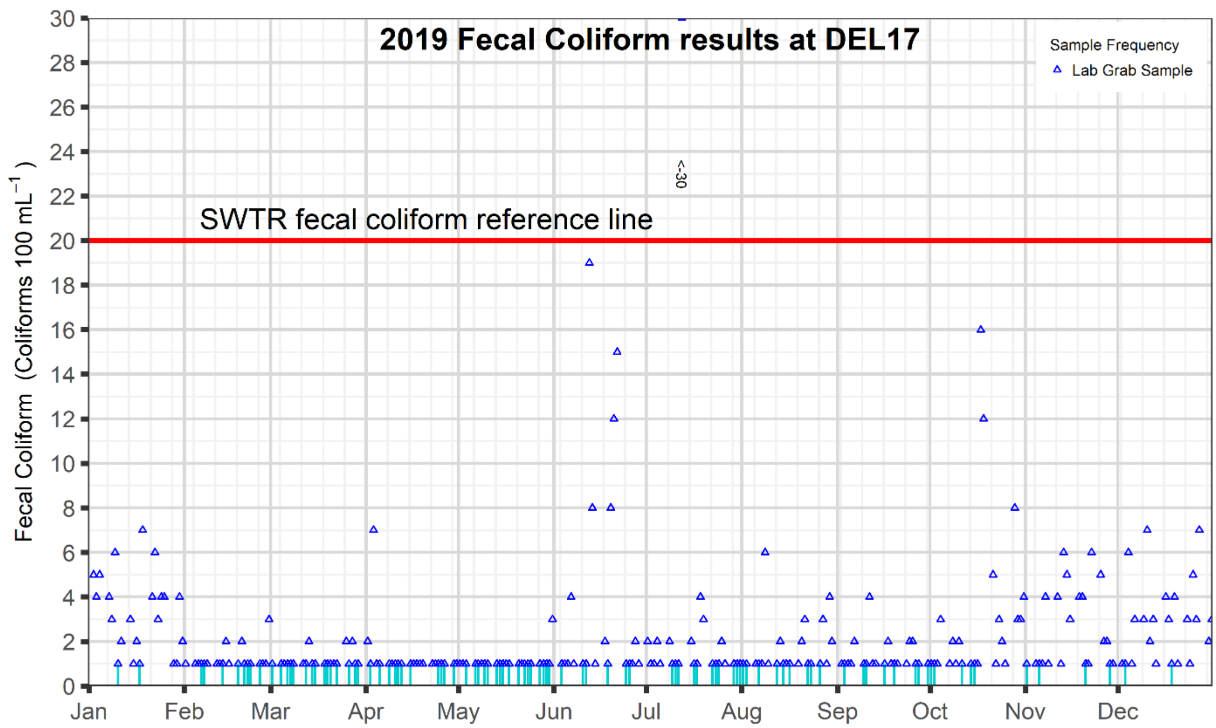
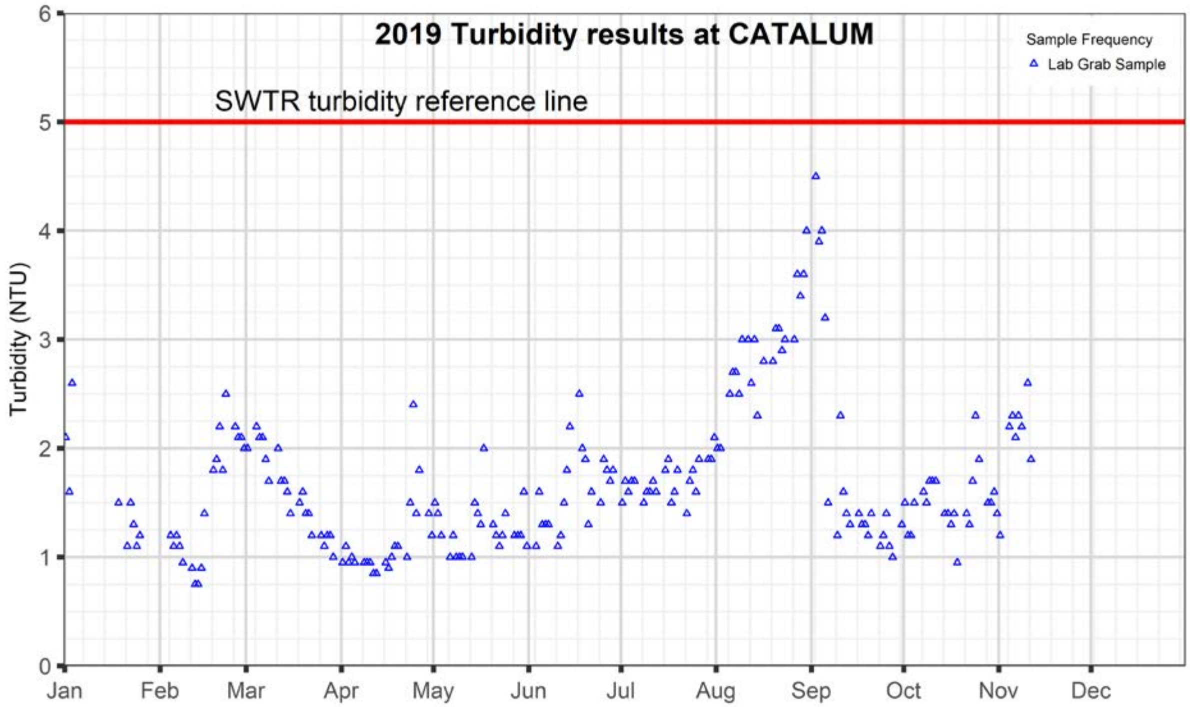


Figure 4.2 Five-day-per-week turbidity and fecal coliform grab samples at DEL17.



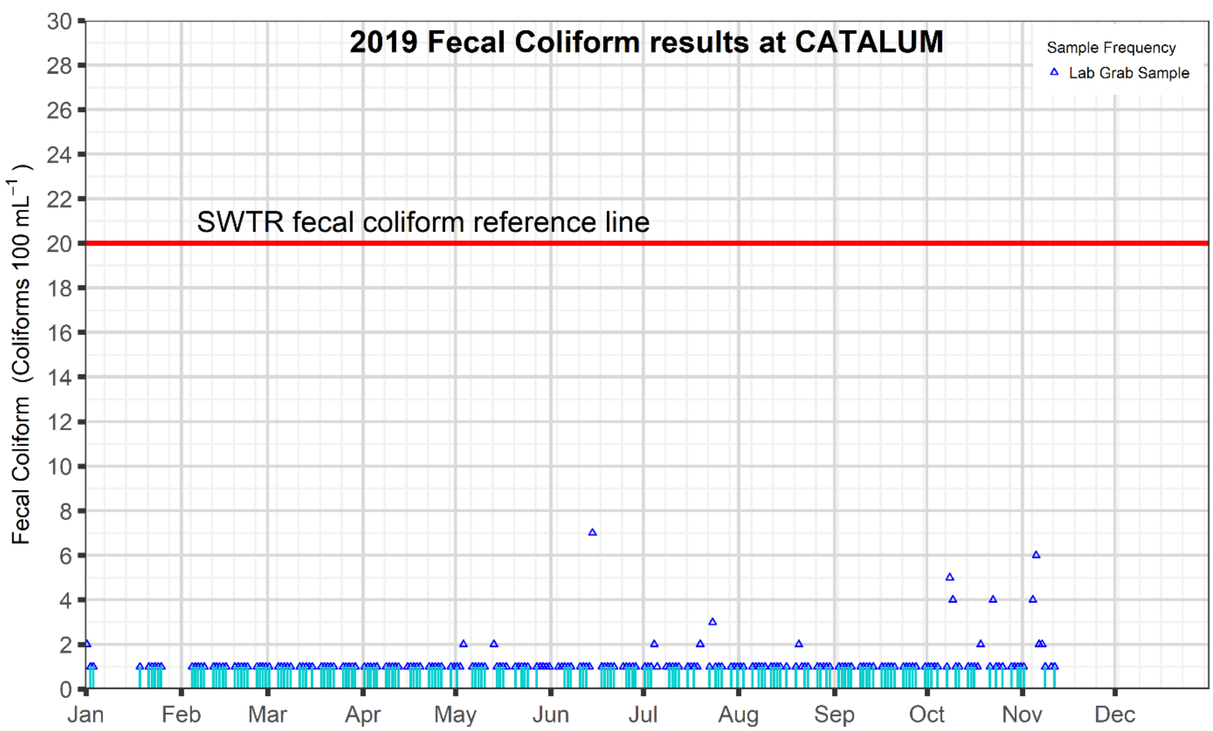
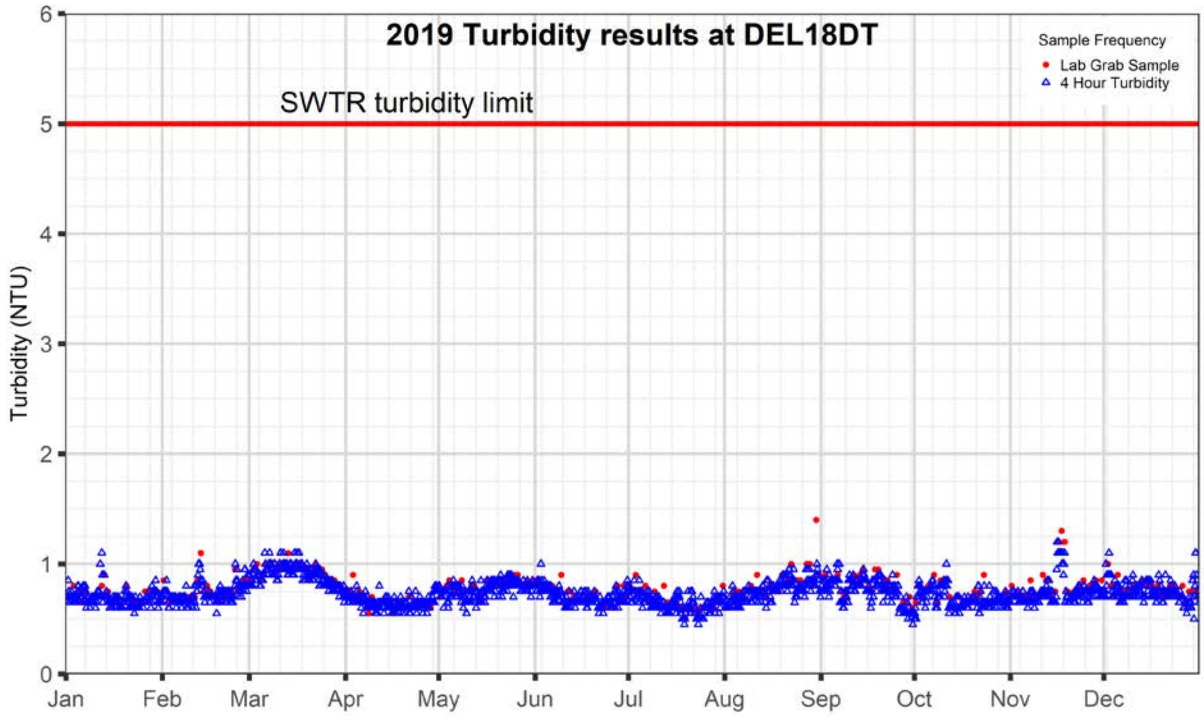


Figure 4.3 Five-day-per-week turbidity and fecal coliform grab samples at CATALUM.



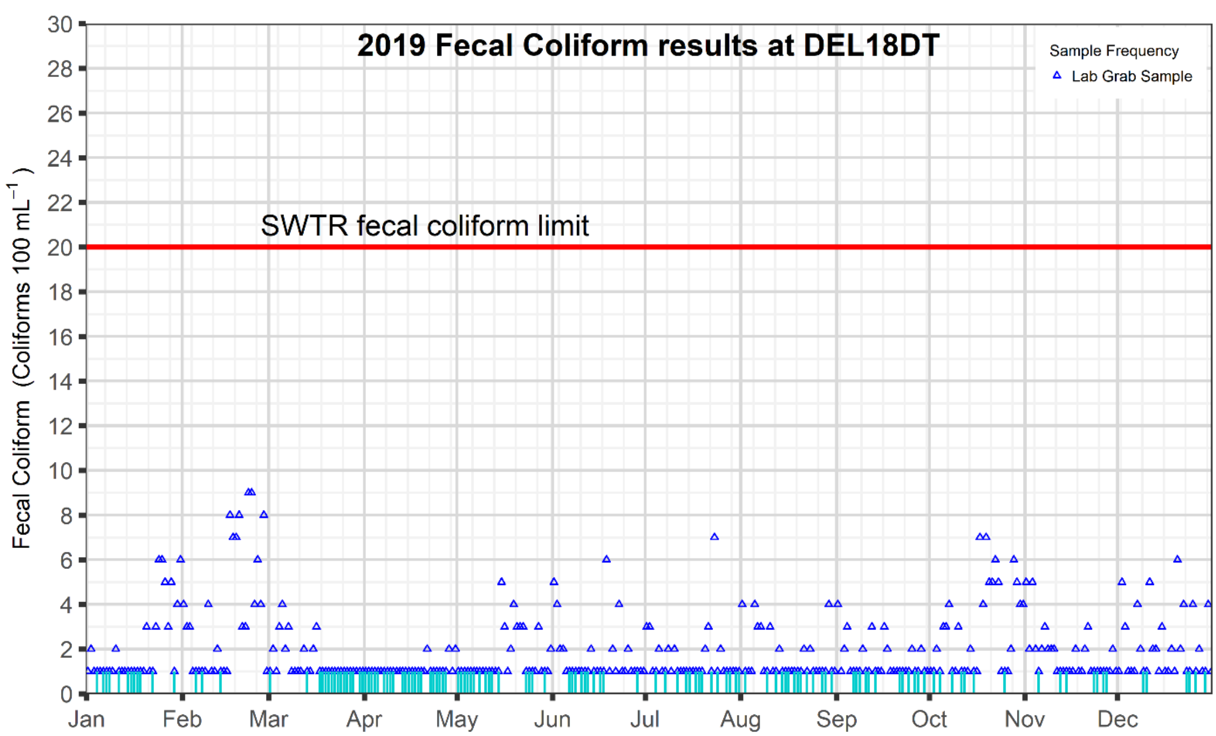


Figure 4.4 Seven-day-per-week turbidity and fecal coliform grab samples at DEL18DT.

4.3 Kensico Watershed Monitoring and Turbidity Curtain Inspections

4.3.1 Kensico Watershed Monitoring

DEP continues to conduct a fixed-frequency monitoring program of stream and reservoir sites in the Kensico watershed. Routine samples were collected from eight perennial streams and 10 locations within Kensico Reservoir as shown in Figure 4.1. Continuous flow measurements continued at eight of the Kensico perennial streams. Flows for WHIP (Whippoorwill Creek) and BG9 (Bear Gutter) are determined via a rating curve. Flows at E11 (Stream E11), E10 (Stream E10), MB-1 (Malcolm Brook), and N5-1 (Stream N5-1) are determined via a V-notch weir. Flows at N12 (Stream N12) and E9 (Stream E9) are determined via an H-flume. Water quality summary statistics for these streams are presented in Table 4.4. Protozoan results for the Kensico streams are reported in section 5.4.

Table 4.4 Summary statistics for Kensico watershed streams for 2019.

Analyte	Site	Obs	ND	Minimum	25th Per-centile	Median	75th Per-centile	Maximum	Note
Ammonia (as N) (mg L^{-1})	BG9	12	1	<0.02	0.02	0.03	0.07	0.10	KM
	E11	12	6	<0.02	<0.02	<0.02	0.02	0.04	ROS
	MB-1	12	1	<0.02	0.03	0.03	0.09	0.11	KM
	N12	12	10	<0.02	<0.02	<0.02	<0.02	0.03	>80%
	N5-1	12	1	<0.02	0.02	0.03	0.08	0.13	KM
	WHIP	12	8	<0.02	<0.02	<0.02	0.02	0.03	ROS
NO3+NO2 (as N) (mg L^{-1})	BG9	12	0	0.08	0.17	0.25	0.29	0.49	
	E11	12	4	<0.02	<0.02	0.03	0.06	0.27	KM
	MB-1	12	0	0.22	0.32	0.43	0.49	0.77	
	N12	12	0	0.32	0.90	1.07	1.15	1.39	
	N5-1	12	0	0.60	0.88	1.23	1.33	1.45	
	WHIP	12	0	0.59	0.75	0.89	0.97	1.20	
Total Nitrogen (as N) (mg L^{-1})	BG9	12	0	0.36	0.40	0.44	0.51	0.63	
	E11	12	0	0.24	0.28	0.32	0.37	0.47	
	MB-1	12	0	0.42	0.56	0.60	0.67	0.88	
	N12	12	0	0.42	0.93	1.08	1.24	1.49	
	N5-1	12	0	1.00	1.19	1.34	1.47	1.61	
	WHIP	12	0	0.72	0.83	0.97	1.08	1.31	
Total Phosphorus (as P) (µg L^{-1})	BG9	12	0	14	18	25	39	54	
	E11	12	0	17	23	34	38	49	
	MB-1	12	0	18	26	43	53	74	
	N12	12	0	11	17	22	29	73	

Table 4.4 Summary statistics for Kensico watershed streams for 2019.

Analyte	Site	Obs	ND	Minimum	25th Percentile	Median	75th Percentile	Maximum	Note
	N5-1	12	0	20	32	44	58	141	
	WHIP	12	0	11	16	22	29	36	
Alkalinity (mg L^{-1})	BG9	12	0	45.9	58.0	63.1	82.4	131.0	
	E11	12	0	83.5	103.5	112.5	129.3	167.0	
	MB-1	12	0	58.2	73.4	83.2	89.8	105.0	
	N12	12	0	46.3	51.1	58.3	64.0	84.4	
	N5-1	12	0	57.2	73.1	81.0	88.9	105.0	
	WHIP	12	0	43.4	47.5	57.2	66.5	98.5	
Chloride (mg L^{-1})	BG9	12	0	66.4	127.0	157.5	270.0	377.0	
	E11	12	0	23.0	51.0	72.5	100.4	139.0	
	MB-1	12	0	82.5	123.8	159.5	189.3	779.0	
	N12	12	0	39.9	54.4	65.1	72.9	1080.0	
	N5-1	12	0	51.2	83.4	95.2	143.3	950.0	
	WHIP	12	0	50.2	67.7	79.4	86.0	168.0	
Dissolved Organic Carbon (mg L^{-1})	BG9	12	0	1.9	2.9	3.7	4.0	5.3	
	E11	12	0	3.1	4.5	5.0	5.2	10.4	
	MB-1	12	0	2.0	2.5	3.0	3.4	4.4	
	N12	12	0	1.6	1.8	2.2	2.3	2.9	
	N5-1	12	0	1.7	2.2	3.0	3.0	3.3	
	WHIP	12	0	1.8	2.1	2.7	2.9	3.3	
TSS (mg L^{-1})	BG9	12	3	<1.0	<1.0	1.5	1.9	4.5	KM
	E11	12	2	<1.0	1.1	2.3	4.8	12.8	KM
	MB-1	12	0	1.0	1.7	2.8	4.6	9.8	
	N12	12	8	<1.0	<1.0	<1.0	1.0	2.2	ROS
	N5-1	12	4	<1.0	<1.0	2.3	5.8	8.9	KM
	WHIP	12	10	<1.0	<1.0	<1.0	<1.0	4.1	>80%
Specific Conductivity (μmhos cm^{-1})	BG9	12	0	345	574	708	1083	1360	
	E10	12	0	698	1102	1180	1270	3180	
	E11	12	0	293	396	500	595	791	
	E9	12	0	382	546	727	856	1030	
	MB-1	12	0	422	609	750	827	2640	
	N12	12	0	258	340	389	422	3560	

Table 4.4 Summary statistics for Kensico watershed streams for 2019.

Analyte	Site	Obs	ND	Minimum	25^{th} Percentile	Median	75^{th} Percentile	Maximum	Note
	N5-1	12	0	326	487	510	601	3140	
	WHIP	12	0	298	370	423	484	701	
Turbidity (NTU)	BG9	12	0	1.3	1.4	2.0	2.6	4.0	
	E10	12	0	0.4	0.6	1.2	1.7	2.0	
	E11	12	0	1.4	2.6	3.2	4.8	8.8	
	E9	12	0	0.6	1.1	1.7	7.1	9.3	
	MB-1	12	0	2.2	3.0	4.1	5.2	6.9	
	N12	12	0	0.5	0.6	0.7	0.9	1.1	
	N5-1	12	0	0.7	1.4	3.2	4.1	5.9	
	WHIP	12	0	0.2	0.6	0.8	1.1	1.5	
Fecal Coliform (Coliform $100mL^{-1}$)	BG9	12	1	<2	10	40	110	860	KM
	E10	12	0	6	28	40	78	280	
	E11	12	3	<2	<2	25	84	E3000	KM
	E9	12	2	<2	12	50	220	580	KM
	MB-1	12	0	5	30	145	320	520	
	N12	12	1	<2	16	50	140	370	KM
	N5-1	12	0	12	25	93	345	820	
	WHIP	12	0	2	9	28	58	E85	
Total Coliform (Coliform $100mL^{-1}$)	BG9	12	0	40	258	485	875	5200	
	E10	12	0	220	475	820	2225	5600	
	E11	12	1	<20	260	840	1400	>=E19000	KM
	E9	12	0	40	388	580	1850	7800	
	MB-1	12	0	180	438	1000	1850	>=3300	
	N12	12	0	160	483	800	1600	6600	
	N5-1	12	0	140	330	975	3000	6600	
	WHIP	12	0	60	200	775	1325	E22000	
Dissolved Oxygen (mg L^{-1})	BG9	11	0	2.8	5.2	6.7	10.8	12.5	
	E10	11	0	7.8	8.1	9.9	12.5	13.3	
	E11	11	0	2.9	5.4	9.0	9.3	11.8	
	E9	11	0	3.1	4.0	5.7	8.6	10.8	
	MB-1	12	0	8.0	8.3	10.5	12.3	13.6	
	N12	12	0	9.1	9.6	11.1	12.7	14.4	

Table 4.4 Summary statistics for Kensico watershed streams for 2019.

Analyte	Site	Obs	ND	Minimum	25th Per-centile	Median	75th Per-centile	Maximum	Note
	N5-1	12	0	7.7	8.2	10.7	12.2	13.5	
	WHIP	12	0	8.6	9.8	11.0	13.2	14.6	
pH (SU)	BG9	12	0	6.87	7.03	7.15	7.24	7.40	
	E10	12	0	7.68	7.79	7.84	7.91	7.96	
	E11	12	0	7.24	7.35	7.39	7.45	7.58	
	E9	12	0	6.47	6.92	6.98	7.06	7.16	
	MB-1	12	0	6.82	7.24	7.46	7.52	7.63	
	N12	12	0	7.69	7.75	7.87	7.89	8.14	
	N5-1	12	0	7.32	7.42	7.54	7.59	7.79	
	WHIP	12	0	7.58	7.68	7.81	7.93	8.50	
Temperature (°C)	BG9	12	0	2.2	4.8	11.6	19.0	24.5	
	E10	12	0	3.9	5.3	11.2	17.1	20.1	
	E11	12	0	3.0	5.2	13.2	19.3	23.1	
	E9	12	0	0.4	2.4	9.5	15.8	19.7	
	MB-1	12	0	2.4	4.7	11.0	17.6	21.2	
	N12	12	0	2.0	6.7	12.0	16.3	18.8	
	N5-1	12	0	1.4	5.1	11.0	17.7	21.2	
	WHIP	12	0	2.5	4.9	12.0	17.8	21.6	

Summary statistics 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). The Note column 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, >80% indicates that greater than 80% of the data are censored and statistics cannot be estimated, so the detection limit, preceded by "<", is reported, and <5 indicates that there were less than five samples so no statistics could be calculated.

"E" indicates that the coliform plate count is estimated based on a non-ideal plate.

">=" indicates that the coliform plate count may be biased low based on heavy growth.

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 UV Treatment 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. DEP continues to visually inspect the turbidity curtains, at least monthly from fixed shore locations around the cove, as part of the on-going maintenance of the curtains. Table 4.5 lists the dates and results of the turbidity curtain inspections carried out in 2019. Due to staffing issues, there was no observations in March 2019. When inspections indicate that maintenance is required, Bureau of Water Supply Systems Operations is notified and operations staff perform the appropriate repairs or adjustments.

Table 4.5 Visual inspections of the Kensico Reservoir turbidity curtains.

Date	Observations
1/23/19	Curtains appear afloat and intact as seen from shore except for the north curtain on the DEL18 point which appears to be hung up on shore.
2/06/19	The turbidity curtains in the CAT UEC cove and on the point appear attached, afloat, and intact as seen from shore. A portion of the curtain on the point appears caught up on rocks and the shore.
4/03/19	The turbidity curtain looks intact and afloat as seen from shore.
5/03/19	The turbidity curtain looks intact and afloat as seen from shore.
5/29/19	The turbidity curtain appears to be intact.
6/12/19	The turbidity curtain looks intact and afloat as seen from shore.
7/24/19	The turbidity curtain looks intact and afloat as seen from shore.
8/07/19	The turbidity curtain looks intact and afloat as seen from shore.
8/21/19	The turbidity curtain appears to be intact and afloat. Pictures added to SharePoint.
9/04/19	The turbidity curtain appears to be intact and afloat. Pictures added to SharePoint.
9/18/19	The turbidity curtain looks intact and afloat as seen from shore.
10/02/19	The turbidity curtain looks intact and afloat as seen from shore.
10/16/19	The turbidity curtain appears to be intact and afloat. Pictures added to SharePoint.
10/30/19	The turbidity curtain looks intact and afloat as seen from shore.
11/13/19	The turbidity curtain looks intact and afloat as seen from shore.
11/27/19	The turbidity curtain looks intact and afloat as seen from shore.
12/11/19	The turbidity curtain looks intact and afloat as seen from shore.
12/24/19	The turbidity curtain looks intact and afloat as seen from shore.

4.4 Wildlife Management

4.4.1 Waterfowl Management

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 and analyzed for fecal coliform bacteria concentrations 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 waterbird counts increased during the avian migratory and wintering periods, fecal coliform bacteria levels also increased. Continued implementation of the avian dispersal measures have 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. Based on these data, DEP determined that waterbirds were the most important contributor to seasonal fecal coliform bacteria loads to Kensico.

The Waterfowl Management Program (WMP) includes standard bird management techniques at several NYC reservoirs that are approved by the U.S. Department of Agriculture’s Animal and Plant Health Inspection Service’s Wildlife Services (USDA), and in part under permit by the U.S. Fish and Wildlife Service (USFWS) and the New York State Department of Environmental Conservation (NYSDEC). DEP maintains annual depredation permits from the USFWS and NYSDEC to manage avian and mammalian populations for water quality improvements.

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 is implemented as needed.

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 4.5). DEP will continue implementation of the WMP to help ensure delivery of high quality water to NYC consumers.

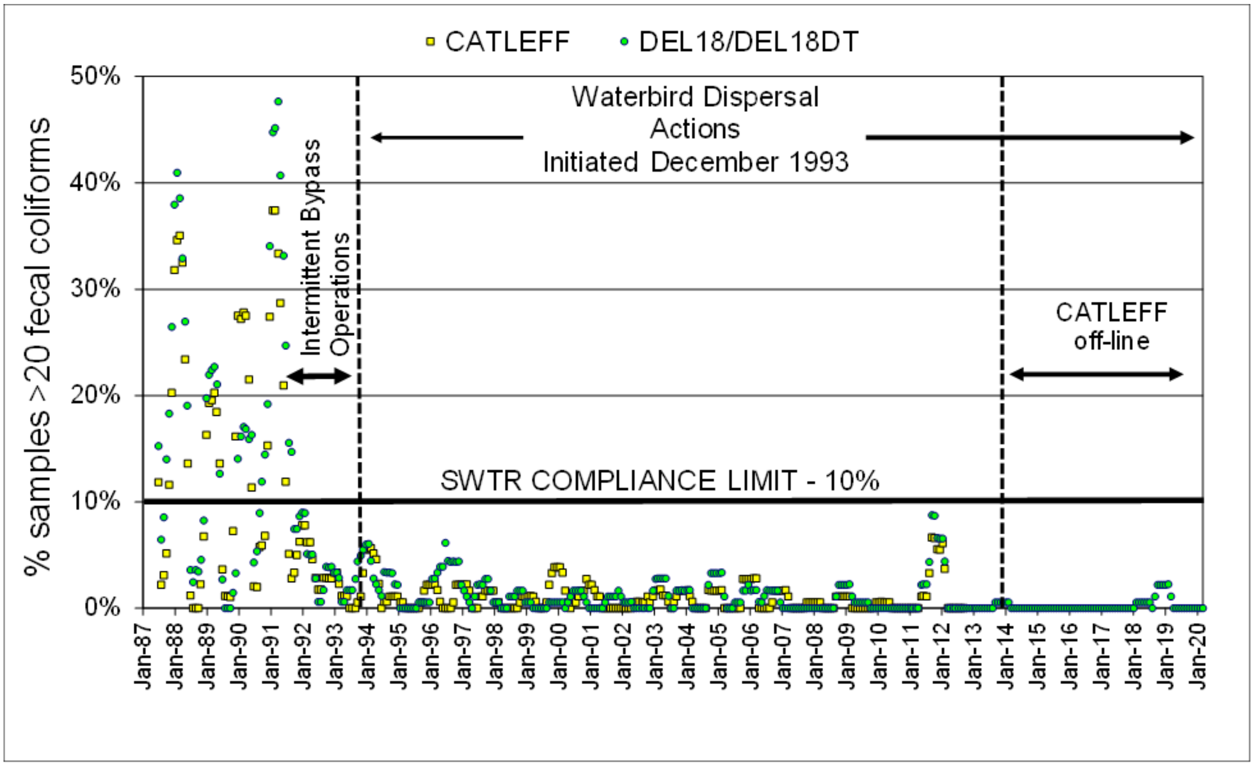


Figure 4.5 Percent of keypoint fecal coliform samples at Kensico Reservoir greater than 20 fecal coliforms $100mL^{-1}$ for the previous six-month period, 1987-2019. The first vertical dashed line indicates the year in which the WMP was implemented.

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 Delaware Aqueduct Shaft 18, the reservoir outflow, and along stream corridors that enter Kensico Reservoir in the vicinity of the source water intake. All wildlife fecal excrement (mostly mammalian) collected during these surveys is identified to species and disposed of in advance of the storms to prevent the feces from being washed into the reservoir.

During 2019, DEP and its contractor conducted 17 wildlife sanitary surveys in advance of significant precipitation events at Kensico Reservoir (Table 4.6). Of the 499 fecal samples collected, 39% were attributed to white-tailed deer (*Odocoileus virginianus*), 17% to rabbits

(*Sylvilagus spp.*), 2% to raccoons (*Procyon lotor*), 1.4% to other mammals, and 3.8% to unknown mammals. Avian species excrement included 19% from Canada geese (*Branta canadensis*) and 16% from passerine bird species. In 2019 an unusually high number of passerine samples were identified and collected compared to previous years, however it most likely does not represent an increase in terrestrial bird use of the area.

Table 4.6 Wildlife sanitary surveys conducted adjacent to Delaware Aqueduct Shaft Building 18.

Date of Survey	White-tail Deer	Raccoon	Rabbit	Canada Goose	Coyote	Fox	Mink	Striped Skunk	Passerine (birds)	Domestic Dog	Mallard Duck	Meadow Vole	Other/ Unknown Mammal	Total (all species)
01/17/2019	39	0	0	0	0	0	0	0	0	0	0	0	0	**39**
01/23/2019	26	0	9	0	0	0	0	0	0	0	0	0	0	**35**
02/11/2019	47	0	0	0	0	0	0	0	7	0	0	0	6	**60**
01/23/2019	36	0	0	0	0	0	0	0	2	0	0	0	2	**40**
03/20/2019	18	1	5	0	1	0	1	0	0	0	0	0	6	**32**
04/05/2019	6	3	4	33	0	0	0	0	0	0	0	0	0	**46**
04/19/2019	3	1	1	1	0	0	0	0	0	0	0	0	0	**6**
05/03/2019	0	0	0	45	1	0	0	0	0	1	1	0	0	**48**
07/16/2019	4	2	0	18	0	0	0	0	64	0	0	0	2	**90**
10/07/2019	1	1	4	0	0	0	0	0	0	0	0	0	0	**6**
10/15/2019	2	2	0	0	0	0	0	0	0	0	0	0	1	**5**
10/30/2019	3	0	1	0	0	0	0	0	5	0	0	0	0	**9**
11/22/2019	6	0	8	0	0	0	0	0	0	0	0	0	1	**15**
11/29/2019	0	0	6	0	0	0	0	0	0	0	0	0	0	**6**
12/08/2019	6	0	16	0	0	0	0	1	0	0	0	1	0	**24**
12/13/2019	0	0	9	0	0	0	0	0	0	0	0	0	1	**10**
12/28/2019	2	0	24	0	0	1	0	0	0	0	0	1	0	**28**
Total by species	**199**	**10**	**87**	**97**	**2**	**1**	**1**	**1**	**78**	**1**	**1**	**2**	**19**	**499**

4.5 Kensico Research Projects and Special Investigations

4.5.1 Bryozoans

Background

Bryozoans have been observed in Kensico Reservoir by DEP staff for decades. Since the late 1980s, the most visible bryozoan has been *Pectinatella magnifica* due to its large, gelatinous, and spherical shape. *P. magnifica* has been seen in coves throughout the reservoir, near the shoreline on branches and rocks, in the narrowed channel by the Rye Lake Bridge, and at the reservoir outflow at Delaware Aqueduct Shaft 18. Moreover, it has been observed in numerous other reservoirs throughout the watershed. Several other bryozoan species can be found in Kensico Reservoir including *Cristatella mucedo*, which looks like a small caterpillar-like bryozoan species whose colonies can grow together to cover surfaces in thin mat-like sheets. The presence of *P. magnifica* was inconsequential until fall 2012 when the Catskill/Delaware Ultraviolet Light Disinfection Facility (CDUV) came on line. Bryozoan colonies found downstream of Shaft 18 CDUV caused clogging issues at the 1-inch perforated baffle plates located just prior to the UV lamps. The openings were manually cleared of the gelatinous colonies, but this was very labor intensive. Control of these organisms in a drinking water supply is particularly challenging because many control measures used for other applications are not an option.

Monitoring

DEP staff began monitoring bryozoan colonies in the sluiceways at Shaft 18 using an underwater video camera in 2014. During each survey, an underwater video camera is lowered on a long set of poles down into the sluiceway (upstream of the traveling screens) and high definition (HD) video recordings are created to document the conditions in each of the five sluiceways. Notes on water quality parameters (temperature, turbidity, etc.) and operational conditions (daily flow) are also taken at the time of each visit. Video monitoring is predominantly focused on the access ladder and adjacent wall area in each sluiceway and still frame photos were captured to document colony sizes.

Due to observations made in recent years, DEP began to intentionally close individual sluiceways on a staggered basis in 2019 to reduce flow and potentially disrupt bryozoan colony growth and abundance. Bryozoan monitoring began on July 10, 2019, with small colonies observed in sluiceways 2 and 3. The second survey occurred on August 7, 2019, and following this survey DEP closed one of the sluiceways to begin the investigation into the effect of staggered closures. To determine the effect of flow on the colonies, some gates were opened and closed at staggered intervals and video observations were recorded at least every other week. The next survey occurred on August 13, 2019, followed by a survey two weeks later on August 27, 2019. In September, the reservoir was operated in float modes while the shoreline stabilization project occurred near Shaft 18. Each sluiceway was surveyed weekly from September 4, 2019, through October 2, 2019.

Results

In all surveys the mat-like growth of *Cristatella mucedo* was considerable, covering large areas of wall and ladder surfaces. As in past years, *C. mucedo* appears earlier in the season at shallow depths before any growth of *P. magnifica*. When *P. magnifica* began growing at shallow depths, *C. mucedo* became scarce at these depths and grew more abundantly at lower depths as the season progressed. Reasons for this transition may include, but are not limited to, *C. mucedo* preferring cooler temperatures than *P. magnifica* or *P. magnifica* out-competing *C. mucedo* at shallower depths. *C. mucedo* colonies were still numerous as of the August 31 survey, especially at lower depths. Freshwater sponges were also present, commonly occurring at depths below 20 feet.

P. magnifica colonies were also observed during each survey this year since monitoring began in July. Colonies at this time of the year were still relatively small (<4 inches in diameter) and not widespread. By the second survey, approximately four weeks later on August 7, *P. magnifica* colonies were more abundant and observed in all five sluiceways. Most were approximately 3-4 inches in diameter with several colonies being much larger and taking up the entire 12-inch ladder rung. By the end of September, colonies of *P. magnifica* were widespread in the sluiceways that had been open the entire season (1, 4, and 5) and each of those sluiceways had at least one colony 16 inches or larger.

Two of the five sluiceways were used to test different intervals of closure, with only one sluice gate closed at a time. This was done to investigate if reduced flow would have a negative impact on the growth of the colonies, since no flow equals no food for these sessile colonies. A reduction in colonial growth could reduce the amount of cleaning and maintenance time needed for divers at the end of the season. During the sluiceway 3 closure (August 7 – 27, 2019) colonies did not increase in size and the surface appeared to change with rosettes of living zooids seeming to contract. A zooid is the individual bryozoan organism which forms the basic unit of a bryozoan colony. The progression from a colony-free rung (July 2019) to a growing colony (early August 2019) to a senescing colony with contracted zooids (by late August, 2019) is visible in Figure 4.6. Sluiceway 2 was closed on August 27, 2019, and remained closed for the remainder of the monitoring season (after October 2, 2019). The growth and later degradation of a large colony in sluiceway 2 is clearly evident in Figure 4.7 and similar to what was seen in sluiceway 3 just three weeks later. For comparison, the colony in Figure 4.8 is a good example of the appearance of colonies growing in sluiceways which remained open for the entire season. It should also be noted that even after sluiceway 3 was reopened at the end of August, the degraded *P. magnifica* colonies did not resume growth and no new colonies were detected in those immediate areas.

Ultimately, the reduction in colonial growth caused by reduced flow resulted in the equivalent of one less day needed for divers. The divers commented on the essentially bryozoan-free condition of the closed sluiceway and were able to perform other needed tasks for DEP on the extra day. A proposal was made to continue staggered flow reductions in sluiceways in the summer of 2020.

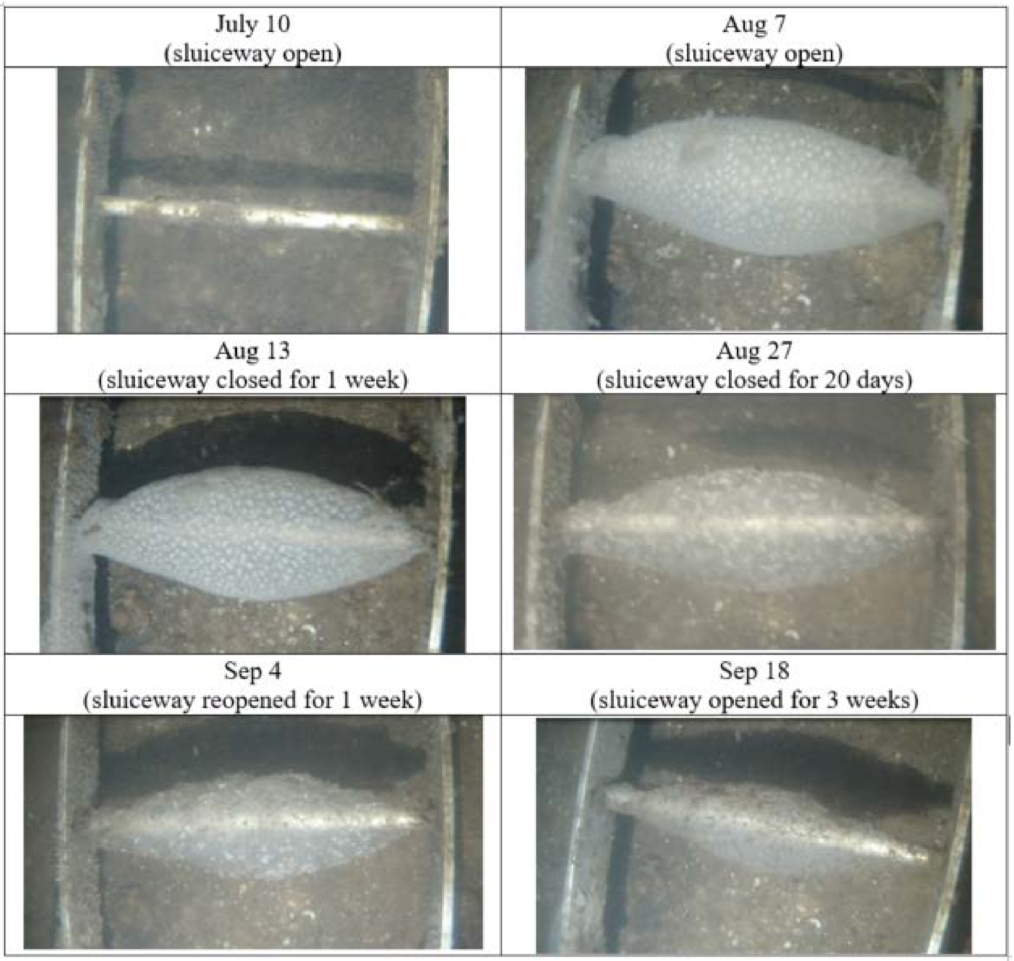


Figure 4.6 Late sluiceway closure - time-series photos from Shaft 18 sluiceway 2 showing the size and condition of *P. magnifica* from July 10 to October 2, 2019, with colony senescence visible at September 18, 2019. For scale, each of the ladder rungs is about 12 inches across.

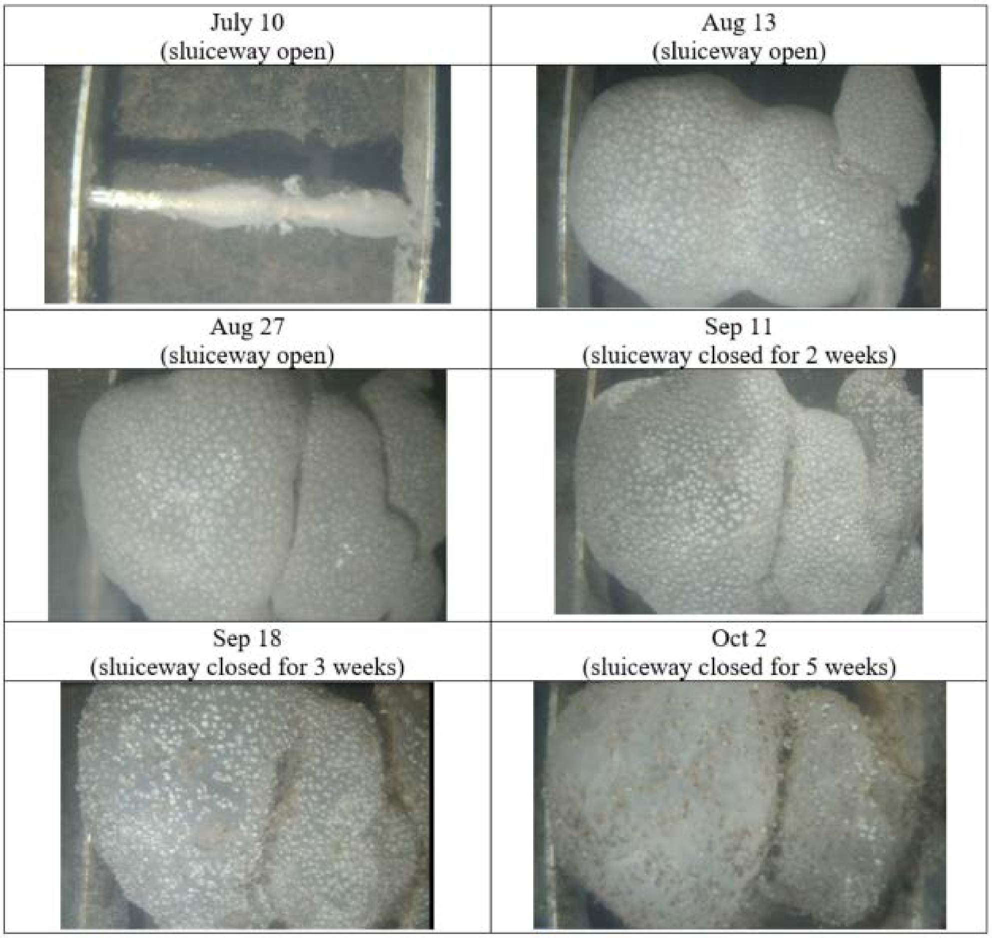


Figure 4.7 Late sluiceway closure - time-series photos from Shaft 18 sluiceway 2 showing the size and condition of *P. magnifica* from July 10 to October 2, 2019, with colony senescence visible at September 18, 2019. For scale, each of the ladder rungs is about 12 inches across.

Figure 4.8 Sluiceway open - photo from Shaft 18 sluiceway 4 on October 2, showing the size and condition of *P. magnifica* in a sluiceway which remained open the entire season. Individual colony rosettes are still visible and appear robust, even late into the season.

4.5.2 Special Investigations within the Watershed

The following special investigations occurred within the Kensico Reservoir watershed during 2019 and are listed below in chronological order. Each of these special investigations evaluated the potential impact to drinking water quality. A brief summary of each investigation and the corresponding results are shown below.

4.5.2.1 E10 Special Investigation: March 5, 2019

On March 5, 2019, Watershed Water Quality Operations (WWQO) field staff performed a routine monitoring survey that including the site E10. WWQO laboratory personnel observed that the E10 samples had a distinct fuel odor. WWQO field staff were requested to resample E10 plus an upstream location (E10-Upstream) on March 6, 2019, for scent. Both sites had an intense (5 on a scale of 1 to 5) petroleum hydrocarbon odor. Additional sampling was conducted on March 7, 2019, for scent, diesel range organics (DRO) and gasoline range organics (GRO) at both locations. Both sites showed decreases in the intensity of the petroleum hydrocarbon odor (E10 Intensity 3 and E10-Upstream Intensity 4), no GRO compounds were detected, and DRO compounds were above the detection limit of 0.105 mg L^{-1} for both sites (E10 0.135 mg L^{-1} and E10-Upstream 0.274 mg L^{-1}). An incident report was written and WWQO staff notified DEP HAZMAT and BWS Police at the Eastview Precinct of the incident and laboratory results.

HAZMAT responded on March 7, 2019, and found a catch basin within a commercial office facility parking lot with diesel fuel in and around the catch basin. HAZMAT took control of the investigation and placed a 5-foot-long soft boom at the catch basin outlet pipe leading into E10. A follow up investigation was conducted by HAZMAT on March 18, 2019. The boom was still in place and the water behind the boom had a very light sheen and odor. It was determined on the same day by WWQO management that DRO/GRO detections were low enough that monitoring was no longer needed because the soft boom was effectively capturing the petroleum product and because the boom would be kept in place until the sheen was no longer observed in future HAZMAT visits to the site.

4.5.2.2 Kensico Shoreline Stabilization Project: May 2019 through December 2019

The shoreline area around the Delaware Aqueduct Shaft 18 building (Shaft 18) intake was identified as a significant contributor to local turbidity issues, especially from an easterly wind direction. As a result, a plan to stabilize the shoreline was developed for both sides of Shaft 18. Construction on the shoreline farthest away and north of the Shaft 18 began in May 2019. The construction contractor is responsible for monitoring turbidity within the actual construction area that was controlled by multiple layers of turbidity curtains within the reservoir. Since construction work could potentially cause and/or contribute to turbidity, a water quality monitoring plan was developed to confirm that no turbidity escaped the construction area. This plan consisted of the deployment of three fixed-depth buoys outfitted with turbidity sensors outside the project construction area to give advanced notice of potential turbidity events. Each buoy has sensors deployed in the middle and near the bottom of the reservoir, if depth allows, which record turbidity results at 15-minute intervals. The plan also utilizes existing fixed-depth buoys that are part of the routine RoboMon Program at sites 2.9BRK and 2BRK. Site 2.9BRK, located upstream (north) of the construction area, acts as a control and gives an indication of background turbidity in the reservoir. Site 2BRK was located between the construction area and Shaft 18 to ensure that turbidity had not migrated out of the project area towards Shaft 18. These data are displayed in near real time via the DEP WaterHub interface and are closely monitored by BWS staff to ensure that elevated turbidity does not reach Shaft 18. This project is ongoing in 2020.

4.5.2.3 Canine Study: June 17 – June 20, 2019

In 2019, the Watershed Protection Programs, Watershed Water Quality Operations, and Water Quality Science and Research directorates partnered with Water Innovation and Research to pilot the use of canines for detection of sewage/septic discharges. Canine sewage detection methods are a complimentary tool to traditional methods such as field inspections and laboratory analysis with the potential to aid in the rapid detection of point-source pollution. The pilot field investigation occurred from June 17 – June 20, 2019; a scenting canine was used in the Kensico Watershed to canvass a larger area than is possible using solely traditional sampling and field inspection techniques. Water quality samples were collected for fecal coliform, bacteroides, specific conductivity, temperature, adenosine triphosphate (ATP) and MST at locations indicated both positive and negative by the canine. Of the 64 locations sampled by the canine, 40 resulted in a positive alert for human waste. Water quality samples collected at 18 of those locations resulted in two positive results for human markers. The areas investigated were prioritized for follow up based on the results. Follow-up investigations will include further field inspections, camera and/or smoke testing of specific sewer lines, and a second on-site canine study with additional water quality sampling.

4.5.2.4 Storm Event Kensico Reservoir - October 16 – October 20, 2019

On October 16, 2019, a storm event of approximately 2.56 inches of precipitation triggered storm event monitoring. The storm event occurred over a period of approximately 72 hours for stream site N5-1 and 96 hours for stream site MB-1. Analytes monitored included turbidity, fecal coliforms, conductivity, and MST**.** Flows at sites N5-1 and Malcolm Brook (MB-1) showed a sharp increase in flow on October 16 with discharges reaching 30.8 cfs at N5-1 and 2.6 cfs at MB-1. Flow at these sites were relatively high during the day of October 17 with N5-1 receding quickly while MB-1 receded more slowly later in the day. Both sites gradually returned to baseflow over the next few days. Turbidity and fecal coliform peaks were different between the two sites. N5-1 turbidity results had no distinct peak and a narrower range (9.1-19 NTU) and peak fecal coliforms (E39000 fecal coliforms 100 mL^{-1}) were observed after the peak of the storm event. At MB-1, the highest fecal coliform and turbidity results (39000 fecal coliforms 100 mL^{-1} and 36 NTU, respectively) coincided with peak stream flow. During the storm event period, MB-1 conductivity ranged from 247 µmhos cm^{-1} to 327 µmhos cm^{-1} and N5-1 ranged from 130 µmhos cm^{-1} to 394 µmhos cm^{-1}.

Turbidity at the Kensico outflow, sampled at DEL18DT, did not appear to be impacted by the storms as turbidity levels never exceeded 1.0 NTU during and for 10 days after the storm. Fecal coliform results did not exceed 7 fecal coliforms $100mL^{-1}$ during and for 10 days after the storm. Conductivity measurements at DEL18DT ranged from a low of 68 µmhos cm^{-1} to a high of 72 µmhos cm^{-1} from October 7 to October 26, 2019.

MST analysis, using the human-associated marker DNA sequence located on the 16S rRNA gene of *Bacteroides dorei* as a target (H1), was performed on seven samples from each stream. Results from N5-1 were consistent with historical data from this site with four samples testing negative for H1 and three samples with trace amounts of H1 (detectable but not quantifiable). Conversely, Malcolm Brook samples resulted in five samples with quantifiable H1 concentrations and two samples with trace amounts of the H1 marker. Concentrations ranged from 598 to 1,710 copies $100mL^{-1}$, with the highest occurring on the descending limb of the hydrograph shortly after peak flow. Two of the five positive samples were resubmitted for H2 and H3 testing in order to add confidence to the identification of a human source by testing with two additional human markers. Both negative and trace level amounts were identified for the H2 marker, and quantifiable results were detected for the H3 marker supporting the H1 data. As this was uncharacteristic for Malcolm Brook, additional sampling was coordinated with the WPP Directorate, and sampling was conducted under rainy conditions at six selected locations on October 31, 2019. Fecal coliform data ranged from 980 to E9000 fecal coliforms $100mL^{-1}$; however, MST results for the H1 marker at all six sites were negative. Another MST sample was collected at site MB-1 as part of a reservoir survey in January 2020, and was also negative for the H1 marker. Due to inconsistent results, a sewer-line inspection is planned for the area.

5. Pathogen Monitoring and Research

5.1 Introduction

Each year DEP monitors the 1,972-square-mile NYC watershed for *Cryptosporidium*, *Giardia*, and human enteric viruses (HEV) as part of compliance and surveillance monitoring. Samples collected for protozoan analysis were analyzed by Method 1623.1 with EasyStain and using heat dissociation. During 2019, 604 samples were collected and analyzed for protozoan enumeration, plus an additional 52 samples were collected and analyzed by a cell culture immunofluorescent assay (CC-IFA) to study the potential infectivity of any *Cryptosporidium* found at Hillview Reservoir. Samples collected from streams and reservoir outflows in the NYC watershed made up the largest portion of the sampling effort (34.3%) with keypoint samples from Kensico and New Croton comprised the second largest component (24.7%). Samples collected at the outflow of the CDUV plant and at the Hillview downtake made up 17.4% of samples, while samples taken from the upstate reservoir outflows and wastewater treatment plants made up the remaining 23.7% (Figure 5.1). Additionally, DEP collected 33 HEV samples in 2019, which were analyzed in-house using a modified version of the Information Collection Rule (ICR) Manual Method (USEPA 1996). In 2019, DEP made a request to the NYSDOH to discontinue HEV monitoring in the watershed. Current sampling locations included the Kensico and New Croton keypoint sites. Approval was granted, and the last HEV samples were collected in October 2019.

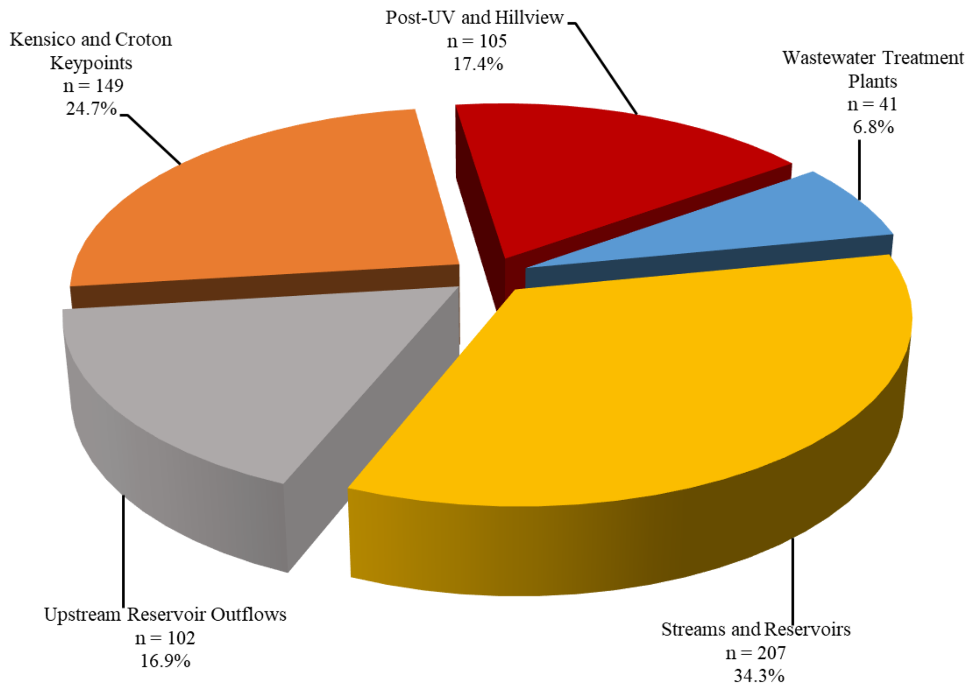


Figure 5.1 DEP protozoan sample collection location distribution for 2019.

Similar to past years, monitoring in 2019 was affected by a few operational changes that warrant mentioning. The Catskill Aqueduct was shut down at various times during 2019 in support of the Catskill Aqueduct Repair and Rehabilitation project, resulting in the inability to collect several protozoan samples at CATALUM, including two non-consecutive samples in January and samples from November 12 through to the end of the year. A shutdown of the Catskill Aqueduct prevented one sample from being collected at CCCLAB on November 12. The Catskill Aqueduct south of Kensico Reservoir (CATLEFF) was shut down in 2012 and has remained so since that time. 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.

The target volume for DEP protozoan samples is 50L (for Method 1623.1), however, sample volumes may vary. This is especially the case at stream sites after precipitation events since they tend to have higher turbidities. The results discussed in this chapter are from samples that were 47-53 liters unless otherwise noted. Mean and maximum concentrations are generally stated as (oo)cysts per 50L. HEV sample volume is targeted at 240 liters and results are provided as most probable number (MPN) per 100L.

5.2 Source Water Results

Catskill Aqueduct Inflow

In 2019, only one sample was positive for *Cryptosporidium* (1 oocyst) out of the 41 samples (2.4%) taken at CATALUM (Table 5.1). This is in contrast to 4 out of 51 samples (7.8%) in 2018. The mean annual *Cryptosporidium* concentration was 0.02 oocysts in 2019, compared to 0.08 oocysts in 2018.

Giardia was detected in 21 out of 41 samples (51.2%) at CATALUM in 2019, with the same number of detections at CATALUM last year; however, 51 samples were collected in 2018 (41.2%). Mean *Giardia* concentrations from 2019 were slightly higher than in 2018 (1.24 and 0.96 cysts, respectively).

HEVs were not detected in any of the 10 monthly samples collected at the Catskill inflow to Kensico in 2019, compared to 3 out of 12 samples positive in 2018 (25%). As mentioned previously, DEP discontinued HEV monitoring in October 2019.

Table 5.1 Summary of *Cryptosporidium*, *Giardia*, and HEV compliance monitoring data at Kensico and New Croton keypoints in 2019.

	Keypoint Location	Number of Positive Samples	Mean[2]	Maximum
Cryptosporidium (oocysts $50L^{-1}$)	CATALUM (n=41)	1	0.02	1
	DEL17 (n=52)	6	0.19	3
	DEL18DT (n=52)	3	0.06	1
	CROGH[1] (n=4)	0	0.00	0
Giardia (cysts $50L^{-1}$)	CATALUM (n=41)	21	1.24	6
	DEL17 (n=52)	45	6.96	19
	DEL18DT (n=52)	37	2.15	12
	CROGH[1] (n=4)	2	2.74	10
Human Enteric Virus $100L^{-1}$ (HEV)	CATALUM (n=10)	0	0.00	0.00
	DEL17 (n=10)	0	0.00	0.00
	DEL18DT (n=10)	0	0.00	0.00
	CROGH[1] (n=3)	1	9.98	29.95

[1]Includes alternate sites sampled to best represent outflow during “off-line” status.
[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.

Delaware Aqueduct Inflow and Outflow

Fewer samples were positive for *Cryptosporidium* at DEL17 in 2019 (11.5%) than in 2018 (17.0%), and the mean annual oocyst concentration for 2019 (0.19 oocysts) was similar to that in 2018 (0.25 oocysts) (Figure 5.2). There were two less *Cryptosporidium* detections at the DEL18DT outflow in 2019 than 2018, with detection rates of 5.8% and 9.4%, respectively. The mean annual oocyst concentration for DEL18DT in 2019 (0.06 oocysts) was similar to 2018 (0.09 oocysts).

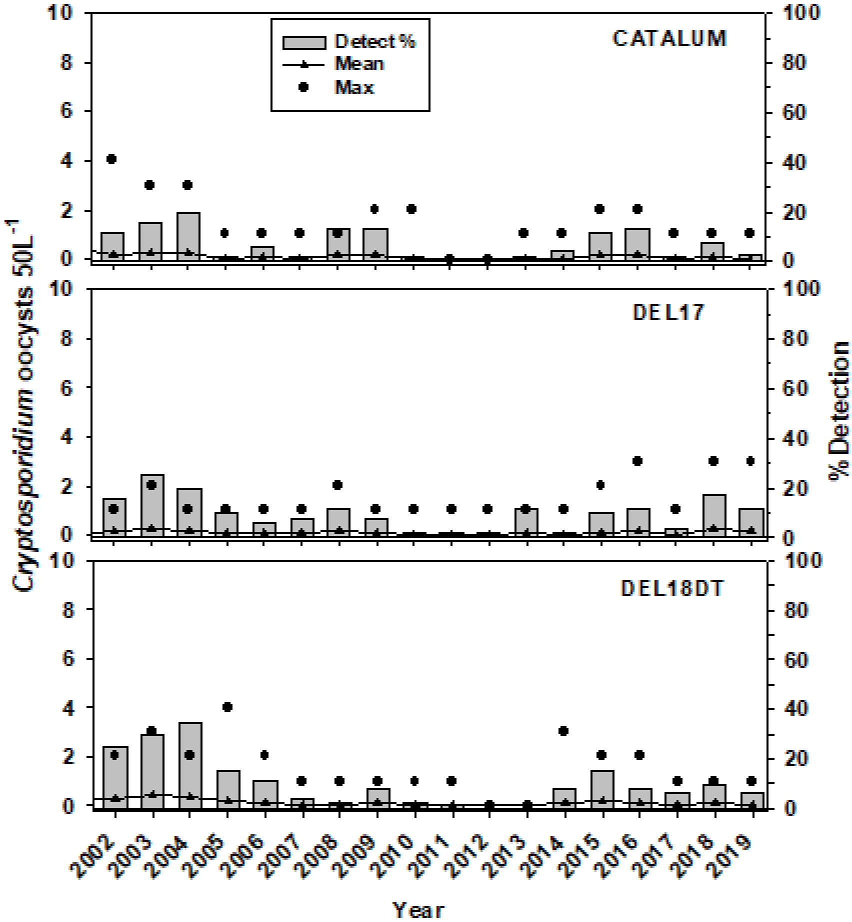


Figure 5.2 *Cryptosporidium* annual percent detection, mean concentrations, and maximum for the Kensico keypoint sites during each year from 2002 through 2019.

The percentage of DEL17 *Giardia* detections in 2019 (86.5%) was slightly higher than in 2018 (81.1%). The mean *Giardia* concentration was also higher in 2019 than 2018 (6.96 and 4.85 cysts, respectively). The Kensico outflow at DEL18DT had the same number of *Giardia* detections in 2019 as in 2018 (both 37). Despite the same number of detections, the mean *Giardia* concentration was higher at DEL18DT in 2019 (2.15 cysts) compared to the previous year (1.60 cysts). The annual *Giardia* mean at DEL18DT was strongly influenced by increased concentrations in a few samples, including the maximum result of 12 cysts on December 2, 2019 (Figure 5.3).

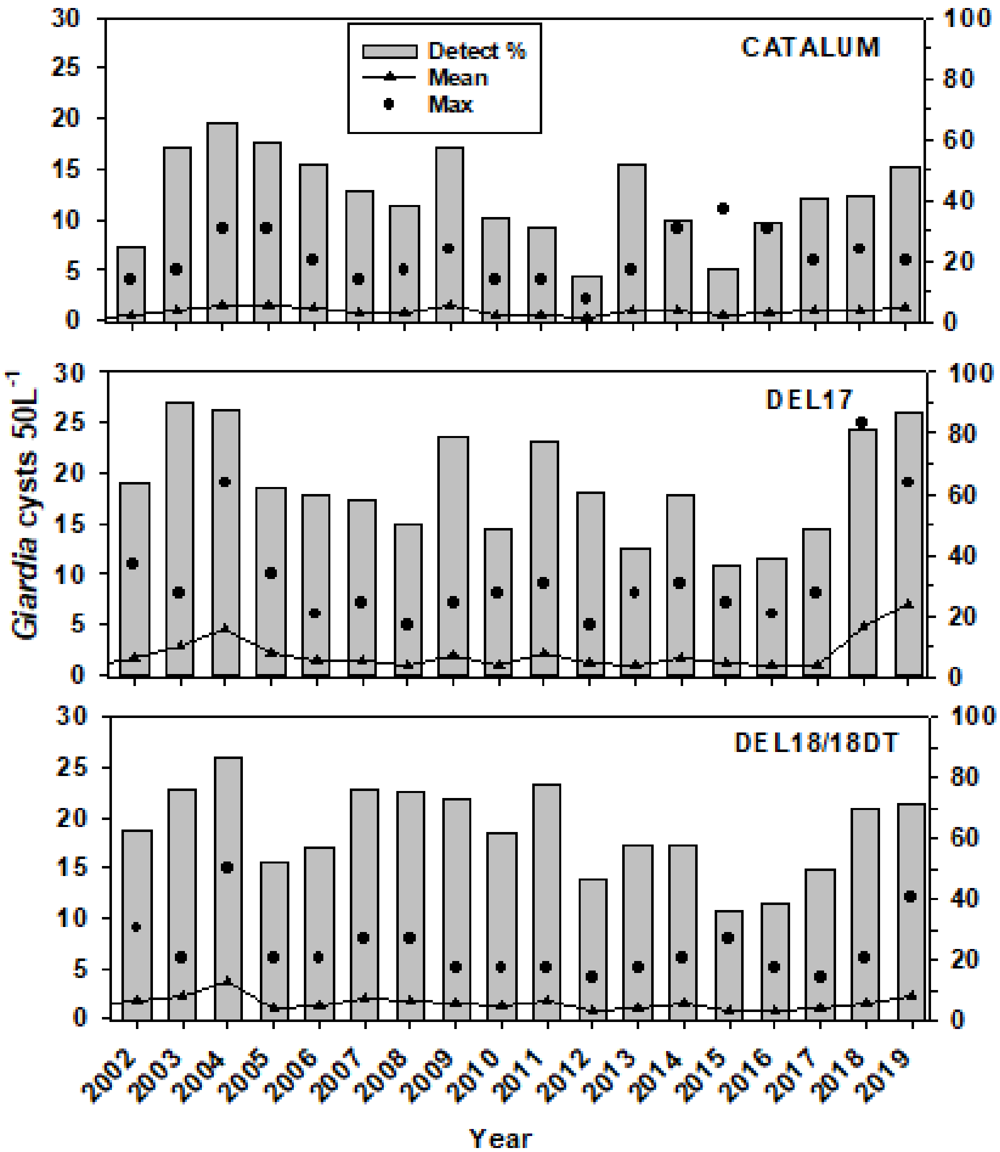


Figure 5.3 *Giardia* annual percent detection, mean concentration, and maximum result for the Kensico keypoint sites during each year from 2002 to 2019.

There were no HEVs detected in the 10 samples collected at DEL17 in 2019, which is less than the two detections in 12 samples in 2018. Kensico Reservoir DEL18DT outflow samples were also all negative for HEVs in 2019.

Croton System

The New Croton Reservoir outflow was sampled quarterly for protozoans in 2019, a reduction from 18 samples collected in 2018. All four routine quarterly samples taken at the New Croton Reservoir outflow were negative for *Cryptosporidium* (Figure 5.4), as was the case in 2018. *Giardia* were detected in two out of the four samples (50.0%), compared to seven of the 18 samples (38.9%) in 2018. The mean annual concentration of *Giardia* was higher in 2019 (2.74 cysts) compared to 2018 (0.94 cysts), with the 2019 mean strongly influenced by a single elevated result of 10 cysts in the February 11 sample (Figure 5.5).

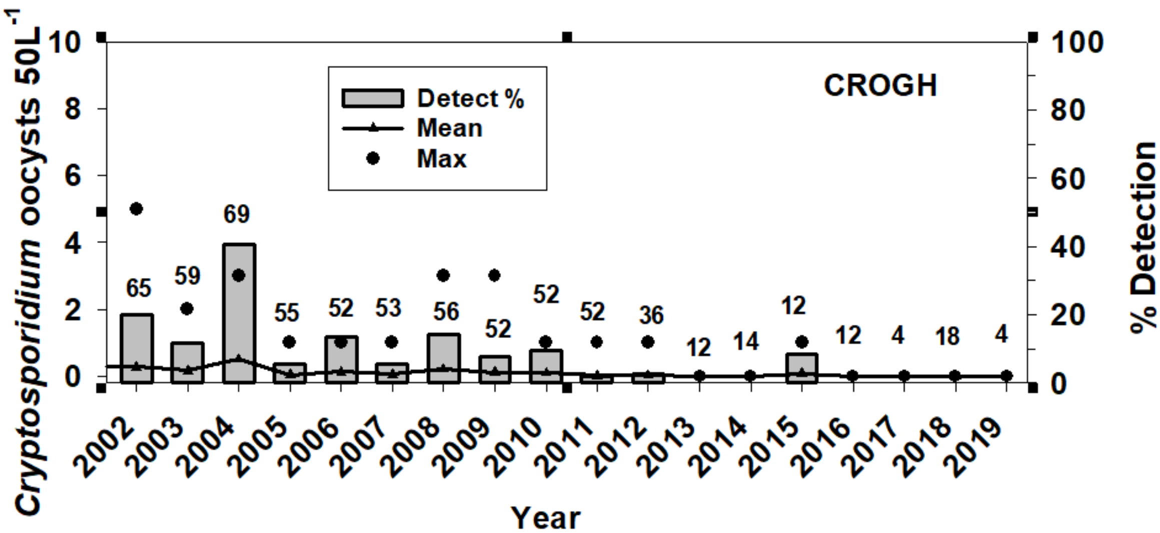


Figure 5.4 C*ryptosporidium* annual percent detection, mean concentration, and maximum result for the New Croton keypoint sites during each year from 2002 to 2019. Numbers above each bar on the Croton System plot indicate sample size.

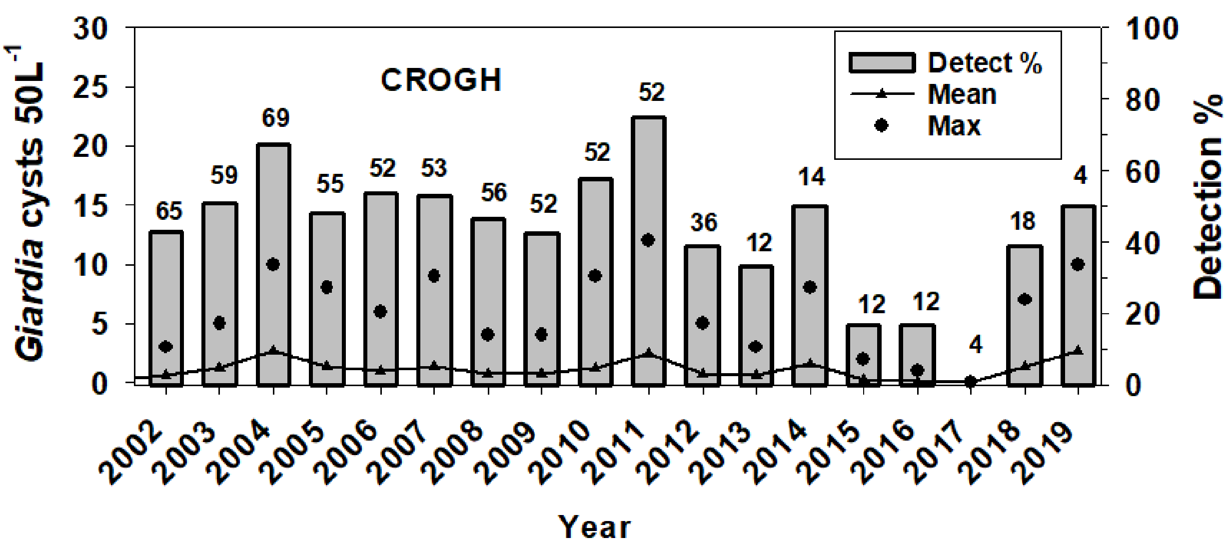


Figure 5.5 *Giardia* annual percent detection, mean concentration, and maximum result for the New Croton keypoint sites during each year from 2002 to 2019.

One of the three quarterly New Croton outflow samples taken in 2019 was positive for HEV with a result of 29.95 MPN 100L-1 (mean annual concentration = 9.98 MPN 100L-1). In comparison, in 2018 all quarterly HEV samples taken at CROGH (or the alternate site CRO1B) were negative. This detection was in the first quarterly sample in February 2019. Detections of HEV are not unusual in the colder months as HEVs have been detected in Croton samples taken during winter months in six of the past seven years. This was the highest result on record at New Croton, with the possible exception of a January 2012, when there was a result of >23.03 MPN 100L-1. Monitoring was discontinued in October 2019, before the fourth quarterly sample was scheduled to be taken in November.

In general, *Giardia* continues to be detected more frequently and at higher concentrations during winter and spring months compared to summer and autumn (Figure 5.6), as has been noted in previous reports. It is important to note that in the last few years, *Cryptosporidium* and *Giardia* results have been affected by analytical changes to Method 1623.1 with EasyStain, and the switch from acid to heat dissociation, in addition to the seasonal and long-term variability in occurrence of these organisms in the environment.

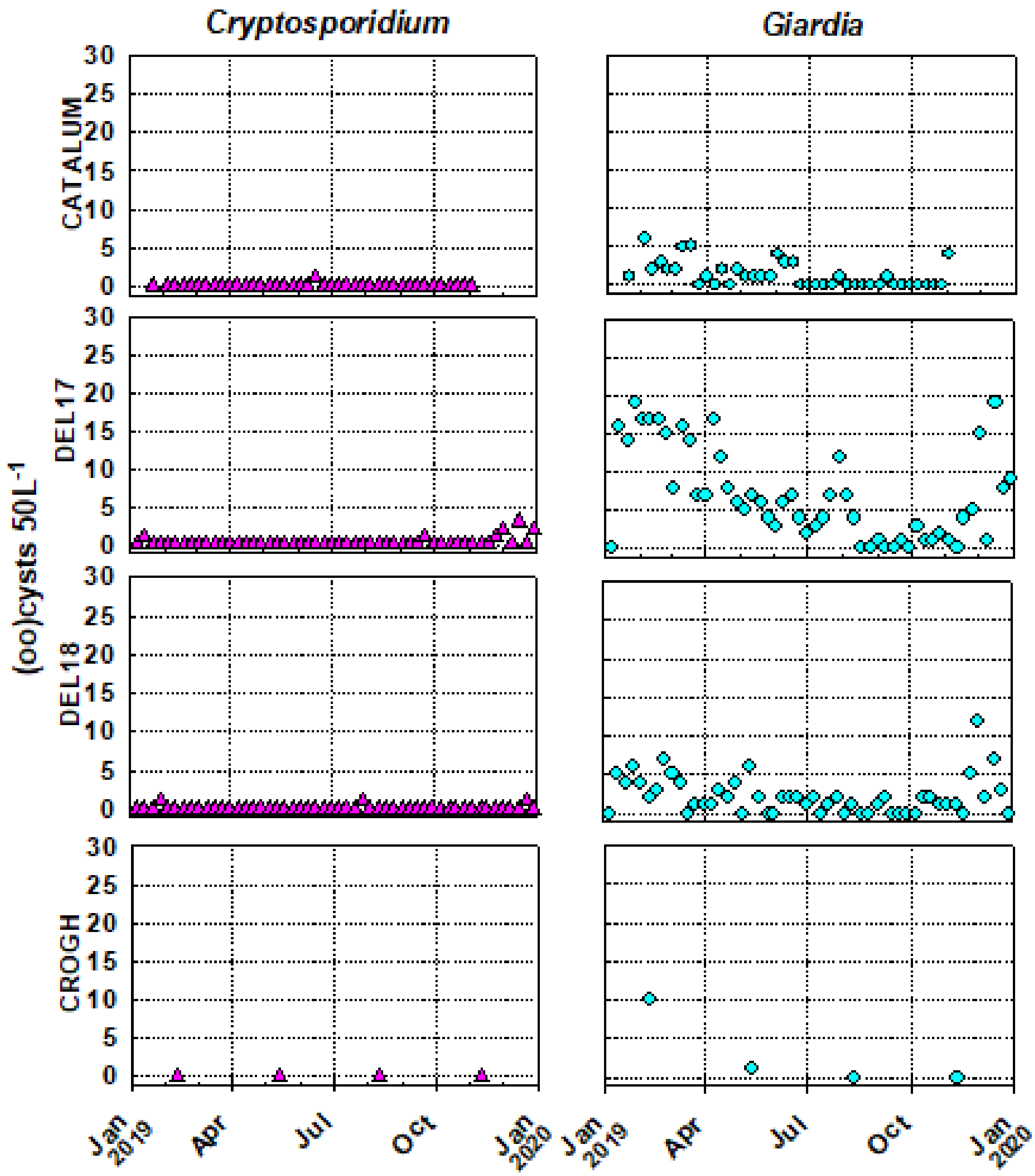


Figure 5.6 Weekly routine keypoint protozoan monitoring results for 2019.

5.2.1 2019 Source Water Results Compared to Historical Data

Water quality at the different source water sites can vary due to the many influences in their respective watersheds (stormwater runoff, impacts from land use, operational changes, etc.). Beginning in October 2001, source water sites were sampled weekly for protozoans and analyzed using Method 1623HV. Since 2001, various changes have affected the program:: New Croton Reservoir outflow monitoring frequency changed from weekly (October, 2001) to monthly (August 2012), and then monthly to quarterly (October 2016); the shutdown of the Catskill Aqueduct outflow from Kensico Reservoir (September 2012); a change in the analytical Method 1623HV to Method 1623.1 with EasyStain (April 2015); the addition of sampling at the Jerome Park Reservoir outflow (1CR21) with the Croton Filtration Plant startup (May 2015); the laboratory's switch from acid to heat dissociation (August 2017); the discontinuation of protozoan sampling at the Jerome Park Reservoir outflow (October 2018) due to having met the obligations of the Long Term 2 Enhanced Surface Water Treatment Rule (LT2); and intermittent shutdowns of the Catskill Aqueduct north of Kensico during 2019 for cleaning and rehabilitation work. Each modification has added a layer of complexity when comparing the current year's data to the historical data.

Kensico Reservoir

Cryptosporidium

Detections - In 2019, seven of the 93 samples (7.5%) were positive for *Cryptosporidium* at the two aqueduct inflows to Kensico Reservoir (CATALUM and DEL17) (Table 5.2). There were fewer detections of oocysts at the Kensico inflows in 2019 than in 2018 (13 out of 104, 12.5%), but more than were observed in 2017 (three out of 104 samples, 2.9%). This is well within the annual historical range from 0.9% to 20.5% when combining data from the two inflows. When data are analyzed by district, CATALUM had three less detections in 2019 than in 2018 (four out of 51 samples) and was similar to 2017 which also had only one detection (n=52). It should be noted that the Catskill Aqueduct was shut down for rehabilitation work a few times in 2019 prohibiting sample collection in January, and from the middle of November through the end of December, so this was not a complete year of monitoring like some past years. DEL17 also had three fewer detections in 2019 than in 2018 (nine out of 53 samples, 17.0%), much more like the detection rate seen in some past years, matching that seen in 2008, 2013, and 2016 (11.5%).

Table 5.2 Annual sample detection and mean oocyst concentration of *Cryptosporidium* at inflow keypoints to Kensico Reservoir 2002-2019.

Site	CATALUM			DEL17		
Year	**Detects**	**% Detects**	**Mean ($50L^{-1}$)**	**Detects**	**% Detects**	**Mean ($50L^{-1}$)**
2002	6	11.5	0.17	8	15.4	0.15
2003	8	15.4	0.25	15	25.0	0.28
2004	10	19.2	0.29	11	19.6	0.20
2005	1	1.7	0.02	6	10.2	0.10
2006	3	5.8	0.06	3	6.0	0.06
2007	1	1.9	0.02	4	7.7	0.08
2008	7	13.5	0.13	6	11.5	0.15
2009	7	13.5	0.15	4	7.7	0.08
2010	1	1.9	0.04	1	1.9	0.02
2011	0	0.0	0.00	1	1.9	0.02
2012	0	0.0	0.00	1	1.9	0.02
2013	1	1.9	0.02	6	11.5	0.12
2014	2	3.9	0.04	1	1.9	0.02
2015	6	11.6	0.15	5	9.7	0.12
2016	7	13.5	0.17	6	11.5	0.17
2017	1	1.9	0.02	2	3.8	0.04
2018	4	7.8	0.08	9	17.0	0.25
2019	1	2.4	0.02	6	11.5	0.19

Cryptosporidium detections at the outflow of the reservoir (DEL18DT) were similar to the inflows in 2019 (three out of 52 samples, 5.8%) were slightly lower than in 2018 (five out of 53 samples, 9.4%) and just about half the historical detection rate 2001-2018 (11.9%, n=1028). The 2019 detection rate was also the same as seen in 2017 (three out of 52 samples, 5.8%).

Concentrations - The annual mean concentration of oocysts at CATALUM was again less than 1 oocyst per 50 liters in 2019 (0.02 oocysts[1]) as it has been for the period of record since 2002 (Table 5.2). This year the annual mean was well below the historical mean of 0.10 oocysts (2001 – 2018, n=901) and on the low end of the historical range of zero to 0.29 oocysts for CATALUM. Similar to the Catskill inflow, the annual mean concentration of oocysts at DEL17 for 2019 was also less than one (0.19 oocysts). The 2019 mean was very similar to the historical oocyst mean for this site (0.11 oocysts) (2001-2018, n=915), and was within in the range of previous annual means (0.02 - 0.28 oocysts).

The 2019 *Cryptosporidium* mean concentration at DEL18DT (0.06 oocysts) (Table 5.3) mathematically fell between the values calculated at the two inflows; however, when dealing with numbers at such low levels they are all essentially the same. The DEL18DT mean was similar to the means observed in 2017 and 2018 (0.06 and 0.09 oocysts, respectively) as well as the mean for the previous 10 years (2009 – 2018 mean = 0.06 oocysts, n=532). The 2019 mean was slightly lower than the historical mean (0.15 oocysts, 2001 – 2018, n=1028).

Table 5.3 Annual sample detection and mean concentration of *Cryptosporidium* at Kensico and New Croton Reservoir source water outflows 2002-2019.

Site	DEL18DT			CROGH/CRO1B (or) 1CR21		
Year	**Detects**	**% Detects**	**Mean ($50L^{-1}$)**	**Detects**	**% Detects**	**Mean ($50L^{-1}$)**
2002	18	25.0	0.31	13	20.0	0.28
2003	21	29.6	0.45	7	11.9	0.17
2004	25	34.7	0.36	28	40.0	0.51
2005	15	15.5	0.23	3	5.5	0.05
2006	7	10.8	0.12	7	13.5	0.13
2007	2	4.0	0.04	3	5.7	0.06
2008	1	1.9	0.02	8	14.3	0.21
2009	4	7.7	0.08	4	7.7	0.12
2010	1	1.9	0.02	5	9.6	0.10
2011	1	1.7	0.02	1	1.9	0.02
2012[1]	0	0.0	0.00	1	2.8	0.03
2013	0	0.0	0.00	0	0.0	0.00
2014	4	7.4	0.11	0	0.0	0.00
2015[2]	8	15.4	0.17	1	2.6	0.03
2016[2]	4	7.7	0.10	9	20.0	5.64
2017[2]	3	5.8	0.06	2	22.2	0.33
2018	5	9.4	0.09	0	0.0	0.00
2019	3	5.8	0.06	0	0.0	0.00

[1]Monitoring at CROGH was modified from weekly to monthly in August 2012, and then reduced to quarterly in Oct 2016.
[2]The source water sampling site for the Croton System was either CROGH or 1CR21 during the LT2 monitoring period (2015-2018).

Giardia

Detections - The *Giardia* detection rate for pooled results at the two inflows (71.0%) was close to the detection rate at DEL18DT (71.2%) in 2019. The rate at DEL17 was 86.5%, which was markedly higher than CATALUM at 51.2%. It must be noted again that the Catskill

Aqueduct to Kensico Reservoir was shut down for several weeks in 2019, reducing the sample size from 52 samples to 41. *Giardia* was detected more often at the Catskill inflow to Kensico Reservoir in 2019 (51.2%) than in any of the previous five years (2014 – 2018), which had annual detection rates ranging from 17.3 to 41.2%. However, the 2019 detection rate fell within the range observed in the earlier five years from 2009 to 2013 (annual detection rates ranged from 15.1 to 57.7%), but was still higher than the historical detection rate of 40.2% (2001-2018, n=900). DEL17 had a slightly higher *Giardia* detection rate in 2019 (86.5%) than in 2018 (81.1%), which was much higher than the past 6 years (range for 2012-2017; 36.5% – 60.4%). The 2019 detection rate well exceeded the historical detection rate of 61.5% (2001-2018, n=914). Similar to 2018, 2019 had the highest detection rate since 2004 (87.5%, n=56).

The 2019 *Giardia* detection rate at DEL18DT (71.2%) was similar to 2018 (69.8%), but was higher in both of these most recent years compared to the mean of the past six years, (47.5% 2012-2017 n=316). Several years prior to 2012 had higher detection rates, such as 2011 (78.0%) and 2004 (86.3%, the historical maximum annual detection). Interestingly, both 2004 and 2011 were years when the watershed experienced significant hurricanes. The 2019 detection rate was higher than the mean historical detection rate for DEL18 (62.4%, 2001-2018 n=1028).

Concentrations - The annual mean *Giardia* concentration at CATALUM in 2019 (1.24 cysts) was the highest since 2009 (1.50 cysts) and slightly higher than the historical average from 2001 through 2018 (0.92 cysts). The annual mean cyst concentration at DEL17 was the highest recorded at 6.96 cysts, compared to previous maxima of 4.85 cysts in 2018 and 4.55 cysts in 2004. The 2019 mean was elevated by 14 samples with results over 10 cysts, mostly occurring in cold weather months from January to April and in December 2019. Cyst concentrations began to increase in mid-November 2018, coincident with those upstream at Rondout Reservoir, and continued to be elevated through winter and spring 2019. Concentrations were lower from May through October (mean = 3.46 cysts). *Giardia* concentrations were likely delivered from Rondout Reservoir, which also had elevated *Giardia* concentrations at that time (those results are discussed in the Upstate Reservoir Outflow section of this report). The maximum concentration at DEL17 in 2019 (19 cysts) was observed in January and again in December. This concentration is the fourth highest *Giardia* result (equivalent with a result from 2004) found at this (or any Kensico keypoint) site since the use of Method 1623.1 began in 2001.

The annual mean concentration at DEL18DT in 2019 (2.15 cysts) was higher than in 2018 (1.60 cysts) and any of the means from the past 14 years (ranging from 0.71 to 1.87 cysts) and approximately 37% higher than the overall historical average from 2001 through 2018 (1.57 cysts). Similar to the detection rate, mean *Giardia* concentrations in 2019 at DEL17 and CATALUM inflows (6.96 and 1.24 cysts respectively) also bracketed the outflow mean (2.15 cysts). Since the flow from DEL17 is usually higher than the CATALUM flow, and the Catskill Aqueduct was turned off during some portions of 2019 (in January and November – December) it makes sense that the DEL18DT outflow would be more influenced by the increased *Giardia* entering at DEL17 (as well as some influence from the local tributaries).

Croton Source Water

Cryptosporidium

None of the four quarterly samples at the New Croton Reservoir outflow (CROGH/CRO1B) were positive for *Cryptosporidium* in 2019 (Table 5.3). *Cryptosporidium* detections have been very infrequent at the New Croton outflow site in the last few years, with only one *Cryptosporidium* oocyst found (February 2015) during the past seven years (2013 – 2019, n=76) (the detections in 2016 and 2017 were at 1CR21). There have been only three detections of oocysts at CROGH in the last nine years (n=164), with a maximum result of one oocyst each.

Giardia

The rate of *Giardia* detection and mean concentration at the New Croton Reservoir outflow were higher in 2019 (50.0% and 2.74 cysts, respectively) than 2018 (38.9% and 1.42 cysts, respectively), albeit there was a much smaller sample size in 2019 (n=4 compared to n=18). While the annual detection rate in 2019 was the same as the historical detection rate (2001-2018 n=685, 50.0%), the 2019 mean concentration was more than twice the historical mean (1.26 cysts), more akin to the mean concentration observed in 2004. The Croton source water site at Jerome Park (1CR21) was not sampled during 2019.

Seasonality

Elevated *Giardia* concentrations at DEL17 in both the early and late months of 2019 made the seasonal variation in *Giardia* results easy to define by a locally weighted regression (LOWESS) smoothed line (Figure 5.7). A variation in seasonal concentrations is also visible for CATALUM, but it is far less pronounced and the smoothed line only indicates the late winter/spring highs and summer lows. The anticipated autumn increase is only suggested by the CATALUM data, as samples were discontinued early in November due to the Catskill Aqueduct shutdown. Seasonal variation was more pronounced in samples at the Kensico Reservoir outflow (DEL18DT) during 2019 than 2018. LOWESS analysis was not performed for the Croton Reservoir outflow since sampling has been reduced to quarterly.

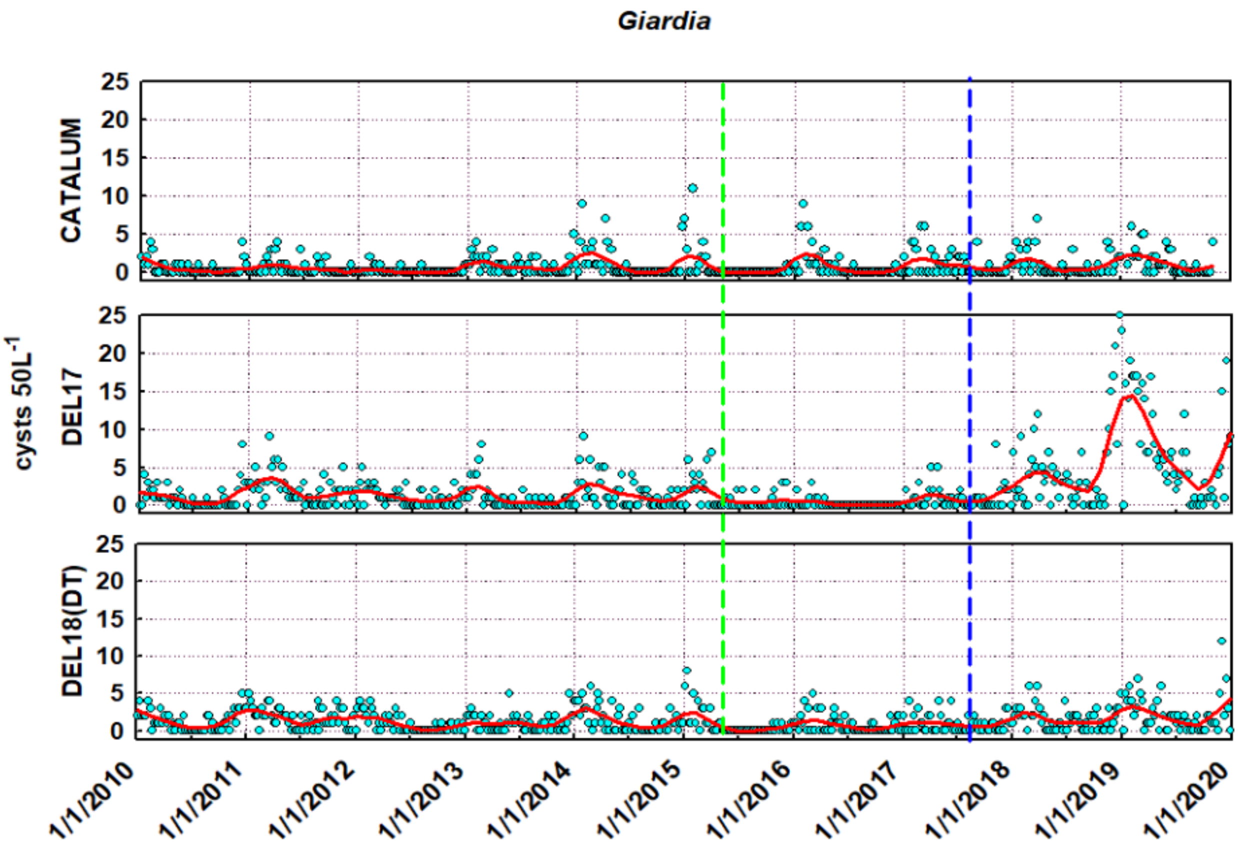


Figure 5.7 Weekly routine source water keypoint results for *Giardia* (circles), and LOWESS 5% smoothed regression (red curved line) from October 15, 2001 to December 31, 2019.The green dashed line indicates the change from Method 1623HV to Method 1623.1 with EasyStain. The blue dashed line indicates the laboratory method modification from acid to heat dissociation. *The New Croton Reservoir outflow is no longer included in this analysis since results are only quarterly.

5.2.2 2019 Source Water Compared to Regulatory Levels

DEP completed its monitoring requirements for the Long Term 2 Enhanced Surface Water Treatment Rule (LT2, USEPA 2006) in 2018; however, the calculation procedure described in the LT2 is still performed annually by DEP to measure results against the thresholds (Table 5.4). The LT2 required utilities to conduct monthly source water monitoring for *Cryptosporidium* and report data from two different two-year periods. The LT2 required all unfiltered public water supplies to "provide at least 2-log (i.e., 99%) inactivation of *Cryptosporidium*" during the monitoring period. If the average source water concentration exceeded 0.01 oocysts L^{-1}, based on the LT2 monitoring criteria, "the unfiltered system must provide at least 3-log (i.e., 99.9%) inactivation of *Cryptosporidium*." The average source water *Cryptosporidium* concentration is calculated by taking the mean of the monthly *Cryptosporidium* mean concentrations at the source water outflows over the course of a two-year period. For filtered supplies, like the Croton System, the LT2 mean needed to be below 0.075 oocysts L^{-1} to remain in Bin 1, which was the category that defined needing no additional treatment. Since the LT2 monitoring is complete, and the frequency of sample collection at New Croton Reservoir has been reduced to quarterly, assessments of the data for comparison to LT2 thresholds are no longer conducted due to the small sample size.

Table 5.4 Number and type of samples used to calculate the LT2 values from January 1, 2018, to December 31, 2019.

Site	Number of routine samples 2018-2019	Number of non-routine samples 2018-2019	Total n
Delaware (DEL18DT)	105	0	105

Unfiltered Supply

The Catskill/ Delaware System is NYC's unfiltered water supply. The *Cryptosporidium* mean of monthly means for 2018 to 2019 is 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 5.8). 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 2004-2005 and continued to decline through 2013. During the 2014-2015 period, an increase was noted in the calculated mean, which coincided with the change to Method 1623.1/EasyStain for protozoan analysis. This method change likely underlies the increase over the last five years (2015 – 2019), as it was predicted to recover more *Cryptosporidium* from samples based on the results of pilot studies.

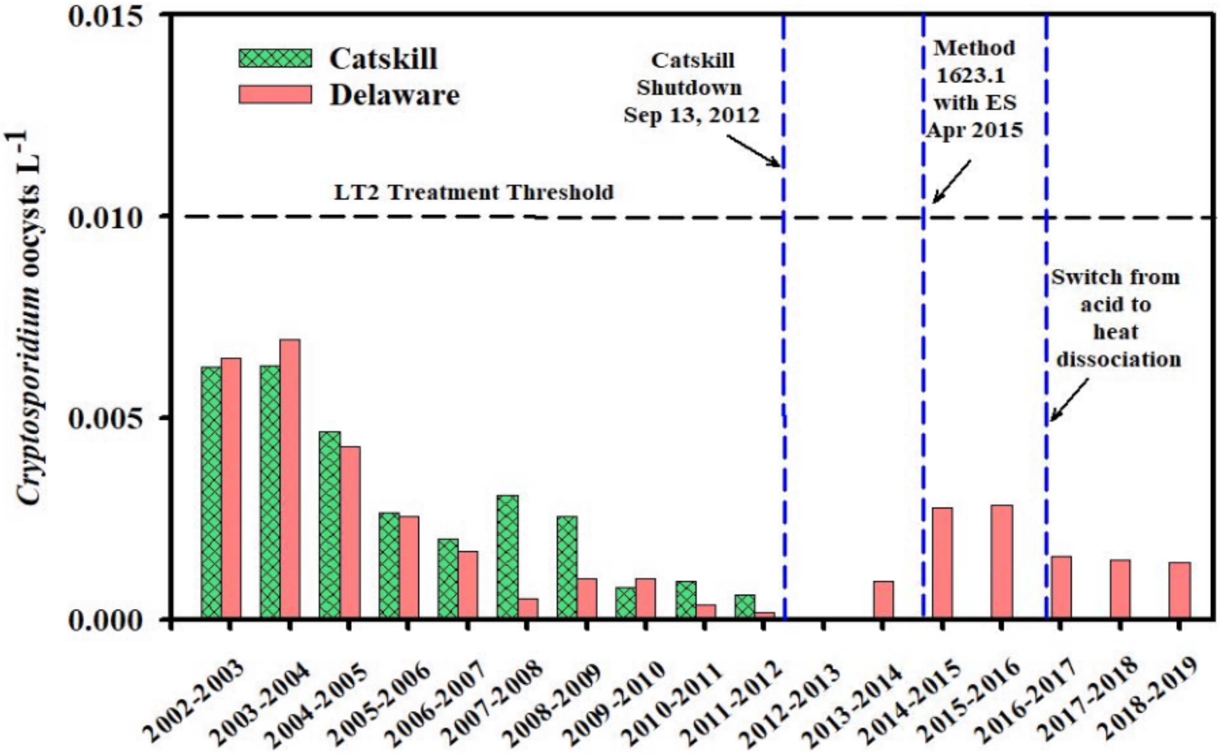


Figure 5.8 *Cryptosporidium* means using LT2 calculation method since initiation of Method 1623HV (1623.1 with EasyStain since April 2015) at the Delaware Aqueduct 2002-2018 and the Catskill Aqueduct 2002-2012.

5.2.3 2019 Source Water Matrix Spike and Quality Control Results

Quality control (QC) testing performed during protozoan analyses includes both matrix spike samples (MS) and ongoing precision and recovery samples (OPRs). 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. Recovery of *Cryptosporidium* from the three Kensico keypoint sites ranged from 21-84%, while *Giardia* recovery was 38-78% (Table 5.5). The lowest *Cryptosporidium* MS recoveries for the year occurred in October at DEL17 (21%) and November at DEL18DT (45%), while the highest recoveries occurred in January (84% at DEL18DT) and May and June (78% at DEL17 and DEL18DT, respectively). The lowest *Giardia* recoveries were in February at CATALUM (38%) and October at DEL17 (48%). The highest cyst recoveries were in June at DEL18DT (79%) and July at CATALUM (76%). All MS results for these sites, performed one in every 20 analyses, were within the acceptable range of the method, with the exception of the *Cryptosporidium* recovery for the October 7 sample at DEL17. No MS samples were collected at the New Croton outflow in 2019.

Table 5.5 Matrix spike results from keypoint sites in 2019.

Date	*Cryptosporidium* % Recovery	*Giardia* % Recovery
	CATALUM	
2/25/2019	57	38
7/1/2019	67	76
	DEL17	
1/14/2019	84	56
5/28/2019	78	63
10/7/2019	21	48
	DEL18DT	
6/24/2019	78	79
11/4/2019	45	64

Weekly OPR testing involves the spiking of reagent-grade water in the laboratory with known amounts of oocysts and cysts. These samples are important for testing the method reagents and the laboratory process without interference from the sample matrix. In 2019, 75 OPR samples were analyzed. Ranges of recovery for protozoan OPR samples in 2019 were 1-101% for *Cryptosporidium* and 0-84% for *Giardia,* which includes data from the few occasions when recoveries did not pass on the first attempt. In these instances, additional OPR samples were analyzed and acceptable results were always obtained before proceeding with the weekly samples.

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 are monitored monthly, while the Ashokan Reservoir aqueduct is monitored weekly at CATALUM further downstream before it enters Kensico Reservoir. When a reservoir is off-line, monthly reservoir sampling is not required since water from that particular basin is not being delivered to a downstream reservoir for eventual consumption. For this reason, three of the WOH reservoirs (Schoharie, Neversink and Cannonsville) do not have samples for all 12 months of 2019. The sample volume goal is 50L, however, all sample volumes are not exact. The results discussed in this section are from 47-53 liter samples unless otherwise noted, with concentrations given per 50L as standard.

There were 143 samples collected at upstate reservoir outflows, which includes 38 special investigation samples collected from the Rondout Reservoir outflow due to elevated *Giardia*, which began late in 2018. DEP responded to the increased *Giardia* with more frequent sampling at the outflow site (monthly to weekly). This increase remained in effect for most of 2019, and went back to bi-weekly in October, and then back to weekly in December 2019. Special investigation samples related to the elevated *Giardia* were also taken at the outflow of Neversink Reservoir, at local streams, and at reservoir locations within the Rondout basin. A brief summary of this special investigation is discussed in Section 3.14.10, which includes a reference to the final report that was issued in December 2019.

There were a few special operational conditions that warranted increases or reductions in monitoring at the upstream reservoir outflows. Due to maintenance activities for the Catskill Aqueduct, several shutdowns took place during 2019, which prevented weekly monitoring downstream of Ashokan Reservoir at the CATALUM site, including three weeks in January, three weeks in November, and all five weekly samples in December. As part of this shutdown, water was pumped from Croton Falls and Cross River reservoirs (EOH) to supplement the Delaware System and help meet demand. A total of 19 protozoan samples were taken from these two EOH outflow sites (15 from Croton Falls and four from Cross River) during start-up and pumping operations. One sample was taken at the outflow of West Branch Reservoir (DEL10) in December 2019 after an elevated *Giardia* count was detected downstream at DEL17.

Cryptosporidium

In 2019, there were 122 samples collected at WOH reservoir outflows and 10 samples were positive for *Cryptosporidium* (8.2%) (Table 5.6). This rate of detection is similar to 2018 (9.4%) and 2017 (6.4%). Cannonsville had the highest oocyst detection rate in 2019 (three out of 8 samples, 37.5%), while Schoharie had the lowest with no oocysts detected; however only four samples were collected. Neversink and Pepacton had one and two *Cryptosporidium* detections, respectively in 2019, with very similar detection rates (14.3 and 16.7%, respectively). In the last 11 years, Neversink has had only seven *Cryptosporidium* detections, with only one oocyst each (2009-2019 6.4%, n=109). Pepacton has had nine *Cryptosporidium* detections since 2008 (6.3%, n=142). Rondout had three detections in 2019 (6.0%, n=50), quite close to its historical oocyst detection rate of 5.6% (2002-2018, n=215), even though the 2019 sample size was much larger due to weekly sampling for the elevated *Giardia* investigation. The water representing the outflow of Ashokan Reservoir is sampled downstream at CATALUM (above Kensico Reservoir) and there was one *Cryptosporidium* detection out of 41 samples (2.4%), which is less than in 2018 (four out of 51 samples, 7.8%), and also less than the historical detection rate of 7.8% (2001-2018, n=901).

Table 5.6 Summary of 2019 protozoan results for upstate reservoir outflows.

		Cryptosporidium				*Giardia*			
Site	**n**	**Mean[1] ($50L^{-1}$)**	**% Detects**	**Max (Liters sampled)**	**Max (L^{-1})**	**Mean[1] ($50L^{-1}$)**	**% Detects**	**Max (Liters sampled)**	**Max (L^{-1})**
Schoharie	4	0.00	0.0	0 (50.0)	0.00	29.91	75.0	87 (51.9)	1.68
Ashokan (CATALUM)	41	0.02	2.4	1 (50.0)	0.02	1.24	51.2	6 (50.0)	0.12
Cannonsville	8	0.37	37.5	1 (50.1)	0.02	4.97	100.0	12 (50.1)	0.24
Pepacton	12	0.25	16.7	2 (50.0)	0.04	2.40	66.7	6 (50.2)	0.12
Neversink	7	0.14	14.3	1 (50.0)	0.02	5.55	85.7	28 (50.0)	0.56
Rondout	50	0.08	6.0	2 (50.2)	0.04	8.77	98.0	22 (50.9)	0.43

[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.

Concentrations of *Cryptosporidium* remained very low at the WOH upstate reservoir outflows with a maximum result of 2 cysts at the Pepacton outflow in October. The highest mean concentration for the year (0.37 oocysts) was found at the Cannonsville outflow. Ashokan, Neversink, Pepacton, Rondout, and Schoharie reservoirs' outflows had annual mean concentrations below 0.25 oocysts.

Giardia

There were 96 *Giardia* detections (78.0%) among the 123 samples collected at the WOH reservoir outflow sites. This is considerably higher than the detection rate in 2018 (60.4%) and higher than any of the previous three years (2015-27.0%, 2016-30.6%, and 2017-43.1%). However, it is important to note there was large variation in sample size among sites and among years, with Rondout having many more samples in 2019 (n=50) than in any previous year, due to elevated *Giardia* in the basin. The highest detection rates for *Giardia* were found at Cannonsville and Rondout (100% and 98.0%, respectively, Table 5.6). The outflow at Cannonsville has had 100.0% detection rate before (2004) but this is well over the historical detection rate of 68.2% (2002-2018, n=176). For Rondout Reservoir, this was higher than the detection rate in 2018 (88.2%) and the historical detection rate of 62.3% (2002-2018, n=215). As part of the special investigation into elevated *Giardia* at Rondout (beginning in late 2018), 38 special investigation samples were collected during 2019 at the Rondout outflow, and all except one were positive for *Giardia*. Rondout *Giardia* concentrations will be discussed in further detail below. Samples taken at the Neversink outflow were 85.7% positive for *Giardia*, similar to 2018 (88.9%) but higher than the historical detection rate of 61.8% (2002-2018, n=170). Schoharie and Pepacton outflows both had similar detection rates in 2019 (75.0 and 66.7%, respectively) compared to 2018 (75.0 and 61.5%, respectively). However, Schoharie remained close to its historical detection rates (2002-2018=79.4%, n=189), while Pepacton was higher (2002-2018=49.0%, n=194) with an increase of approximately 18%. *Giardia* was also detected more frequently in 2019 in the CATALUM samples representing the Ashokan outflow (51.2% positive) compared to 2018 (41.2%) and the historical detection rate (2001-2018=40.2%, n=900).

As for *Giardia* concentrations in the upstate reservoirs, results were higher at most sites than those found in prior years. For the fourth year in a row, Schoharie had the highest annual mean *Giardia* concentration in 2019 (29.91 cysts), which was similar to the mean in 2018 (25.17 cysts) and higher than the historical mean (10.93 cysts, 2002-2018, n=189). Rondout annual mean concentration in 2019 (8.77 cysts) was quite similar to the mean from 2018 (8.03 cysts) and higher than the historical mean of 2.50 cysts. The Cannonsville mean concentration was 4.97 cysts in 2019, lower than 2018 (7.21 cysts) but very similar to the historical mean of 4.48 cysts (2002-2018, n=176). The annual mean for Pepacton (2.45 cysts) was essentially the same as that found in 2018 (2.52 cysts) and higher than the historical mean (2002-2018=1.30 cysts, n=193). The mean *Giardia* concentration at Neversink this year (5.55 cysts) was higher than in 2018 (2.63 cysts) and higher than the historical mean (2002-2018=2.86 cysts, n=170). Ashokan (monitored at CATALUM) was similar in 2019 (1.24 cysts) to 2018 (0.96 cysts) and higher than the historical mean (2001-2018=0.90 cysts, n=900).

An analysis of historical data at Rondout determined that 2019 had the highest mean *Giardia* concentration (8.77 cysts) since the implementation of Method 1623 in 2002 with the second highest concentration in 2018. *Giardia* concentrations were elevated at the outflow in late winter/early spring 2018 and then again in November through December2018, at which time DEP began to monitor the site more frequently. These elevated results continued into 2019 showing the typical seasonality of *Giardia* at reservoir outflows, with the highest results tending to be in colder months (January – March), decreasing in the spring and then increasing again late in the year (Table 5.7). Results downstream of Rondout at the inflow to Kensico Reservoir (DEL17) displayed similarly elevated results, with concentrations also following the aforementioned seasonal pattern. Elevated *Giardia* at Rondout in 2018-2019, along with the investigation to identify the cause(s), are the subject of a special investigation report published by DEP on December 23, 2019 (DEP 2019d).

Table 5.7 Summary of *Giardia* results for 2019 special investigation at Rondout Reservoir and DEL17.

Month	RDRRCM Mean (cysts $50L^{-1}$)	RDRRCM n	DEL17 Mean (cysts $50L^{-1}$)	DEL17 n	Other Sites Investigated: Sites	Other Sites Investigated: n
January	16.87	5	12.25	4	RD4, RDOA, RDOB, RGB, RS Lodge A, RS Lodge B	8
February	14.15	4	16.50	4	RD5, 1.3RR1, 1.3RR4, 1.7RR1, 1.7RR4, 1.9RR1, RDOB, RS Lodge, RS Lodge D	11
March	11.48	5	11.25	4		
April	7.20	4	9.99	5		
May	8.36	5	5.50	4	NRR2CM, Pizza Pond, Pizza Tributary (3 100L)	7
June	9.22	4	4.99	4	Pizza Pond, Pizza Tributary (2 100L)	6
July	6.12	5	5.60	5		
August	4.19	4	2.75	4		
September	3.73	4	0.40	5		
October	5.89	3	1.75	4		
November	5.50	2	2.50	4		
December	8.36	5	10.40	5	DEL10	1

Additional Sampling

As part of required monitoring during preactivation start-up and pumping operations at Cross River and Croton Falls reservoirs (required for water to be pumped into the Delaware Aqueduct), 19 samples were collected at these reservoir outflows in 2019. Four weekly protozoan samples were collected at the Cross River Pump Station between October 27 and November 17. All four of these samples were negative for *Cryptosporidium* and one was positive for *Giardia* (2 cysts on November 12). Fifteen protozoan samples were collected at the Croton Falls Pump Station during two periods: June 9 through the June 30 and from October 20 through the end of 2019 (last sampled on December 30). Three of the 15 samples (20.0%) were positive for *Cryptosporidium*, each with one oocyst. *Giardia* were found in 60% of samples taken at the Croton Falls Pump Station, with a mean concentration of 1.60 cysts. Individual results were generally low with all but one of the results at or below 3 cysts (maximum result of 11 cysts on December 23).

Additionally, since West Branch Reservoir flow can also impact DEL17, a sample was collected at DEL10 to assist in the investigation into the source of elevated *Giardia* at DEL17. This sample result had 8 *Giardia* cysts and 1 *Cryptosporidium* oocyst. However, West Branch Reservoir was put on float operation mode just prior to sampling, so the sample was likely representative of water from Rondout Reservoir only.

5.4 Watershed Streams and WWTPs

Routine monitoring for protozoa was conducted at 18 stream sites in the WOH and EOH watersheds in 2019. Fourteen additional sites were monitored as part of the Rondout *Giardia* special investigation and are discussed in Section 3.14.10 as well as in the final report. A total of 206 watershed samples were collected and analyzed, with 91 from the WOH watershed and 115 from the Kensico Reservoir (EOH) watershed. Monitoring locations upstream of PROXG were modified a few times in 2019, including sample collection at site PROXG-3, 3.4 and 4. EOH stream monitoring continued monthly at the eight perennial tributaries to Kensico Reservoir with 19 additional samples collected in response to elevated results in routine samples. The 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 2019, 41 samples were collected at 10 WWTPs, with five samples positive for protozoans. A discussion of WWTP results follows the stream results discussion for each corresponding watershed.

West of Hudson Streams

As has occurred in the past two years, four of the eight WOH stream sites were sampled monthly in 2019 (S7I, PROXG, and two upstream PROXG sites) with the remaining four streams sampled bimonthly (CDG1, S4, S5I, and CBS), for a total of 66 samples at these routine sites (Figure 5.9). The previously mentioned special investigation samples make up the remaining 25 samples. Monitoring to determine sources of *Giardia* in the East Branch of the Delaware River (upstream of PROXG) began in May 2016 and the sites have been adjusted occasionally to help narrow down the geographic source of elevated *Giardia*. There were 35 samples collected as part of the PROXG investigation in 2019. Seven routine samples were missed or canceled in 2019 for a variety of reasons including samples freezing during filtration, scheduling conflicts, and field or lab errors.

The target volume for protozoan monitoring conducted by DEP is 50 liters; however, these streams do not always allow for full target volume due to filters clogging. The method allows for a minimum of 10 liters for an acceptable sample. As long as 10 liters is achieved, samples are still analyzed. Of the 66 routine samples filtered and analyzed from WOH streams, 51 were between 47 and 53 liters. Fifteen samples had volumes less than 47 liters due to clogging or other issues during field filtration. Due to disparate sample volumes, results are presented in several different ways: mean of all results calculated to a 50L volume; percent detection; maximum count per actual sampled volume; and maximum value per liter (Table 5.8).

Cryptosporidium oocysts were detected in 36 out of the 66 routine WOH stream samples (54.5%) in 2019, slightly less than were detected in 2018 (59.2%). Percent detection of oocysts ranged from 33.3% to 81.8% at nine of the 10 different stream sites (Table 5.8). The tenth stream site, PROXG-3.4, tested positive, but was only sampled once in 2019, so is not included in further analysis. Similar to 2018, three sites sampled in 2019 had an annual mean below one oocyst, however only one site in 2019 had a mean concentration above 2.50 oocysts compared to five sites in 2018. PROXG-2 had the highest mean concentration (2.57 oocysts). The highest *Cryptosporidium* result in 2019 was 12 oocysts in a sample from PROXG-2 in November, however, the same result (12 oocysts) was observed at S7i in October (but in a slightly higher volume).

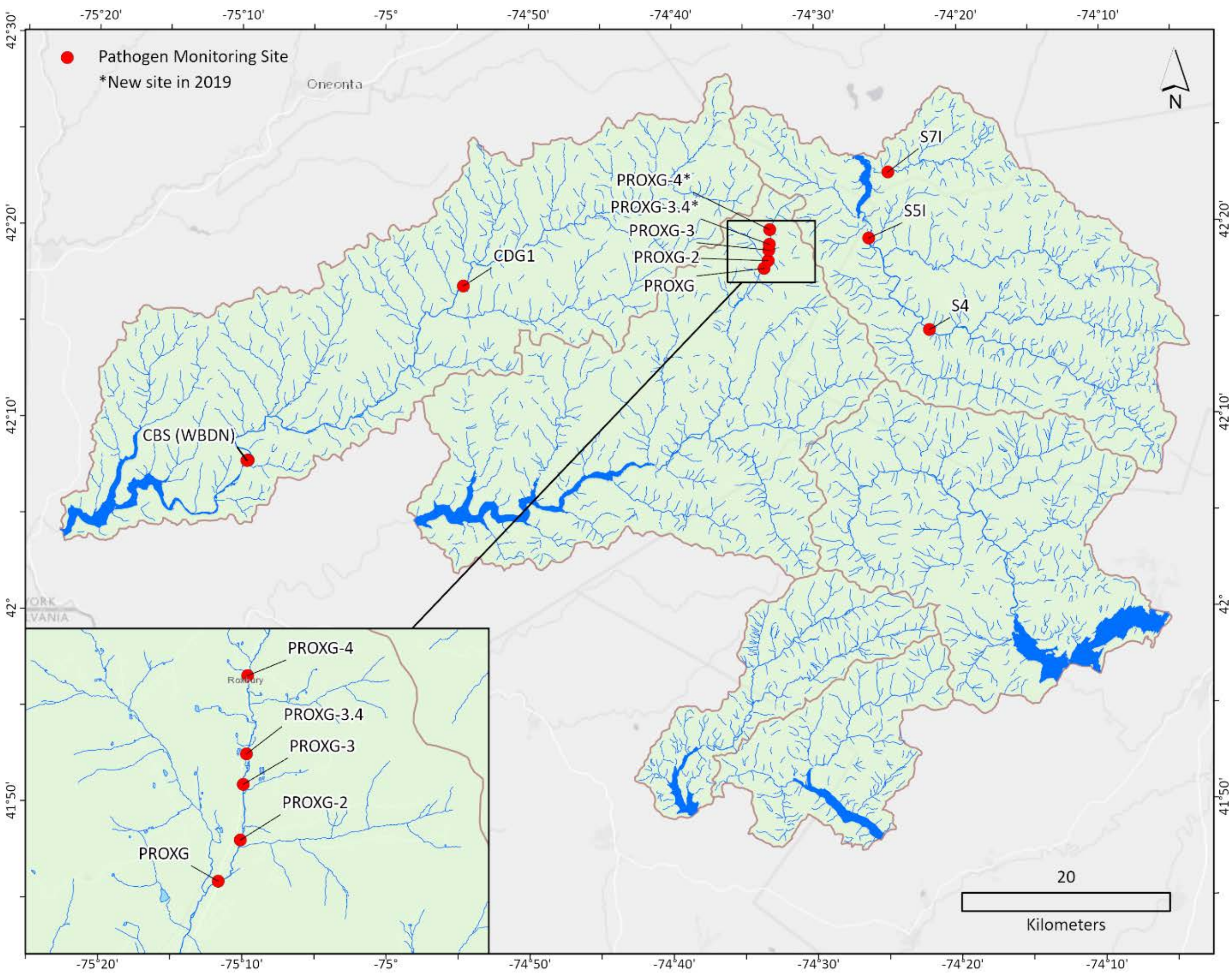


Figure 5.9 WOH stream sites monitored for protozoans in 2019.

Table 5.8 Summary of WOH stream protozoan results in 2019.

		Cryptosporidium				*Giardia*			
Site	**n**	**Mean[1] (50L^{-1})**	**% Detects**	**Max (Liters sampled)**	**Max (L^{-1})**	**Mean (50L^{-1})**	**% Detects**	**Max (Liters sampled)**	**Max (L^{-1})**
CBS	6	0.57	50.0%	1 (35.4L)	0.03	42.59	100.0%	82 (35.4L)	2.32
CDG1	6	1.67	50.0%	7 (50.0L)	0.14	132.28	100.0%	216 (50.5L)	8.36
PROXG	11	1.49	81.8%	3 (50.0L)	0.06	134.51	100.0%	342 (50.4L)	6.79
PROXG-2	12	2.57	66.7%	12 (50.0L)	0.24	248.18	100.0%	693 (51.3L)	13.51
PROXG-3	9	0.48	33.3%	2 (50.3L)	0.04	270.44	100.0%	656 (50.6L)	12.96
PROXG-3.4	1	6.97	100.0%	7 (50.2L)	0.14	138.45	100.0%	139 (50.2L)	2.77
PROXG-4	2	0.50	50.0%	1 (50.0L)	0.02	51.78	100.0%	73 (50.3L)	1.45
S4	5	1.63	40.0%	7 (50.5L)	0.14	120.63	80.0%	244 (50.5L)	4.83
S5	5	1.63	40.0%	5 (37.6L)	0.13	167.80	100.0%	302 (37.6L)	8.03
S7i	9	2.09	44.4%	12 (50.6L)	0.24	142.52	100.0%	547 (50.6L)	10.81

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

Giardia cysts were detected in 65 of the 66 routine WOH stream samples (98.5%) collected in 2019, very similar to the detection rate in 2018 (97.2%), but slightly higher than in 2017 and 2016 (84.7 and 87.0%, respectively). All WOH stream samples in 2019 resulted in 100% detection of *Giardia*, with the exception of S4, which was positive for four out of the five sampling events. 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 greater than two orders of magnitude (Table 5.8). PROXG-3 had the highest annual *Giardia* mean (270.44 cysts) while the highest single sample result was found just downstream at PROXG-2 (693 cysts) in October 2019. This is quite similar to 2018 when the highest annual mean and highest single sample result were found at PROXG-3 (170.78 and 575 cysts, respectively). As might be expected, the next two highest sample results in 2019 were found at PROXG-3 in June and May (656 and 532 cysts, respectively).

As noted previously, sampling upstream of the PROXG site continued in 2019 to help narrow the search for the geographic sources of *Giardia*. Annual means for PROXG and PROXG-2 remained quite high in 2019 (134.51 and 248.18 cysts, respectively) compared to 2018 (146.38 and 107.03 cysts, respectively). Individual results were frequently elevated with most results at PROXG and PROXG-2 over 50 cysts. PROXG-2 concentrations were over 100 cysts for 83.3% of samples. *Giardia* cysts were similarly at predominantly elevated concentrations in samples taken at PROXG-3, with seven of the eight (87.5%) monthly samples analyzed from January to September having results over 100 cysts.

Upon assessment of this data, indicating a source further upstream, a new upstream site (PROXG-4) was selected and sampled in October (with sampling discontinued at PROXG-3) (Figure 5.9). Comparing results from the October set of samples, the PROXG-4 *Giardia* results (31 cysts) were much lower than those found at downstream sites PROXG and PROXG-2 (342 and 693 cysts, respectively), with downstream sites an order of magnitude higher. Another site was selected between PROXG-3 and PROXG-4 (PROXG-3.4), and both PROXG-4 and PROXG3.4 were sampled in November. Results from this November set of samples indicated that while results downstream continued to be quite high (over 250 cysts) at both PROXG and PROXG-2, they were closer to results at upstream sites than those in October. The November result from PROXG-3.4 (139 cysts) were quite high but still lower than downstream at PROXG. Likewise, the *Giardia* result at PROXG-4 was elevated (73 cysts) but much lower than downstream sites. In December, sampling returned to PROXG-3 (along with PROXG and PROXG-2), as access to the other upstream sites was an issue. All December results at the PROXG sites were over 100 cysts, with PROXG-3 having the highest result of the three sites (330 cysts).

West of Hudson Wastewater Treatment Plants (WWTPs)

Protozoan monitoring of WWTPs was scheduled on a quarterly basis at the eight WOH WWTPs and 32 samples were collected in 2019, satisfying the sampling requirement. From this set of samples, there were four positive for *Giardia* (12.5%) (Table 5.9). None of the 2019 WWTP samples were positive for *Cryptosporidium*.

Table 5.9 Protozoan results from the four WOH WWTPs detections in 2019.

Date	**Site**	**Plant**	**Sample Volume (L)**	***Cryptosporidium*** **($50L^{-1}$)**	***Giardia*** **($50L^{-1}$)**
3/20/2019	PFTP	Fleischmanns	50.0	0	3
3/26/2019	Hunter Highlands BD	Trailside at Hunter	50.0	0	82
8/27/2019	Windham WTP	Windham	50.0	0	2
12/4/2019	Windham WTP	Windham	50.0	0	1

On March 20, a sample was taken at Fleischmanns WWTP and found to have 3 *Giardia* cysts. The facility operator was contacted to obtain background information on plant operations during the time of the sample. The sample was collected after three days of air lancing of the continuous backwash upflow dual sand filters (CBUD) and air lance cleaning of the filters continued on the day of sampling. The filter being cleaned at that time was in recirculation mode, so flow was not going to discharge. The detection may have been caused by the sample picking up cysts freed up from either the air lancing of filters on prior days or by potential spread of air-lanced material from the isolated filter being cleaned at the time to nearby filter effluent troughs. This issue will be discussed with the operator to see if air lancing can be done with the plant offline completely, as this plant is typically operated in plug flow mode.

On March 26, a protozoan sample taken at the Trailside at Hunter LLC wastewater plant was found to have 82 *Giardia* cysts in the sample. After the positive result, plant operators were asked about any operational issues or process abnormalities. Operators did not note any mechanical or process abnormalities at the plant. The sand filters are cleaned with chlorine and air lanced every month, with the last cleaning noted on March 20. Positive samples have been noted at this plant over the past few years, most often in the colder months as ski season brings visitors to the area. Quarterly protozoan samples taken in February 2017 and February 2018 were both positive (10 and 73 *Giardia* cysts, respectively).

On August 27, a protozoan sample taken at Windham wastewater treatment plant was found to have two *Giardia* cysts in the sample. DEP obtained the daily turbidity report for the plant, which indicated turbidity remained below 0.50 NTUs for the entire day. The plant operator was not aware of any process abnormalities that may have caused the positive detection on that day. It should be noted that the protozoan sample was taken at about 11 a.m. when effluent flow reached the maximum for the day (138,000 gallons per day (GPD)).

The Windham wastewater treatment plant was sampled again December 4. This quarterly sample was also positive for *Giardia* (one cyst in the sample). DEP obtained the plant's daily turbidity report, which indicated there were three readings above 0.50 NTUs at about 11 AM. This was also during the time when the plant recorded its maximum daily flow (352,000 GPD). The operator stated that the higher turbidity readings were found during a scheduled generator test run when the plant's power source switches from electrical grid to generator for one hour from 11 a.m. to 12 noon. The protozoan sample collection began just before noon and ended shortly after noon. While the transfer from grid to generator power should not directly impact protozoan sample results, the sample did overlap the generator test run and it is possible that a power disruption to the plant pumps could cause disturbances to pipe biofilms, which could harbor protozoans. The short-term increases in turbidity are indicative of such disturbances. There were no readings that were above the 5.0 NTU SPDES limit. No other abnormalities occurred that day.

East of Hudson Streams

The Kensico perennial streams were monitored at least monthly for protozoans in 2019. In addition to the 96 routine monthly samples, 19 additional samples were taken to follow up on elevated concentrations found in routine samples. Each of the eight sites had at least one follow-up sample taken in 2019, and two of the Kensico stream sites (BG9 and N5-1) had five follow-up samples. A total of 115 samples were collected at the Kensico streams this year.

Cryptosporidium

Cryptosporidium oocysts were detected in 23 out of 96 (24.0%) routine samples at Kensico stream sites in 2019, which was a lower rate of detection than in 2017 and 2018 (30.0% and 40.6% of 96 routine samples each year, respectively). *Cryptosporidium* was detected less frequently at each of the eight sites in 2019 compared to 2018, with the exception of BG9 which had four detects in 2019 (33.3%) compared to two in 2018 (16.7%).

Mean concentrations increased or remained similar at five of these sites (BG9, E10, E9, MB-1, and WHIP) while results at the remaining three sites (E11, N12, and N5-1) decreased when compared to 2018 means (Figure 5.11). MB-1 had the highest mean concentration of *Cryptosporidium* in 2019 (5.89 oocysts), higher than the mean from 2018 (3.49 oocysts) and the means from the prior three years (2015-2017) (

Table 5.10 and Table 5.10). MB-1 also had the highest single routine sample concentration for the Kensico streams in January (38 oocysts 34.1L^{-1}) within 48 hours of over an inch of precipitation recorded at the nearby weather station at Westchester County Airport. It is notable that despite having the highest mean oocyst concentration for the year, 10 of the 12 routine samples at Malcolm Brook were negative for *Cryptosporidium*. *Cryptosporidium* at BG9 were detected in four out of the 12 routine samples and the mean concentration in 2019 (1.00 oocysts) was slightly higher compared to 2018 (0.33 oocysts). WHIP, similar to BG9, had a 2019 mean that while still low (1.50 oocysts) was higher than the 2018 mean (0.50 oocysts). The *Cryptosporidium* mean declined at N12 for the second consecutive year, with a mean of 3.99 oocyst.

Table 5.10 Summary of routine Kensico perennial stream protozoan results for 2019.

Site	n	*Cryptosporidium* Mean[1] (50L^{-1})	% Detects	Max[2] (50L^{-1})	Max (L^{-1})	*Giardia* Mean (50L^{-1})	% Detects	Max[2] (50L^{-1})	Max (L^{-1})
BG9	12	1.00	33.3%	7	0.14	31.87	75.0%	230	4.60
E10	12	0.75	16.7%	5	0.10	2.42	41.7%	16	0.32
E11	12	3.33	25.0%	37	0.74	3.80	58.3%	27	0.54
E9	12	2.67	25.0%	30	0.60	6.97	66.7%	38	0.76
MB-1	12	5.89	16.7%	38 (34.1L)	1.11	11.73	58.3%	62 (34.1L)	1.82
N12	12	3.99	33.3%	34 (50.2L)	0.68	4.66	66.7%	30	0.60
N5-1	12	2.94	33.3%	18	0.36	5.29	66.7%	29 (47.9L)	0.61
WHIP	12	1.50	8.3%	18 (50.1L)	0.36	1.91	25.0%	20 (50.1L)	0.40

[1]Sample volumes not exactly equal to 50L are calculated to per L concentrations and then recalculated to 50L for determination of means. 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.

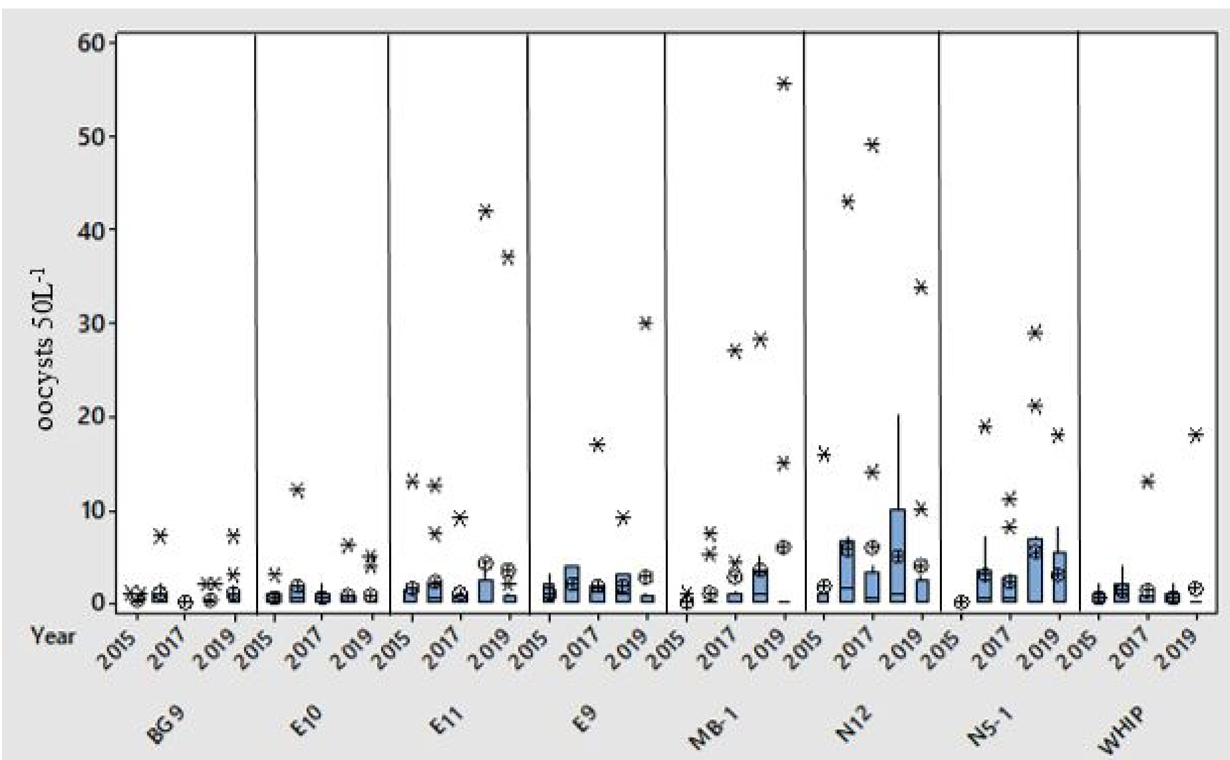


Figure 5.10 *Cryptosporidium* concentrations by year for routine samples at the eight Kensico streams from 2015 through 2019.

Giardia

The *Giardia* detection rate for all routine samples at Kensico streams in 2019 was 57.3%, which was lower than in 2018 (70.8%), but very close to the rate in 2017 (56.3%) and within detection rates observed in some previous years (2012 to 2016 annual range 34.0-75.0%). Individually, the Kensico streams had detection rates ranging from 25.0% (at WHIP) to 75.0% (at BG9) in routine samples (Table 5.10).

Of the eight sites, six had lower (E11, E9, and N5-1) or relatively similar (<25% change at MB-1, N12 and WHIP) mean *Giardia* concentrations in 2019 compared to 2018, while two of the sites (BG9 and E10) had means that more than doubled in 2019. BG9 exhibited the largest increase in annual mean *Giardia* concentrations compared to 2018 (4.15 cysts) (Figure 5.11). In addition to having the highest *Giardia* detection rate, BG9 also had the highest mean concentration (31.87 cysts) and the highest single sample result (230 cysts). The 2019 mean was the highest on record for BG9 and well over the historical mean of 9.63 cysts (2002-2018, n=186). The largest decrease in annual mean was at E9, where 2019 was less than one quarter the 2018 mean (29.48 to 6.97 cysts [1]), and well below the historical mean of 50.13 cysts (2002-2018, n=199). Two sites (E10 and WHIP) displayed small increases in their annual means of less than 2 cysts in 2019.

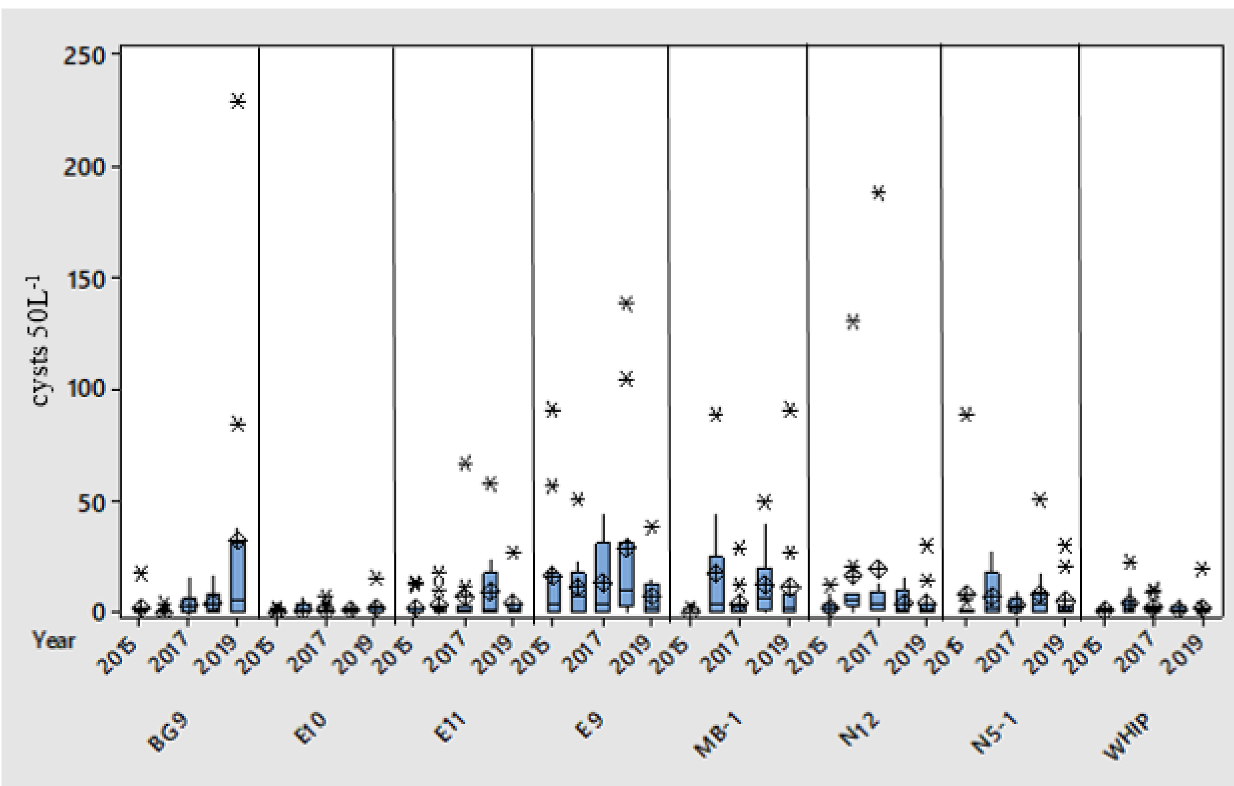


Figure 5.11 *Giardia* concentrations by year for routine samples at the eight Kensico streams from 2015 through 2019.

Additional Samples

Nineteen additional samples were collected in 2019 as part of follow-up investigations after routine samples were found to have elevated levels of protozoans relative to their 10-year 95th percentile guideline. Results for these, as well as routine samples, are provided in Figure 5.12 and Figure 5.13 with the 95th percentiles noted for each individual stream.

The first additional sample was taken on January 22 at MB-1 after the routine sample on January 2 showed results of 38 oocysts and 62 cysts in a 34.1L sample, above both the *Cryptosporidium* and *Giardia* 95th percentiles for this site (3.96 and 28.10 (oo)cysts, respectively). The follow-up sample was negative for both *Cryptosporidium* and *Giardia* cysts. The next monthly routine sample was taken about two weeks later on February 5 and results for MB-1 were again well below the 95th percentile thresholds. Investigation into meteorological records prior to the original sample on January 2 indicate approximately just over 1 inch of precipitation was recorded the day before at Westchester County Airport, indicating a strong likelihood that results were influenced by stormwater.

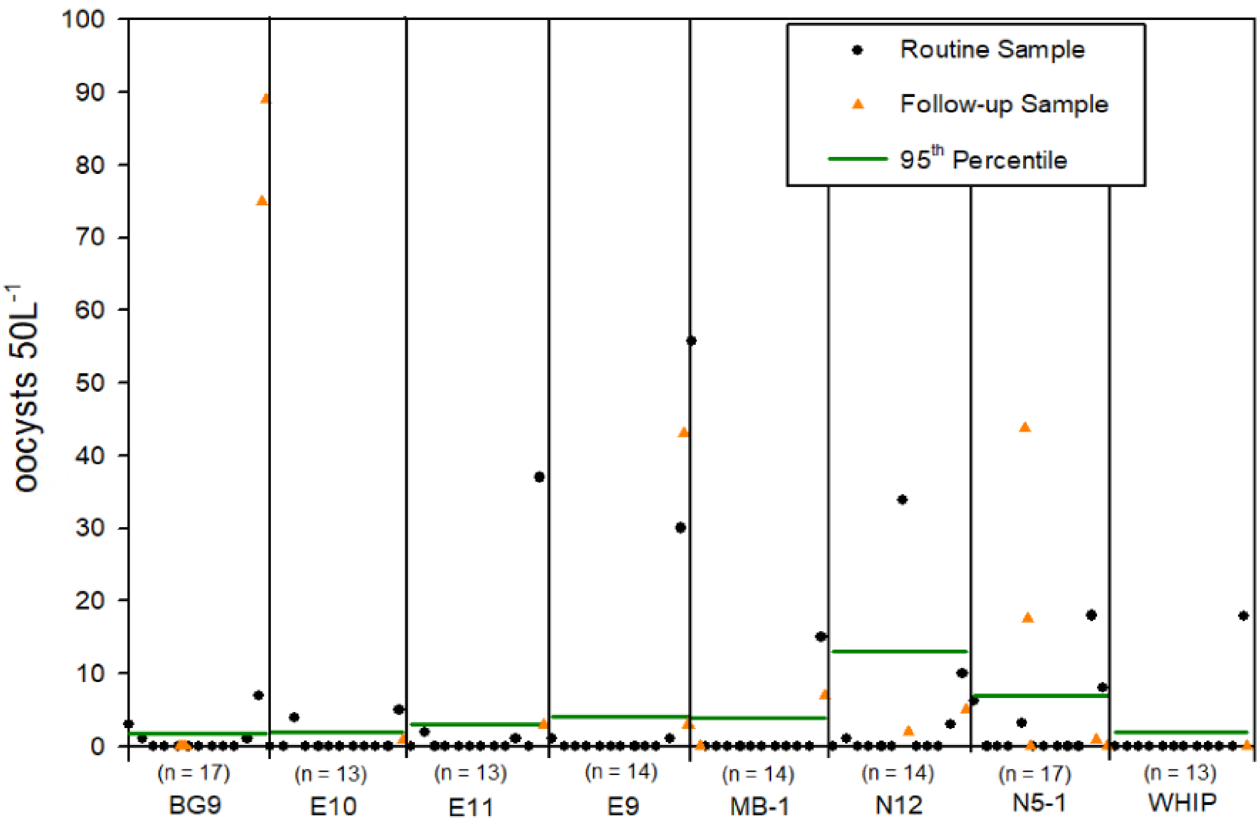


Figure 5.12 *Cryptosporidium* concentrations for samples collected at Kensico streams relative to 10-year 95th percentile values (horizontal green line).

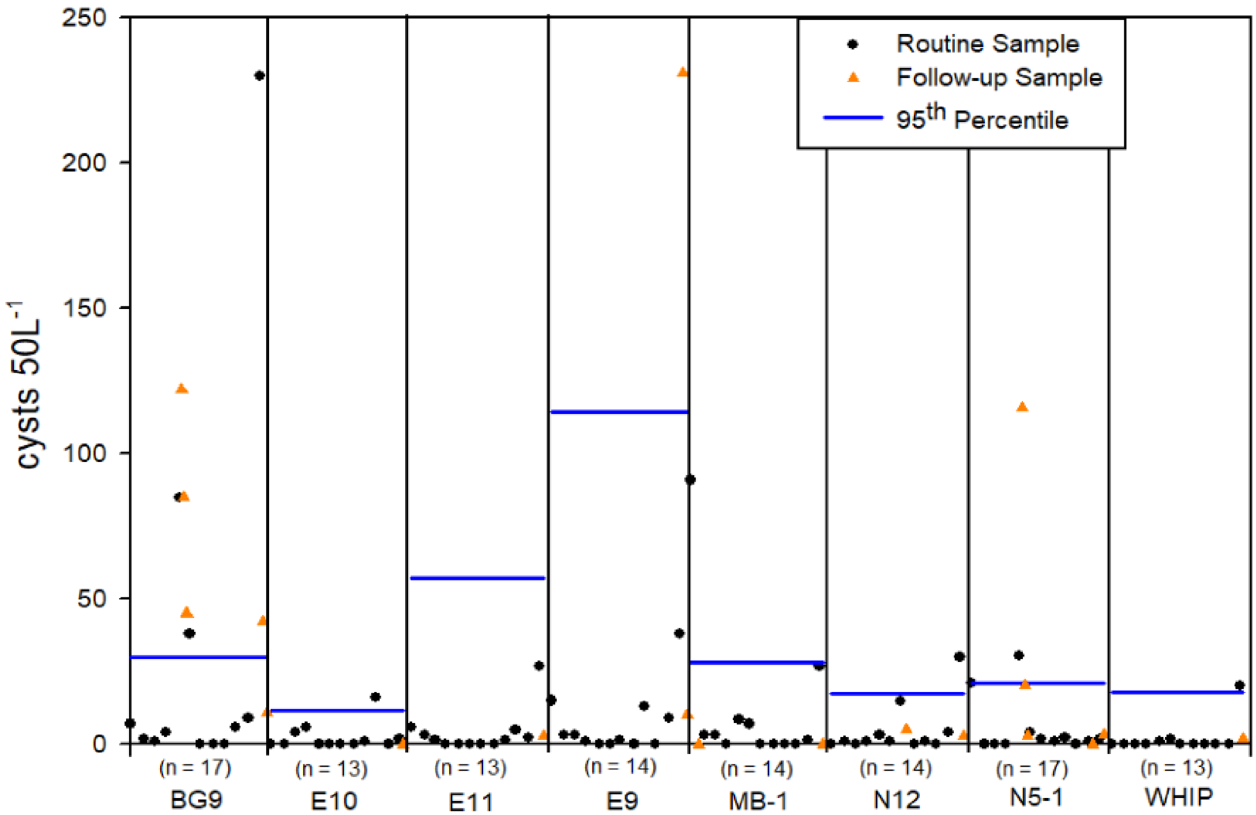


Figure 5.13 *Giardia* concentrations for samples collected at Kensico streams relative to 10-year 95th percentile values (horizontal blue line).

The May 7 samples from BG9 and N5-1 had elevated routine results *Giardia* above the 95th percentile guidelines. The *Giardia* result from BG9 (74 cysts 43.5L^{-1}) was above the guideline value of 30.0 cysts, while *Cryptosporidium* was negative. The result at N5-1 (29 cysts) exceeded the guideline (20.83 cysts), while the *Cryptosporidium* result of three oocysts was below the 95th percentile of 7.06 oocysts. Follow-up samples were scheduled at the two sites on May 14, and *Giardia* concentrations were higher at both BG9 and N5-1 (94 cysts 34.5L^{-1} and 45 cysts 19.8L^{-1}, respectively). Moreover, the *Cryptosporidium* result for N5-1 (17 oocysts 19.8L^{-1}) was well over the guideline. Additional follow-up samples were collected on May 20, and while results were lower at BG9 and N5-1, concentrations of *Giardia* remained high at BG9, and *Cryptosporidium* was still elevated at N5-1. Another set of samples was taken on May 28. N5-1 results for this set of samples were well below the 95th percentile, while the BG9 *Giardia* result (21 cysts 23.3L^{-1}) was still over the guideline. The next sample at BG9 was the routine sample approximately six days later on June 4 (26 cysts 34.2L^{-1}), which was still elevated. Precipitation levels were found to be a likely factor to the first three May samples with more than an inch of rain in the two days prior to the May 7 and May 14 samples, and almost a half inch of rain recorded on May 20.

A follow-up sample was collected on July 15 at N12 after the July 1 routine sample had 34 oocysts, exceeding the 10-year 95th percentile guideline (13.10 oocysts). The follow-up sample resulted in two oocysts in the sample, well below the 95th percentile for *Cryptosporidium*.

The routine sample at N5-1 taken on November 4 had 18 cysts, which was above the 10-year guideline (7.06 oocysts). A follow-up sample collected on November 14 had a much lower concentration (one oocyst). Storm flow likely had an influence on the elevated concentration in the routine sample, with a total of 1.01 inches of precipitation recorded at Westchester County Airport on October 31 and November 1.

In December, all eight streams were resampled after seven of the eight routine results exceeded *Cryptosporidium* 95th percentile guidelines (1.72 to 7.06 oocysts), with results ranging from five to 37 oocysts. The highest *Cryptosporidium* concentrations were at E11 (37 oocysts) followed by E9 (30 oocysts). *Giardia* results also exceeded guidelines for three of the sites (BG9, N12 and WHIP) with results of 230, 30, and 20 cysts, respectively.

Follow-up samples were taken on December 12 and results for five of the eight sites (E10, E11, N12, N5-1, and WHIP) were at or below the guidelines for both *Cryptosporidium* and *Giardia*. The remaining three streams were still above the guidelines for at least one of the protozoans. The follow-up *Cryptosporidium* result for MB-1 decreased to seven oocysts which was acceptably close to the threshold level of 3.96 oocysts and no additional samples were collected. However, the follow-up results were higher for both protozoans at E9 (43 oocysts and 231 cysts) and only higher for *Cryptosporidium* at BG9 (75 oocysts). A second set of follow-up samples was taken at E9 and BG9 on December 23. *Cryptosporidium* concentrations decreased to three oocysts at E9 which is below the guideline, while the BG9 result (89 oocysts) was once again higher than the previous result. *Giardia* concentrations were lower at both BG9 and E9 (11 and 10 cysts, respectively), both below threshold for each site (30.00 and 114.26 cysts, respectively). Samples from BG9 were sent to the Centers for Disease Control and Prevention in Atlanta, Georgia for genotyping and cysts were identified as *Giardia microti*, most commonly found in muskrats and voles, and is not infectious to humans.

East of Hudson WWTPs

Two EOH WWTPs, Carmel and Mahopac, were sampled quarterly in 2019. All of the WWTP samples at EOH sites were negative for *Cryptosporidium*. On May 20, a protozoan sample taken at the Carmel wastewater treatment plant was found to have one *Giardia* cyst in the sample. DEP inquired with plant operators about any abnormal processes around the time of sampling. No abnormal conditions were noted on or before May 20, and the filtrate turbidity ranged from 0.07 to 0.10 NTU on the day of collection. A follow-up sample was taken at the plant on May 30 and was negative for both *Giardia* and *Cryptosporidium*. It should be noted that this May 20 sample was the first detection of a protozoan at this plant in over 10 years of quarterly monitoring.

5.5 CAT/DEL UV Plant and Hillview Reservoir Monitoring

CAT/DEL UV (CDUV) Plant

Monitoring of the outflow of the CDUV began in December 2017 and was conducted weekly throughout 2018 and 2019 at the tap known as CCCLAB. Of the 53 samples collected in 2019, eight (15.1%) were positive for *Cryptosporidium* (Table 5.11), similar to 2018 (7 out of 53, 13.2%). The annual mean concentration for *Cryptosporidium* in 2019 was 0.26 oocysts and the highest result was four oocysts. This was again similar to 2018 when the mean was 0.15 oocysts and the highest result was two oocysts. *Giardia* were detected in 33 out of 53 samples (62.3%) at CCCLAB in 2019, more than were detected in 2018 (27 out of 53, 50.9%). The annual mean concentration in 2019 (1.64 cysts) was also higher than the 2018 mean (0.68 cysts). The maximum *Giardia* result at CCCLAB in 2019 (12 cysts, May 14) was much higher than 2018 (three cysts), however, this occurred at a time when Kensico Reservoir was being operated in float mode and Rondout water containing elevated *Giardia* concentrations was going directly to the UV Plant. Kensico Reservoir was returned to normal operation (reservoir mode) on May 16.

Table 5.11 CAT/DEL UV Plant protozoan monitoring results summary for 2019.

	***Cryptosporidium* oocysts**	***Giardia* cysts**
n	53	53
Number of Detects	8	33
% Detects	15.1%	62.3%
Mean ($50L^{-1}$)	0.26	1.64
Maximum ($50L^{-1}$)	4	12

The detection of *Cryptosporidium* oocysts and *Giardia* cysts immediately post-UV treatment is a strong reminder that the USEPA method for recovering these protozoans from water (1623.1) is unable to provide a true measure of public health risk. Cysts and oocysts are counted with this method, even though they have been deactivated by UV light and are no risk to public health.

HILLVIEW

Giardia and *Cryptosporidium* have been routinely monitored weekly at Hillview Reservoir Site 3 since August 2011 as part of the Hillview Administrative Order and Hillview Consent Decree and Judgement. During 2019, 52 weekly samples were collected and analyzed by EPA Method 1623.1 with EasyStain and heat dissociation and results are presented in Figure

5.14 and Figure 5.15. In addition, weekly samples (100L) were analyzed by CC-IFA at Hillview for *Cryptosporidium* infectivity, and all 52 samples were negative.

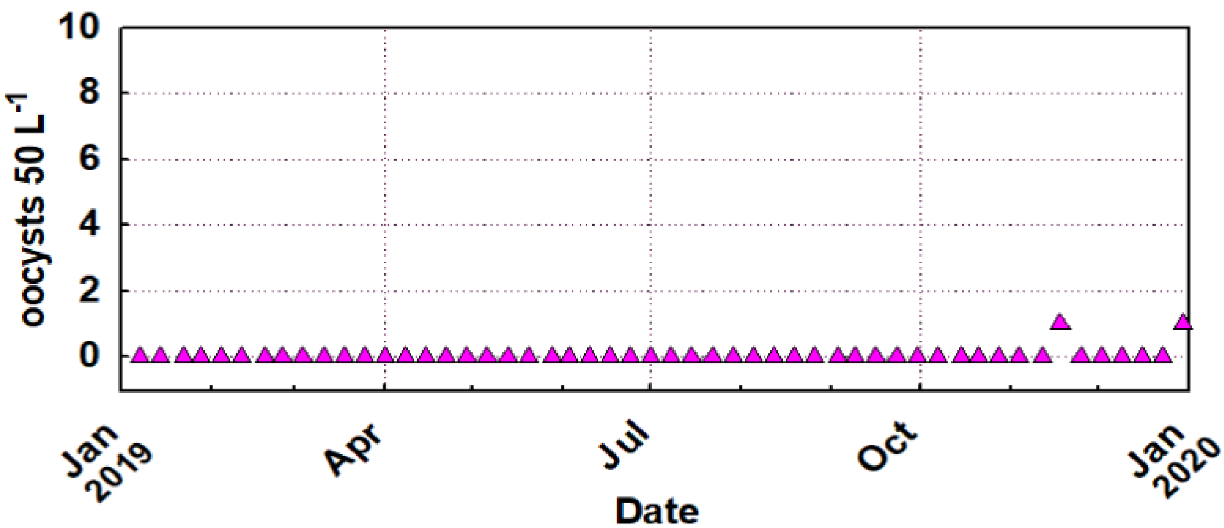


Figure 5.14 *Cryptosporidium* oocyst concentrations for routine samples at Hillview Site 3 in 2019.

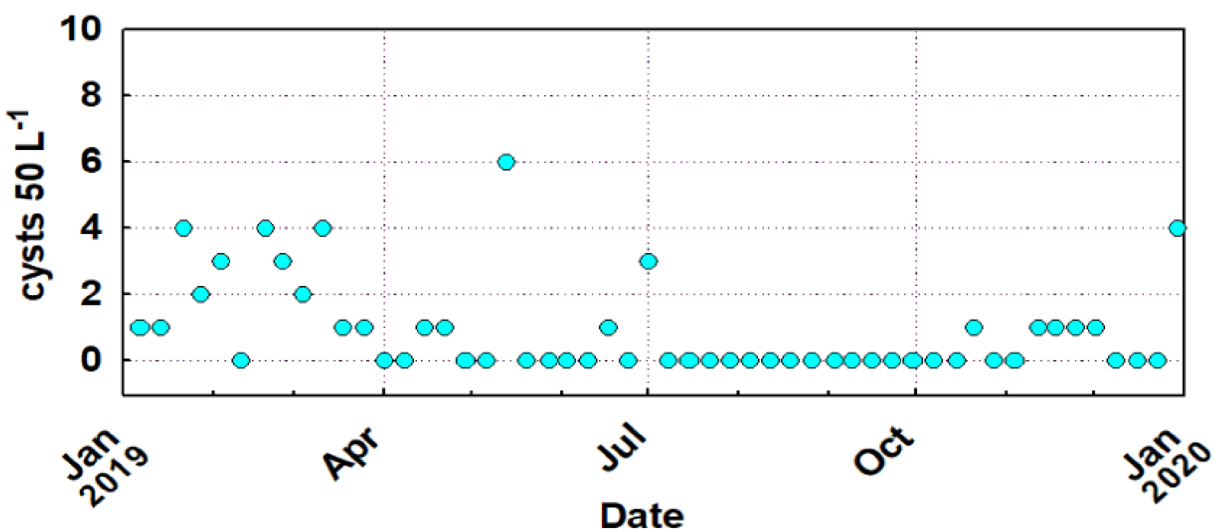


Figure 5.15 *Giardia* cyst concentrations for routine samples at Hillview Site 3 in 2019.

Cryptosporidium was detected in 3.8% of Hillview samples and the annual mean concentration was 0.04 oocysts (Table 5.12). *Cryptosporidium* detection rates in 2019 were lower than those in 2018, but the same as those in 2013, 2014, and 2017 (Table 5.11). Likewise mean concentrations were lower in 2019 (0.04 oocysts) than 2018 (0.11 oocysts), but again the same as those from 2013, 2014, and 2017. The *Giardia* detection rate was substantially higher in

2019 (42.3%) compared to 2018 (17.0%), but only slightly higher than the detection rates in 2013 and 2014 (34.6% and 35.2%, respectively). Annual mean *Giardia* concentrations were also higher in 2019 (0.90 cysts) compared to any of the years from 2011 to 2018 (0.13-0.67 cysts) or the overall mean for those years (2011-2018 mean = 0.42 cysts).

Table 5.12 Hillview Site 3 protozoan detections from 2011 to 2019.

	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	3.8%	18	34.6%
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%

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

As noted in previous sections, *Giardia* results from the Rondout Reservoir outflow have been elevated since late 2018, with increasing detections and concentrations at sample points downstream (Kensico Reservoir inflow and outflow, etc.) and this has had some effect on results at Hillview. An additional factor likely resulting in increased *Giardia* at Hillview was the mode of operation of the water supply during several periods of shoreline stabilization work at Kensico Reservoir in 2019. During those periods, when operated in float mode, Rondout water is not receiving the benefit of residence time in Kensico, resulting in higher than normal *Giardia* concentrations downstream. Detections and concentrations for both *Cryptosporidium* and *Giardia* were lower at Hillview Site 3 compared to upstream.

6. Water Quality Modeling

6.1. Overview

The Water Quality Modeling section supports protection and improvement of water quality by developing and applying quantitative tools that relate climate, natural and anthropogenic conditions in watersheds, fate and transport processes in reservoirs, water demand, and water supply system operation to the quality of drinking water. These models allow DEP to evaluate and forecast the impact of reservoir operations, watershed protection programs, climate change, and supply system infrastructure on water quantity and quality, including turbidity, eutrophication, and disinfection byproduct precursors.

This chapter contains an overview of major activities in the Water Quality Modeling Program that took place in 2019.

6.2. Prediction of Precipitation at Ungauged Locations in the West of Hudson Watersheds

The details of the research described in this section appear in the peer-reviewed publication Yeo et al, 2019. This section provides an overview of this work.

6.2.1. Introduction

The testing, validation, and application of hydrologic models for the water supply watersheds requires that the spatial variation of precipitation over the entire area of the watershed be specified over the time period of the simulation. This is true both when using the model for hindcasting of historical conditions, and for forecasting for future conditions of interest such as scenarios that reflect climate change. All precipitation measurements are made using gauges that are essentially point measurements over the time period of deployment. However, many watersheds do not have an adequate network of precipitation gauges to accurately capture the spatial variation. This is particularly true in a region like the Catskill Mountains, where the geographical and topographical features of the region result in complex and irregular spatial patterns of precipitation. In regional hydrologic studies, information on the spatial distribution of precipitation, at a sufficiently high resolution, is essential in order to accurately predict streamflow using a hydrologic model. There are various methods for distributing the point measurements of precipitation over the area of a watershed. A simple and widely used procedure is Thiessen polygons. Here we describe an improved method that is based on a robust statistical analysis of observations. Note that this procedure is dependent on observations from a network of precipitation stations, and the implementation of this procedure does not affect the underlying need for such a network

This method uses a technique known as regionalization. Regionalization methods have two main objectives: characterizing spatial dependency or homogeneity and reducing uncertainty in the modeling of precipitation at different locations. The implication of spatial dependency is that the precipitation records from two or more stations in a delineated homogenous region have similar statistical characteristics. These methods have been employed to understand the spatial behavior of precipitation in order to effectively transfer precipitation information from a location with sufficient observations to another where available records are scarce. Development of a regionalization procedure is more complicated for precipitation than for most other meteorological variables because precipitation is a two-dimensional vector composed of both occurrence, a discrete binary quantity, and amount, a highly skewed continuous quantity. We developed a regionalization technique based on the similarities of both precipitation amount and occurrence at different locations using two approaches: principal component analysis (PCA) and ordinal factor analysis (OFA). These statistical techniques identify groups of stations with similar precipitation statistics based exclusively on the station records; other station properties such as spatial location (latitude/longitude) or elevation are not included in the analysis. The reason that they are sometimes referred to as “regionalization” techniques is that, due to the physics of precipitation processes, stations with similar statistical properties often naturally fall into spatially contiguous regions.

PCA and OFA are applied sequentially in order to identify homogeneous groups of daily precipitation stations. PCA is performed first to identify “groups” with correlated precipitation amount. OFA is then performed on each PCA group independently. As a result of the combined application of PCA and OFA, each observation station is placed in one group with other stations that have similar statistical properties for precipitation occurrence and amount.

Following regionalization, data from stations within each region are used to estimate precipitation at ungauged locations throughout the area identified by the regionalization process, and including probabilistic information derived from using a stochastic model. This precipitation model uses statistics that have been quantified using the observed precipitation in the region. Those statistics are then applied to determine, or estimate, precipitation over the entire region. This statistical model has a stochastic component; multiple realizations of the predicted time series of precipitation at an ungauged site are generated. Each realization is determined based on the computed statistics and on random sampling from those distributions. Use of these multiple time series as input to a hydrologic model can then generate multiple streamflow time series, allowing the uncertainty in the streamflow predictions to be quantified.

6.2.2. Data

Historical precipitation data from 80 rain gauge stations within the Catskill Mountains region, and in or nearby the water supply watersheds, were obtained from National Oceanic and Atmospheric Administration databases. The number of stations measuring daily precipitations in this region has decreased significantly, with only 38 stations active in the 1980s. The period

1949–1959 was chosen to calibrate the model, while 1981-91 was used for model validation. A comparison of the regionalization analyses conducted during the calibration (1950s) and validation (1980s) periods is used to indicate whether the results are dependent on time. The location of the rain gauges, and observed average spring season precipitation amounts for the calibration period are shown in Figure 6.1.

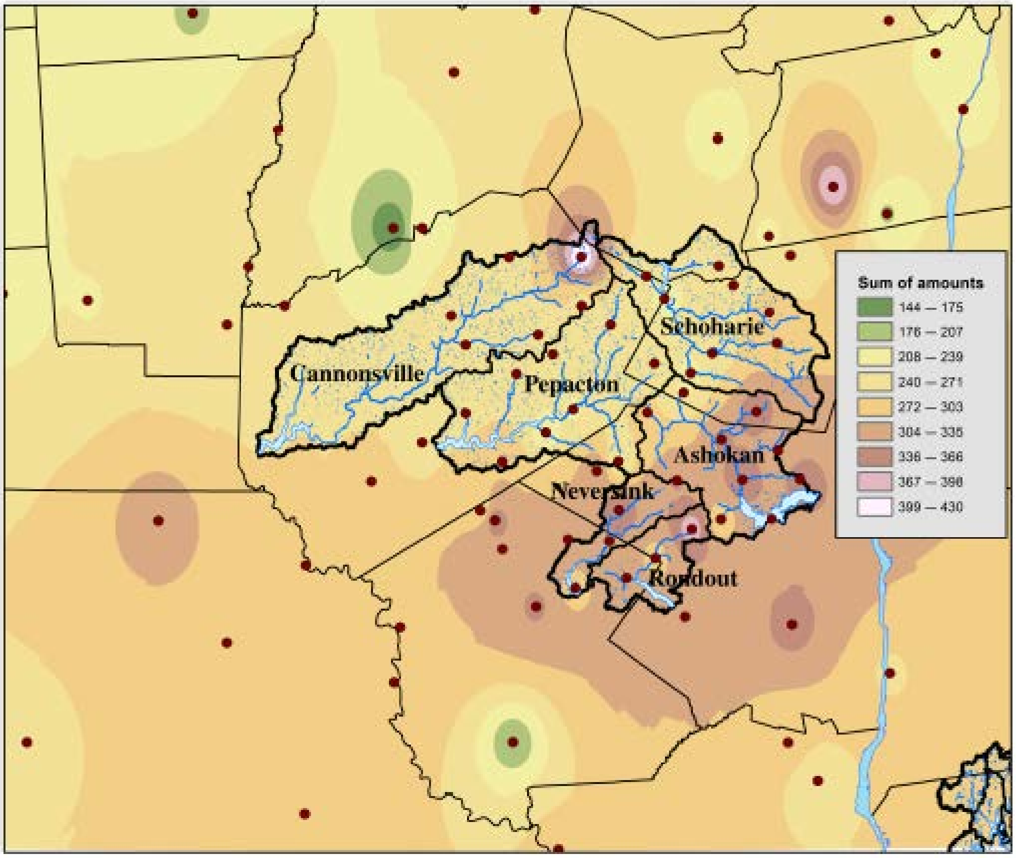


Figure 6.1 Interpolated mean precipitation (mm) for March-May for the 1949-59 calibration period. The thick black lines are the watershed boundaries for the West of Hudson reservoirs, while the thin black lines are New York State county boundaries. The circular black symbols are the precipitation gauge locations.

6.2.3. Model Validation

To validate the model, the following procedure was used. Validation was undertaken by removing the observations from a selected station from the data set, effectively assuming that site was ungauged rather than gauged. The model was then applied to the reduced data set to generate realizations of the simulated or estimated time series at that site. The individual realizations or, more importantly, the statistics of those realizations were then compared to the observations.

For the validation shown here, the observations from the station at Grahamsville were selected. The computed precipitation series at Grahamsville was then statistically analyzed and compared to the observed precipitation data using and number of metrics. Two precipitation quantities, annual total precipitation and annual number of wet days, are shown in Figure 6.2 to indicate typical results from this validation step. The good agreement between the median of 20 realizations and the range of those realizations, with the observed quantities, provides the validation of this model.

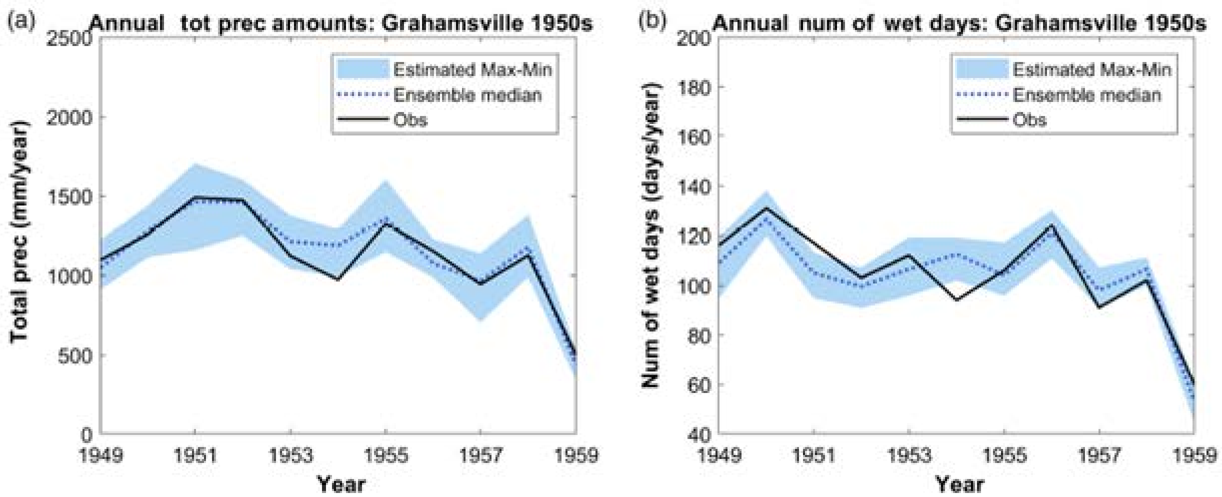


Figure 6.2 Observed and estimated annual means of (a) precipitation, and (b) and number of wet-days for the calibration period (1949–1959) for the Grahamsville gauge. The maximum and minimum (blue range) and median (black dotted line) are for the 20 predicted ensemble time series, and the black solid line is the observed values.

6.3. Historic Streamflow Reconstruction

The historic streamflow reconstruction is designed to estimate annual average streamflows for years before the start of actual stream gaging programs using paleoclimatic data. Temporal disaggregation of the annual streamflows to produce estimates of monthly average or daily average values is also investigated. This project involves paleoclimate-based streamflow reconstructions for six streamflow gages measuring inflow from Catskill/Delaware watersheds, as well as drought analyses for the NYCDEP reservoir/water system using these reconstructions. The six USGS gage sites for which the reconstructions will be done are Esopus Creek at Coldbrook, Schoharie Creek at Prattsville, East Branch Delaware River at Margaretville, West Branch Delaware River at Walton, Neversink River at Claryville, and Rondout Creek at Lowes Corners. The usage of the reconstructed streamflows for validating both hydrologic models, such as SWAT, and weather generator models may also be explored.

Paleoclimate reconstruction of streamflow is desirable as it may lead to a more complete, robust description of the frequency and return periods of major hydroclimatic events, as well as for better understanding the overall trends in streamflow regime behavior. The length of the observed streamflow record for these six gages ranges from 70 to 118 years. The influential climate drivers of streamflow regime behavior may have low-frequency oscillatory patterns with multi-decadal cycle lengths. It is therefore difficult to estimate the return periods of significant regime shifts based on the observed flow records, and to detect the critical patterns of regime shifts over time and link these to causal climate mechanisms. Reservoir operations planning in the Catskill and Delaware watersheds have used the 1960s drought of record to plan for dry periods, when in fact a longer record of flow may reveal other dry periods with a range of severity or duration. Global climate models (GCMs) often do not replicate the drought of the 1960s properly, and this is also a concern for water planners.

Paleoclimate streamflow reconstructions, which extrapolate existing streamflow records further back into the past, are carried out using tree ring data from local trees as predictors in a supervised learning model. These tree ring data inform the reconstructions of the streamflow based on the assumption that hydroclimatic factors that influence streamflow also influence the growth cycle of nearby trees. Hence, the thickness of the annual ring formations provide a record describing moisture availability over the life span of the tree. Such data has to be decoupled from the influences of radiation, temperature, energy, and other confounding factors, and the growth trends in the tree must be removed. The raw tree ring data that have been processed into usable data for the reconstruction model are called tree ring chronologies. This processed data is used in the analysis described here.

6.3.1. Study Area and Data

The study area for the reconstructions and flow regime analysis are the Catskill and Delaware watersheds as shown below in Figure 6.3. The data used consists of observed streamflow and tree ring chronologies. Daily streamflow data were obtained from the USGS website for the six sites. The daily streamflow data was aggregated to water year totals, as defined by USGS (October 1 – September 30). Tree ring chronology data from 19 trees located in and around the watershed (Pederson et al 2013) were collected. The tree with the longest span of data extends back to 1450 and the most recent is for 2002. Hence, it is possible, to create reconstructed streamflow data for all six gages for the period 1450 – 2002, yielding a 553 years of reconstructed data for each gage.

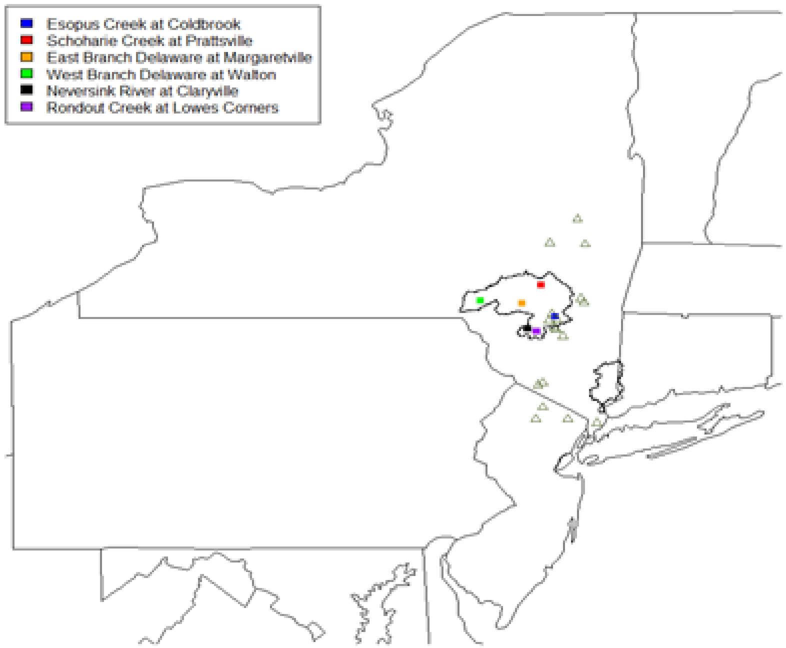


Figure 6.3 The region for the streamflow reconstruction study. The boundaries of the West of Hudson and East of Hudson watersheds are the heavy black lines. The locations of the 19 trees used in ring analysis are the green triangles. The six USGS streamflow gages, from which the streamflow observational data is sourced, are the colored squares.

6.3.2. Modeling Plan

After collecting and processing all of the data, the model was selected from among various choices. The model of choice is a hierarchical partial-pooling Bayesian regression model with a nesting approach to make use of all of the data available in the multiple tree ring chronologies, therefore extending the reconstructions as far back in time as possible. The model is a regression model that in some aspects is similar to the classical linear regression model, but is considerably more complex. The model is based on the fundamental assumption that streamflow follows a lognormal distribution which may be expressed as

$$\ln(y_{t,i}) = \alpha_i + \boldsymbol{\beta}_i^T \boldsymbol{x}_t + \varepsilon_{t,i} \tag{6.1}$$

where $y_{t,i}$ is the streamflow at time t and at streamflow gage i, and $\boldsymbol{x}_t$ is a vector containing all tree ring observations at time t. The lognormal assumption was validated for the observed streamflow used here. As the streamflow gages are all within close in close proximity to one another (Figure 6.3), the variability in the streamflow behavior at each of the gages that is not explainable by the tree ring data, and is captured in the error term ε in Equation 6.1, are assumed to be significantly correlated to one another. The physical rationale is that the climatic factors that influence streamflow variability, but are not captured in the trees rings, are common to all streamflow sites as a result of their close proximity. Hence, there exists a strong spatial correlation structure among the residual error terms across the sites.

This spatial correlation in the error is modeled at each point in time as coming from a multivariate normal distribution with a common correlation/dispersion matrix specifying the spatial correlation structure across the streamflow gages. The slopes in the model $\boldsymbol{\beta}_i^T$ (Equation 6.1), which depict the strength of the relationship between streamflow and tree ring data, are given a prior distribution of a multivariate normal with a common mean vector and correlation matrix across the sites. This reflects the fact that the climatic influence on the streamflow variability at each gage are effectively the same. The slope $\boldsymbol{\beta}_i^T$ and intercept α_i are estimated using a Bayesian method. Since the tree ring chronologies all start at different points in time, some going as far back as the mid-fifteenth century, a nesting approach is taken, whereby several hierarchical models are designed and estimated using the available tree ring chronologies at each time step in building the model. The streamflow reconstructions from each of these models are then spliced together for each gage to give us the final product of a tree ring reconstruction that runs from 1450 – 2002. The output from such a model is distributional, as opposed to the usual point-based time series, yielding a clear description of the uncertainty in the reconstructions.

Testing of this proposed model is underway, and the initial results appear to support the underlying assumptions of the approach as described above. Results will be shown in a future report.

6.4. Development of Climate Change Indices for the NYC Water Supply

Global climate models generally concur that the NYC water supply watersheds will continue to experience higher temperatures and increased precipitation with more extreme storm events. The OST Expert Panel recommended that “NYCDEP should consider coordinating with other New York City and regional agencies to create and update a Climate Resiliency Indicator and Monitoring System for the New York metropolitan region and assess climate change.” Based on this recommendation, the Water Quality Modeling Section has begun the development of a project to calculate indicators of climate change based on meteorological, hydrologic, reservoir operations and water quality data. The project aims to leverage long term data sets to describe trends of climate change in the watershed as well as related trends in changes to impacts on the water supply system, and to revise these trends over time as more data sets are updated with new observations.

6.4.1. Methods

DEP has developed a list that currently includes more than 80 individual metrics which must then be calculated at a variety of locations throughout the watershed. The indicators identified can be broadly grouped into four categories (**Table 6.1**).

Table 6.1 Summary of the categories and indices of climate change expected to be calculated.

Water supply operations and water quality
Alum addition days and mass
Diversion temperature at EWRM sites
Diversion turbidity
Watershed snowpack
Drought warnings
Seasonal reservoir spill
Meteorology
Frost and icing days
Growing season length
Minimum and maximum temperature
Precipitation volume and intensity
Wet/Dry spell
Hydrology
Mean monthly streamflow
Magnitude of extreme flow
Timing of extreme flow
Reservoir Characteristics
Thermocline depth
Ice on/Ice off

Where more than one data set is available for a given metric, the indicator is calculated using all available sources. To accomplish this volume of calculations, automation scripts are being developed to perform the following:

1. Gather and store the raw data in a DEP database
2. Aggregate and summarize data for each indicator
3. Produce summary data sets and charts

In 2019, with the assistance of a BWS graduate summer intern, the Modeling Section began work on this project. The initial focus has been on developing a flexible analysis framework that will enable DEP to add or modify indicators and perform additional trend analyses. Since meteorological conditions are the most direct measure of climate change, and various long-term meteorological data sets are publicly available with established quality control, meteorological indicators were selected as the first category to begin the analysis.

Python was selected as the coding language as the foundation of the analyses, as it is a powerful language that can easily integrate with SQL databases, internet-based data sources as well as geospatial data sets and software such as ArcGIS for spatial analyses. Python has robust statistical and visualization packages, and can also communicate with the R statistical coding language to access specific functions if desired.

6.4.2. Data Sources

The data sets currently being used to calculate climate change indicators have been selected from both publicly available and internal DEP sources.

6.4.2.1. NOAA Data

The National Oceanic and Atmospheric Administration (NOAA) publishes a variety of meteorological observation and forecasts through the National Weather Service. For this project, we are using the Integrated Surface Daily (ISD) data set, which provides hourly data observations as airport weather stations throughout the nation. DEP use the data for three airports near the watershed: Albany, Binghamton and Westchester. The hourly data are aggregated to daily values to calculate the climate indicators.

6.4.2.2. USGS Data

The United States Geologic Survey (USGS) operates hydrologic gages throughout the nation. DEP is gathering daily time series data for all gages operating in the watershed, focusing on streamflow volume.

6.4.2.3. PRISM Climate Data

The Northwest Alliance for Computational Science & Engineering, based at Oregon State University, publishes the Parameter-elevation Relationships on Independent Slopes Model (PRISM), a regularly gridded data set available from 1981-present. PRISM uses a suite of observational data sets from many sources across the nation to generate an interpolated set of meteorological observations at daily and monthly time steps. DEP uses the daily time series for temperature and precipitation to calculate climate change indicators.

6.4.2.4. DEP Data

DEP operates a robust monitoring network throughout the watershed which includes sampling of streams, reservoirs, and the distribution system, as well as meteorological stations at select locations. Meteorological stations were installed starting in the 1990s. Water quality and operations data include both in-situ measurements which can be measured sub-hourly and field sampling with varying frequencies depending on the sampling objective.

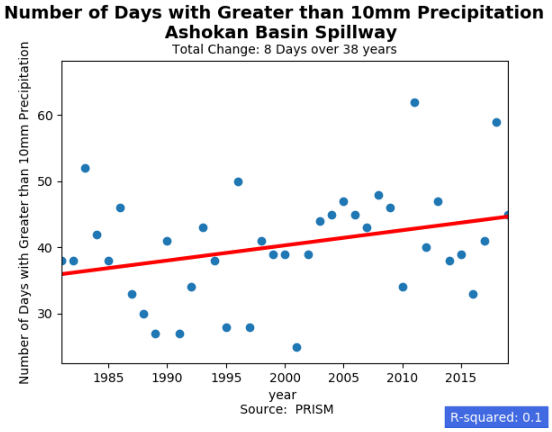
6.4.2.5. Remote Sensing Data

In addition to tabular observations, DEP is exploring the use of remote sensing data to quantify spatial patterns of change in the watershed. Satellite platforms including LandSat and MODIS (Moderate Resolution Imaging Spectroradiometer) have been gathering multispectral data on regular intervals for several decades. Landsat, operated by USGS and the National Aeronautics and Space Administration (NASA), typically overflies the watershed every 16 days, and produces imagery at 30-meter resolution. MODIS, operated by NASA, typically overflies the watershed every two days, and produces imagery at 500-meter resolution.

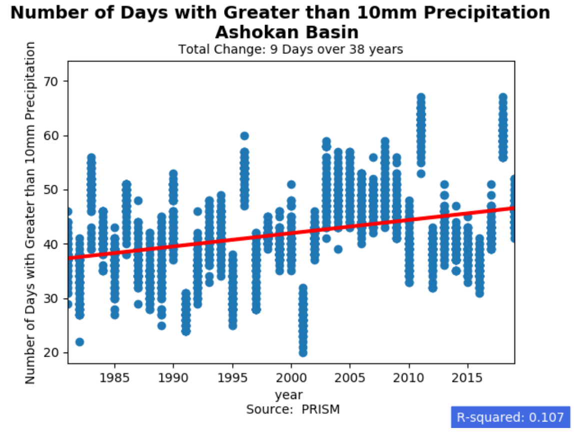
6.4.3. Results

In 2019, the primary data sources analyzed were NOAA and PRISM meteorology data. Figure 6.4 shows summary results for a climate indicator of the number of days per year with greater than 10 mm of precipitation. As shown in the figure, PRISM data can be analyzed as a single grid cell, as a combination of all grid cells within a watershed, or as an average value of all grid cells within a watershed, whereas NOAA airport data is only summarized as a single time series trend for each airport. Table 6.2 lists the suite of meteorological climate indicators that have been calculated in 2019. As this project is at an early stage, the results presented above represent a preliminary trends analysis completed in 2019.

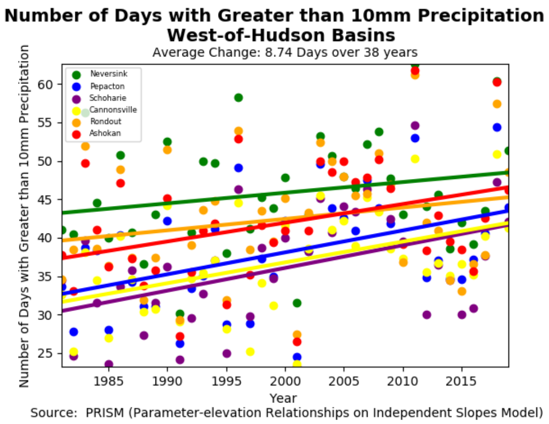
a. PRISM results for a single grid cell located at the spillway for Ashokan Reservoir



b. PRISM results for all individual grid cells located within the Ashokan Reservoir watershed.



c. Average results for each watershed in the WOH district using PRISM data



d. Results of NOAA airport observations.

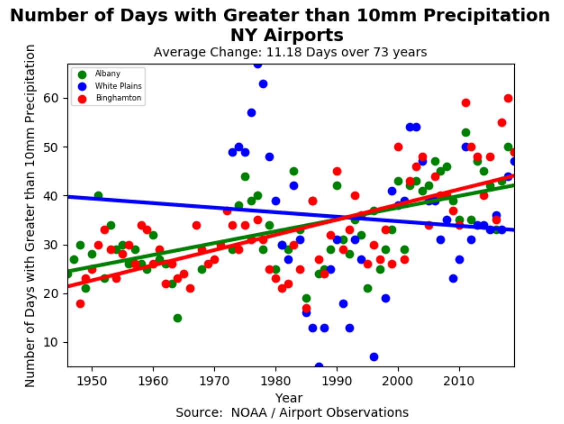


Figure 6.4 Sample results of a climate indicator calculated for the NYC watershed.

Table 6.2. Results of climate change indicators for West of Hudson (WOH) watersheds calculated using NOAA and PRISM.

Climate Change Indicator	Change	
	NOAA	PRISM
Number of Tropical Nights (min temp. < 20° C)	5.0	0.7
Number of Summer Days (max temp. < 25° C)	-0.8	10.4
Growing Season Length (days)	25.0	28.0
Number of Frost Days (min temp. < 0° C)	-13.1	-8.6
Number of Icing Days (max temp. < 0° C)	-5.0	0.7
Earliest Autumn Frost Day (day of year)	15.5	20.6
Latest Winter Frost Day (day of year)	-9.4	-7.3
Number of Wet Days	51.2	30.6
Total Annual Precipitation (mm)	338	213
Maximum length of dry spell (daily precip. < 1 mm)	*	-1.7
Maximum length of wet spell (daily precip. > 1 mm)	*	-0.5
Maximum Annual Consecutive Days of 10th Percentile Min Temp.	-1.6	-2.3
Maximum Annual Consecutive Days of 90th Percentile Max Temp.	-0.8	-0.1
Total Annual Precipitation (mm) when daily precip. > 95th percentile of historical period (pre-2000)	122	18
Total Annual Precipitation (mm) when daily precip. > 99th percentile of historical period (pre-2000)	53	-8
Number of Days with Greater than 10mm Precipitation	11.2	8.7
Number of Days with Greater than 20mm Precipitation	4.4	6.6

6.4.4. Future Work

The full results on all categories of climate change indices will be reported in future work. The meteorological indicators will be expanded to include DEP weather stations in watershed. The trends calculated are linear regressions, which will likely be replaced with more complex trend analysis in future phases of the project. Coding is continually being revised and modules added in 2020 as indicator definitions are revised. In 2019, small sets of remote sensing data were used to test their utility in generating time-series data. This analysis will be expanded to full period of record time-series to describe new indicators.

6.5. Modeling Stream Nutrient Loading in the Cannonsville Watershed

This stream nutrient loading study is a follow-up to recent DEP work that developed and tested a modified version of the Soil and Water Assessment Tool (SWAT) hydrological and water quality model (Hoang et al., 2017; Hoang et al., 2019), developed future climate scenarios for the study region (Gelda et al., 2019), and investigated the impact of climate change on streamflow and stream turbidity in the Cannonsville watershed (Mukundan et al., 2018; Mukundan et al., 2019). The focus of this work is to simulate nutrient loading in the Cannonsville watershed where management practices have reduced nutrient inputs during the last 25 years (Figure 6.5). DEP (2011) and Hoang et al. (2019) report on the sources of dissolved phosphorus (P) in the Cannonsville Reservoir watershed and the relative contribution of point and nonpoint sources. Studies have also shown the importance of nitrogen (N) loading on algal production in this reservoir, particularly during mid- to late summer (Effler and Bader, 1998). The relative contribution of terrestrial sources (point and nonpoint) of nitrogen (N) to streams in the Cannonsville watershed remain unknown. The specific objectives of this study are (1) to simulate terrestrial N loading in the Cannonsville watershed, and to estimate and partition contributions from major point and nonpoint sources; and (2) to simulate the impact of climate change on N and P loading.

6.5.1. Sources of Stream Nitrogen and Relative Contributions

The SWAT-HS model was calibrated using observed terrestrial sources of N as input (Table 6.3). Simulations showed that forest land use that occupies 64% of the watershed area contributed the most to stream nitrate loading while pasture land use contributed most of the total N loading due to close proximity to streams and runoff generating areas causing high loads of total N being transported with sediment (Table 6.4). Nonpoint sources contribute about 95% of the nitrate exported from the watershed. Model simulations also indicate that only about 23% of the total annual anthropogenic N input is exported out of the watershed by streams, suggesting significant storage and/or loss of N within the watershed. While monitoring the watershed outlet can provide valuable information on total nutrient and sediment exported from a watershed, models allow for the breakdown of contributions from various watershed sources and their relative importance. Such information can be valuable for watershed management planning efforts as sources and relative contributions vary among watersheds.

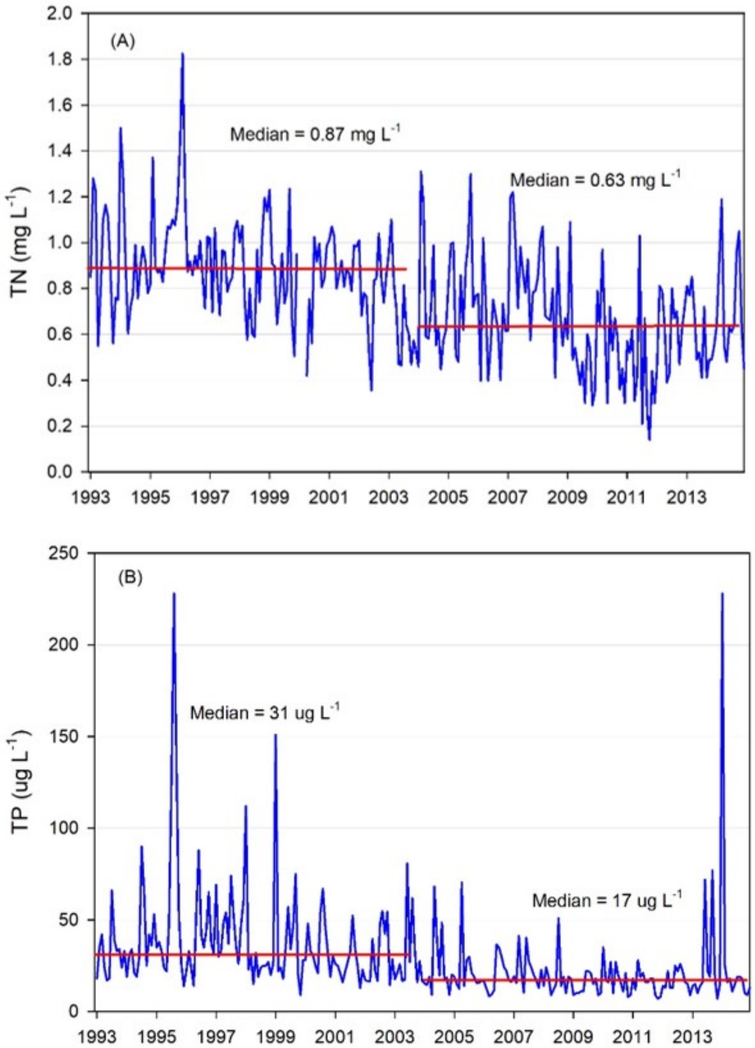


Figure 6.5 Change in (A) total nitrogen and (B) total phosphorus concentration between 1993-2003 and 2004-2014 in the West Branch of the Delaware River near Walton. Data shown are monthly averages based on biweekly to monthly grab samples collected by NYC DEP.

Table 6.3. Average annual anthropogenic sources of total N in SWAT input (2001 to 2010).

Source	**Contribution (kg N/km^2/yr)**	**% Total**
Atmospheric deposition	1087	37.8
Fertilizers	926	32.2
Manure	782	27.2
Septic systems	59	2.1
WWTPs (point source)	19	0.7
Total	2873	100

Table 6.4. Predicted nitrogen loading into Cannonsville Reservoir from different sources for the period 2001-2010.

	Nitrate		**Total Nitrogen**	
Source	Metric tons N/yr	% Total	Metric tons N/yr	% Total
Cropland	16.5	4.6	76.6	9.9
Pasture	40.0	11.0	260	33.8
Woodland	28.8	8.0	61.0	8.0
Forest	141	39.3	164.5	21.4
Shrubland	63.2	17.6	120.5	15.7
Urban	30.7	8.5	48.0	6.2
Septic systems	21.9	6.1	21.9	2.8
WWTPs	17.0	4.7	17.0	2.2
Total	359		770	

6.5.2. Impact of Climate Change on Nutrient Loading

Simulated nutrient loading under the baseline period (2001-2010) and a future period (2051-2060), using projected climate from 20 CMIP5 GCMs, based on the RCP 8.5 (“worst case”) emission scenario, were compared to assess the impacts of climate change. Projected average annual change in air temperature for the watershed is between 1.4 degrees Celsius and 4.7 degrees Celsius with an average change of 3 degrees Celsius. Projected average change in precipitation is between -2.0% to +17.8% with an average change of +5.5%. Figure 6.6 shows the impact of climate change on average annual streamflow and water quality constituent loads.

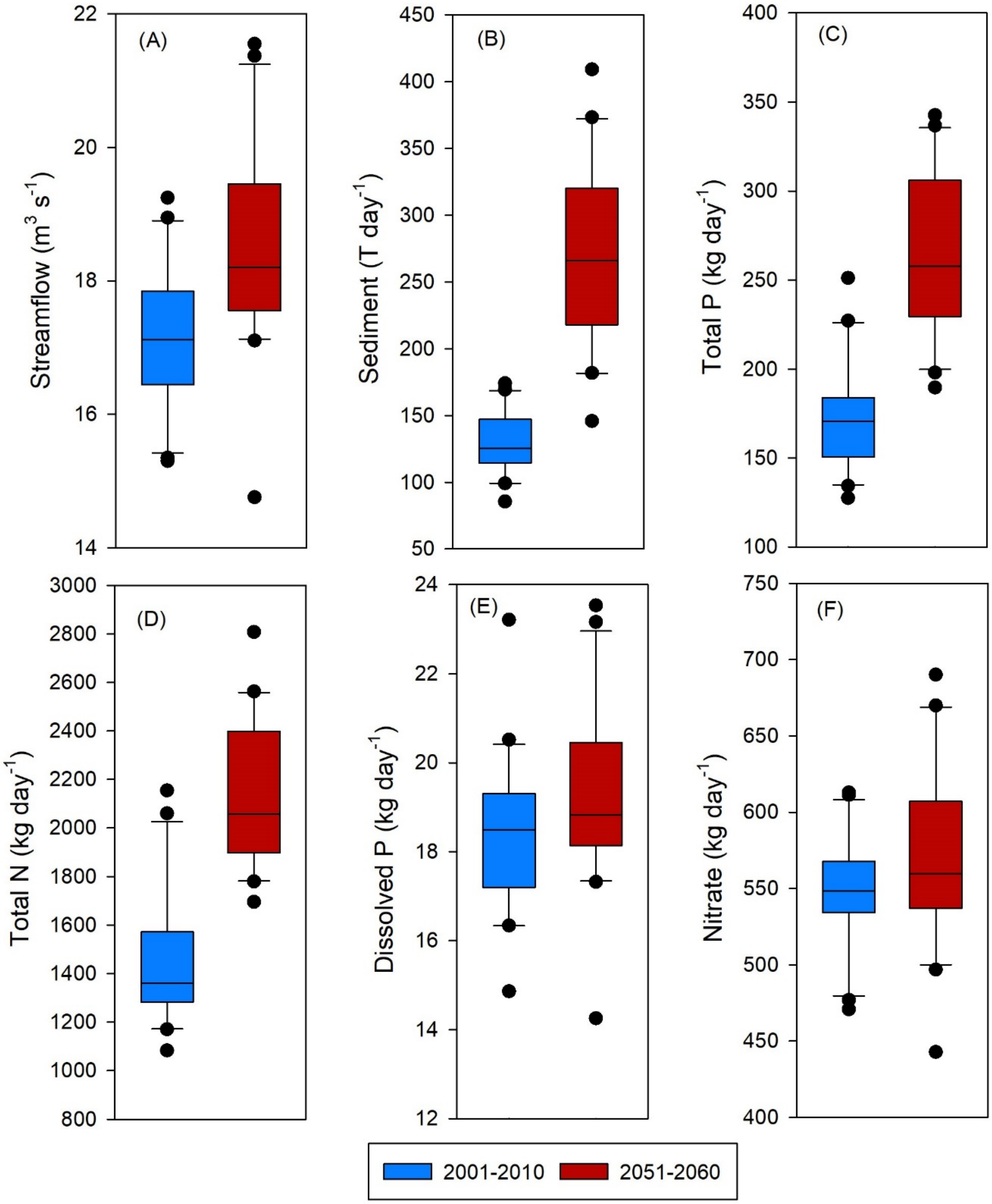


Figure 6.6. Simulated average annual streamflow, suspended sediment and nutrient loading under historical and future scenarios using 20 GCMs for the RCP 8.5 emission scenario.

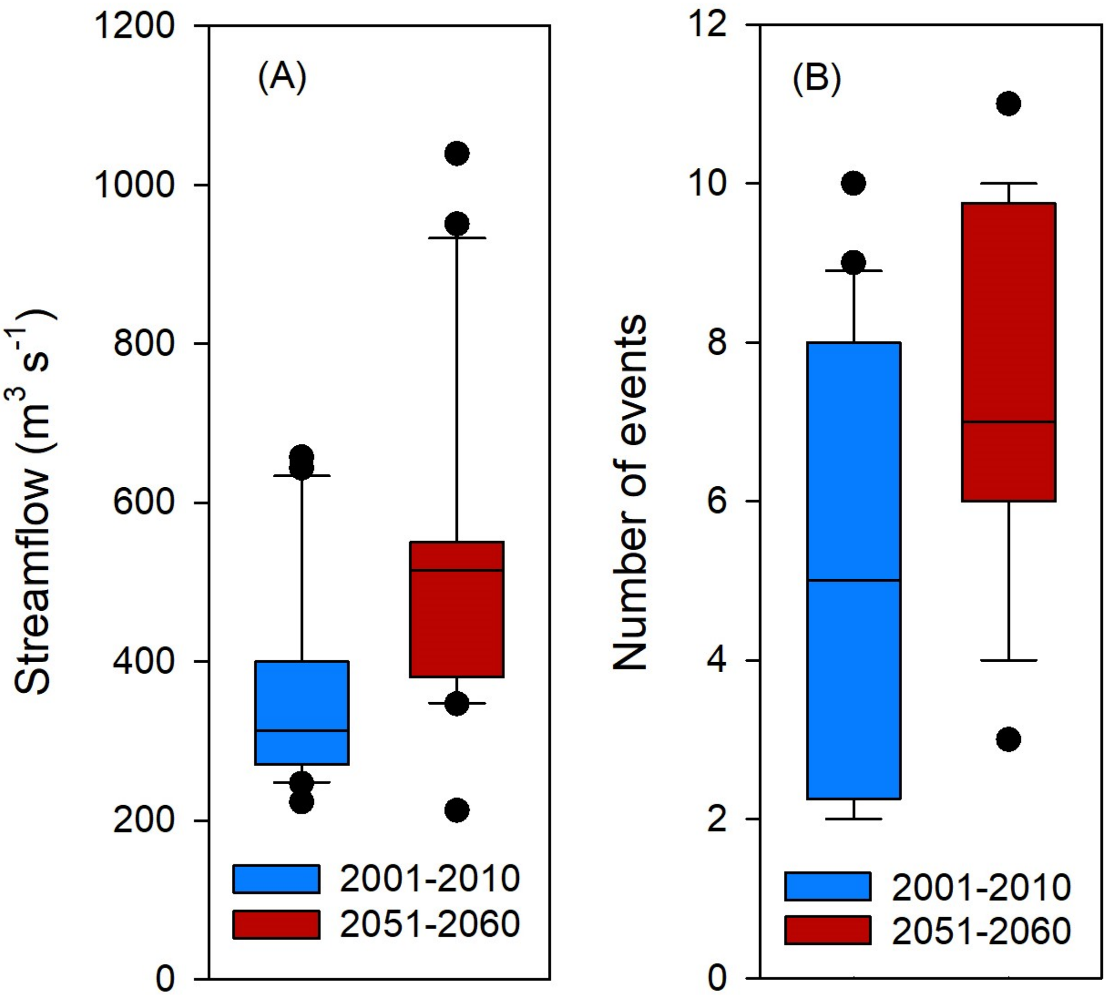


Figure 6.7. (a) Simulated magnitude of largest event in a 10-year period by each of the 20 GCM for the RCP 8.5 emission scenario (b) Projected change in frequency of events when streamflow exceeds 200 $m^3 s^{-1}$ at the West Branch Delaware River at Walton USGS flow station.

SWAT-HS simulations using future climate from 20 GCMs indicated that average annual loading of dissolved forms of nutrients (N and P) will have no change or a moderate increase under future climate. The change in average annual dissolved P loading is between -21% to +35% with a mean and median change of +5.2% and +2.4% respectively. Average annual nitrate loading is projected to change between -19% to +42% with a mean and median change of 4.8% and 2.4% respectively. In contrast, loading of particulate forms of nutrients and sediment are projected to increase due to an increase in the magnitude (Figure 6.7a) and frequency (Figure

6.7b) of large storm events that transport a disproportionate amount of nutrients associated with sediments into the streams. A combination of changes in the frequency and magnitude of large events is predicted to increase the average annual sediment loading by over 100% and total nutrient loading to increase N by 50% and P by 56%. Although large events have occurred in the past (June 2006, August-September 2011), a long-term impact on reservoir water quality due to excess nutrients from these events has not occurred. In the case of P, the observed decreasing trend in soil P values over the past 20 years (Dewing, personal communication) in several farms in the watershed is promising. Reduction in P input due to changes in management practices over the years is expected to result in a long-term watershed response that attenuates the contribution of P in runoff. A shift in the timing of peak spring runoff towards earlier in the year due to warming winter temperatures, greater proportion of precipitation falling as rain, and earlier melting of snowpack may also shift the seasonal pattern of nutrient loading. Use of a large number of GCMs in climate change impact assessment studies capture a wide range of possible future climates given the model uncertainty, particularly in the amount of precipitation estimated. Additional details of this study can be found in Mukundan et al. 2020.

A summary of this study is as follows (1) the SWAT-HS model estimated contributions of point and nonpoint sources of N, (2) model simulations indicate significant terrestrial storage of N in the watershed, (3) future scenarios indicate moderate increase to no change in dissolved nutrients loading, and (4) total nutrient loadings are influenced by large storm events.

6.6. Streamflow Simulation in West of Hudson Watersheds using SWAT-HS

SWAT-hillslope (SWAT-HS) is a modified version of the Soil and Water Assessment Tool (SWAT) for simulating variable source area (VSA) hydrology in mountainous regions with humid climate. This model gives a better estimation of surface runoff and the ability to predict the location of saturated areas, both of which are key elements in transferring substances from upland areas to the valley bottom and eventually to the receiving waterbody. We first applied and tested SWAT-HS model for a small (~37 km^2) headwater watershed of Town Brook in the Catskill Mountains, which showed its ability in predicting streamflow and saturated-excess runoff with reasonable accuracy when compared to field observations (Hoang et al., 2017). Later, we scale-up the application of the model to Cannonsville watershed, which is a larger watershed encompassing Town Brook, to evaluate the model performance in predicting soluble P (total dissolved P), particulate P, and sediment (total suspended solids). The result of this analysis also showed acceptable performance of the model in water quality simulations (Hoang et al., 2019).

Having tested and validated the performance of SWAT-HS model, we have applied the model to all six West of Hudson (WOH) watersheds. In this section, we report on the model set up and calibration for streamflow at the major inflow location of each reservoir watershed, and model performance evaluations for the simulation period of 2001 to 2018.

6.6.1. SWAT-HS Model Setup for West of Hudson Watersheds

The SWAT-HS model was set up separately for each watershed. The input layers necessary for model set up include a digital elevation model (DEM), soil map, wetness map, land use map, and the location of watershed outlet where the river enters the reservoir. Overlaying these layers makes watershed delineation and hydrologic response unit (HRU) discretization possible. HRU is the smallest simulated unit in SWAT-HS, which is determined using a unique combination of land use, soil type, and wetness class. The physical properties of each HRU is determined based on their spatial location in the watershed.

The land use map of each watershed was derived from classified 2009 aerial photography data obtained from New York City Department of Environmental Protection (NYCDEP). The land use and land cover classifications of this map were simplified and adjusted based on the standardized classification provided in the SWAT-HS model specifications. The main classifications are three types of forests: coniferous, deciduous, mixed forests; agricultural land, rangeland, pastures, urban areas, wetlands, water, and septic systems. Other inputs to SWAT-HS are soil and wetness class maps, which have to be combined before they are used in the model. A wetness class map is a conceptual map dividing the watershed based on increasing soil-water-storage capacity, from downslope to upslope regions and the likelihood of getting saturated. This specification of hillslope improves the simulation of lateral and surface runoff from upslope ("drier" wetness classes) to downslope ("wetter" wetness classes). Topographic index (TI) is the technique used to delineate wetness classes. TI is derived from the fraction of upslope contributing area per unit contour length, and the local surface topographic slope, both calculated using a 10-meter DEM of the watersheds. Each watershed was classified into 10 wetness classes, which were then combined with the soil map. The WOH soil map was extracted from the Soil Survey Geographic (SSURGO) database (USDA-NRCS, 2012). The soil map was overlaid with the wetness class map and sub-basin map to create a new soil map with the dominant soil for each wetness class within a sub-basin of each watershed.

For the purpose of model calibration and validation, the USGS gaging stations at the main tributary of each watershed nearest to its reservoir was used (Figure 6.8). The stations considered are located on Esopus Creek at Cold Brook, Schoharie Creek at Prattsville, West Branch Delaware River at Walton, East Branch Delaware River at Margaretville, Neversink River near Claryville, and Rondout Creek near Lowes Corners. These stations have long-term records of daily discharge measurements, which is the time step required for SWAT-HS model.

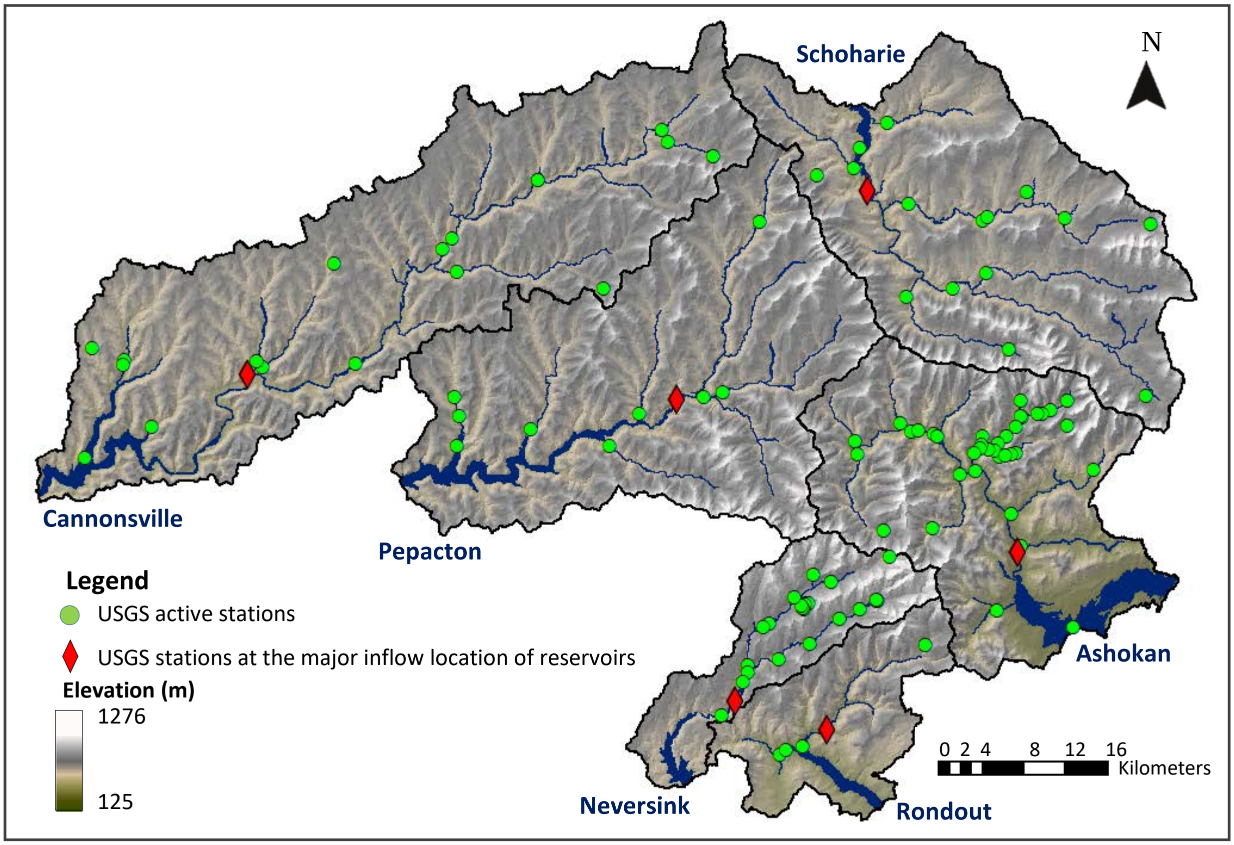


Figure 6.8 USGS station location at West of Hudson watersheds.

Combining the input maps described, a SWAT-HS model with multiple sub-basins (Ashokan - 10 sub-basins; Cannonsville - 12 sub-basins; Neversink – 3 sub-basins; Pepacton – 5 sub-basins; Rondout – 5 sub-basins; Schoharie – 12 sub-basins), and each sub-basin divided into multiple HRUs (Ashokan - 400 HRUs; Cannonsville – 1326 HRUs; Neversink - 291 HRUs; Pepacton - 499 HRUs; Rondout - 393 HRUs; Schoharie - 700 HRUs) were created separately for each watershed. Daily precipitation, minimum and maximum air temperature, solar radiation, and relative humidity data, available in a 4-by-4-kilometer gridded format, were used to drive the model.

6.6.2. Model Calibration, Uncertainty Analysis, and Evaluation of Model Performance

The sequential uncertainty fitting (SUFI-2) algorithm in the SWAT-CUP (Calibration and Uncertainty Programs) calibration software (Abbaspour, 2013), was used to calibrate simulated streamflow to USGS observations, and to do uncertainty analysis. The calibration and validation periods are 2001-2010 and 2011-2018, respectively. Fifteen parameters related to processes including snowmelt, surface runoff, lateral flow, groundwater contribution, and evapotranspiration as described in Hoang et al. (2017), were calibrated by conducting two to three iterations of 2,000 simulations each. A parameter set for each simulation was generated using a Latin hypercube sampling procedure which reduces the number of simulations required for calibration compared to a random sampling procedure. The suggested parameter range from each iteration was used for subsequent iterations resulting in a narrow range in parameter values and predictive uncertainty. Parameter range used in the final iteration of the calibration period was used for a single iteration with 2,000 simulations for the validation period. For each watershed, the best parameter set based on Nash-Sutcliffe efficiency (NSE) as the objective function was chosen as the final parameter set. Model performance using the best parameter set was evaluated using standard metrics including coefficient of determination (R^2), NSE, percent bias (PBIAS), and Kling Gupta Efficiency (KGE). The R^2 that describes the collinearity between simulated and measured data ranges from 0 to 1 with higher values indicating less error variance. The NSE (Nash and Sutcliffe, 1970) indicates how well the plot of observed versus simulated data fits the 1:1 line. Values of NSE ranging from 0 to 1 are considered acceptable with higher values indicating better model performance. The PBIAS measures the average tendency of the simulated values to be larger or smaller than the observed values. Positive values indicate model underestimation, and negative values indicate model overestimation (Gupta et al., 1999). The KGE (Gupta et al. 2009) which is less sensitive to high values provides a better estimate of model predictions at all ranges of flows (a value of 1 indicates perfect model fit). In addition to the best parameter set, a number of behavioral parameter sets were identified based on a threshold (NSE > 0.65), to determine the uncertainty in streamflow prediction originating from various sources including input parameters, driving variables, and measured data. The threshold value was lowered if no simulations were found to give NSE value above the specified threshold. Uncertainties in the parameter values result in model output uncertainties which are quantified by the 95% prediction uncertainty (95PPU) and the p- and r-factors. The fraction of the measured data bracketed by the 95PPU is indicated by the p-factor. The r-factor is the ratio of the average width of the 95PPU band and the standard deviation of the measured data. A p-factor of one and r-factor of zero indicates perfect fit between measured and simulated data (Abbaspour, 2013). Table 6.5 presents the model performance measures for daily simulations.

Table 6.5 Model performance statistics for daily average streamflow.

			Ashokan	Cannonsville	Neversink	Pepacton	Rondout	Schoharie
Daily Simulations	Calibration Period (2001-2010)	*NSE*	0.72	0.79	0.69	0.75	0.7	0.74
		R2	0.72	0.79	0.69	0.75	0.7	0.74
		PBIAS	5.4	0.8	0.5	-6.4	5.5	-8.3
		KGE	0.79	0.85	0.79	0.81	0.77	0.77
		p-factor	0.78	0.74	0.72	0.67	0.71	0.77
		r-factor	0.33	0.67	0.31	0.35	0.32	0.38
	Validation Period (2011-2018)	*NSE*	0.79	0.79	0.63	0.64	0.75	0.65
		R2	0.79	0.79	0.63	0.65	0.75	0.66
		PBIAS	5.5	1	1.5	-5.3	8.5	2.8
		KGE	0.86	0.78	0.76	0.71	0.79	0.77
		p-factor	0.71	0.81	0.6	0.66	0.69	0.73
		r-factor	0.36	0.73	0.25	0.3	0.38	0.26

Overall, statistical evaluation of the SWAT-HS model for daily streamflow showed "good" performance (based on Moriasi et al. 2007 model evaluation criteria) as results show NSE, R^2, and KGE values exceed 0.7 in 16 of 18 cases for the calibration period, and in 12 of 18 cases for the validation period. In addition, PBIAS values in most cases are less than ±6 across all watersheds. Measures of uncertainty (p-factor closer to 1 and r-factor less than 1) also indicate the overall acceptable performance of SWAT-HS in streamflow simulations. Figure 6.9 and Figure 6.10 show the monthly time series and monthly variation of both simulated and observed average monthly streamflow values, along with uncertainty bands.

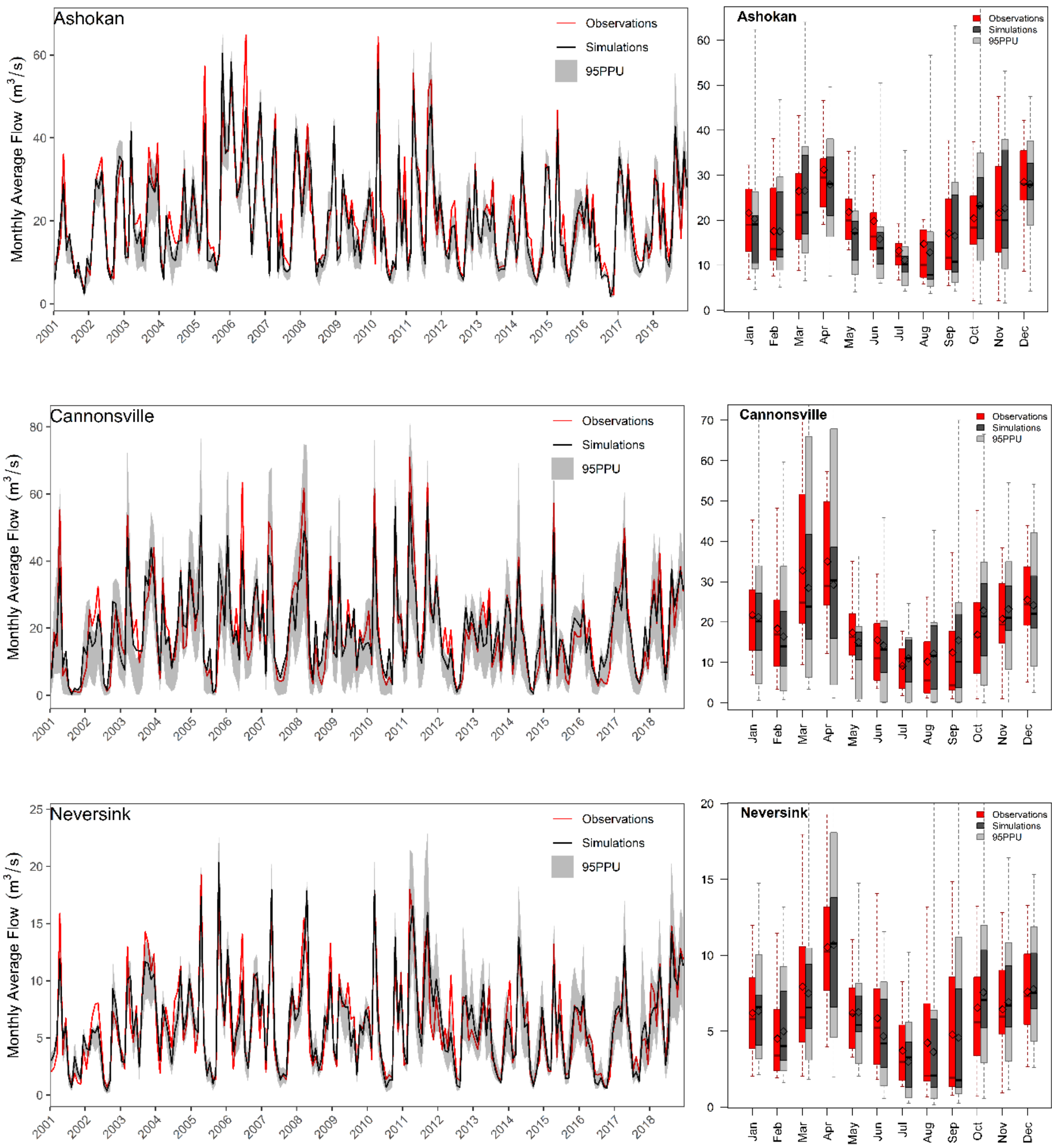


Figure 6.9. Observed simulated monthly discharge time series and boxplots for Ashokan, Cannonsville and Neversink watersheds (95PPU is the 95% prediction uncertainty; the diamonds in boxplots are mean values).

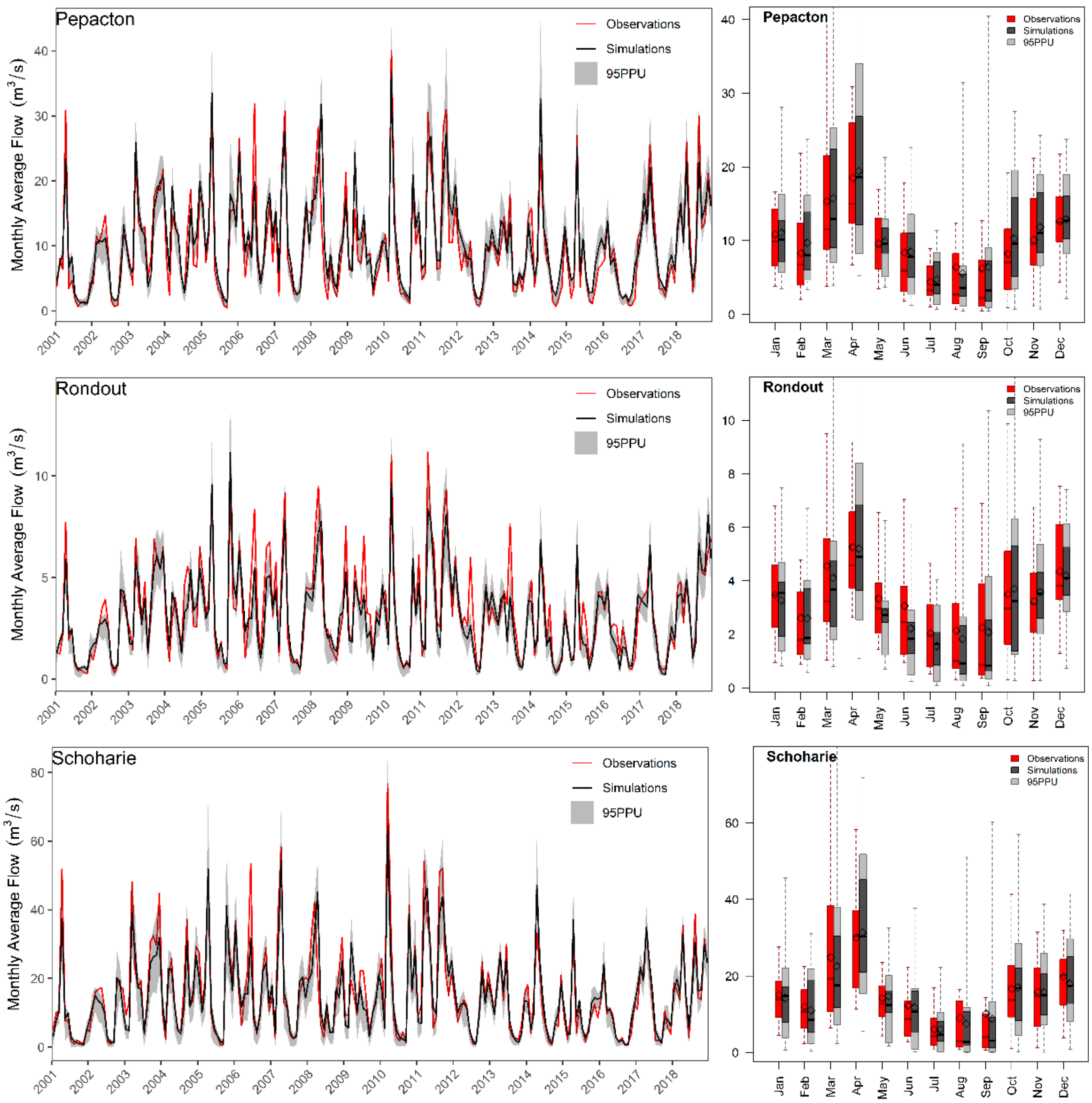


Figure 6.10. Observed simulated monthly discharge time series and boxplots for Pepacton, Rondout, and Schoharie watersheds (95PPU is the 95% prediction uncertainty; the diamonds in boxplots are mean values).

Having achieved acceptable model performance in predicting streamflow in WOH watersheds, the hydrologic component of the model is suitable for water quality simulations, evaluation of watershed protection programs, and climate change impacts. Analysis on the field evaluation of spatial location of saturated areas would strengthen and further validate the wider model application.

6.7. Assessment of Climate Change Impacts on Water Supply System Using the Operations Support Tool (OST)

Drinking water quality impacts of climate change were assessed using mathematical models. Models for global climate, watershed hydrology and water quality, receiving waterbodies, and system operations were linked and simulations were conducted for an array of future climate scenarios. This approach is illustrated in Figure 6.11 for the New York City water supply system. DEP developed GCM-scenario combinations using output from 20 GCMs and two RCP scenarios (RCP 4.5 and RCP 8.5; total = 20 × 2 = 40) for Catskill and Delaware watersheds centroids and reservoirs, and the terminal Kensico Reservoir locations (Gelda et al. 2019).

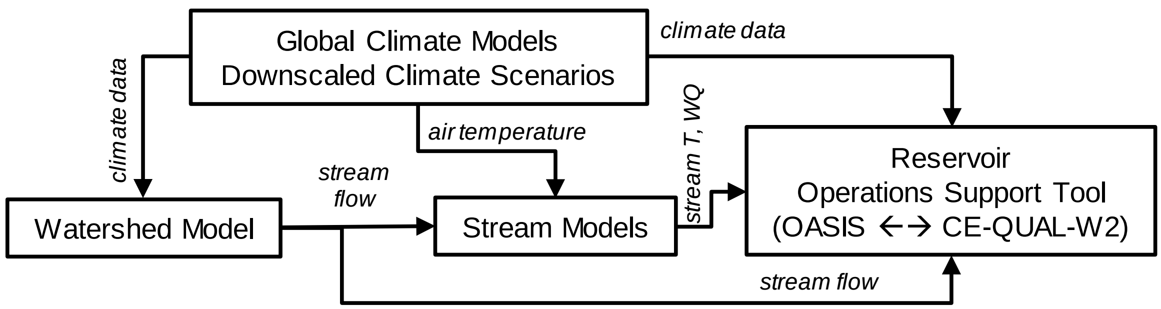


Figure 6.11. System of models for assessing impact of climate change on NYC's water supply system. Stream T, WQ refers to stream temperature and water quality; OASIS and CE-QUAL-W2 are reservoir operations and reservoir water quality models, respectively.

The temperature and precipitation changes as projected according to the 20 GCMs and two climate scenarios for Ashokan Reservoir watershed are presented in Figure 6.12. All projections indicate warmer climate while six projections indicate decrease in precipitation by up to 5% and in one projection by 10%, for 2041-2060 as compared to for 2001-2020 interval. Typical magnitude of increases in annual average daily temperature and precipitation are 2 degrees Celsius and 5%, respectively for all NYC watersheds.

Multi-model ensemble average values of snowfall and snowpack indicate decreasing trend in both metrics. From the baseline conditions of 2001-2020 to future conditions of 2041-2060, annual snowfall is projected to decrease by 25% and annual snowpack (by March 15) is projected to decrease by 54% in the watersheds, with potential to decrease further in late century. Decrease in snowfall is a direct result of warmer temperatures causing more of the precipitation to fall as rain and melting of snowpack earlier in the year. These changes in snowpack accumulation and melt manifest into increased streamflow during December through mid-March, and decreased streamflow during mid-March-April. December to mid-March streamflow in Esopus Creek at Coldbrook is 27% higher for 2041-2060 than for 2001-2020, while mid-March-April flow is 14% lower. Average summertime low flow is largely unchanged and annually, streamflow is greater by 6%. Mukundan et al. (2019) present further analyses on impact of climate change on streamflow in the streams of the NYC WOH watershed.

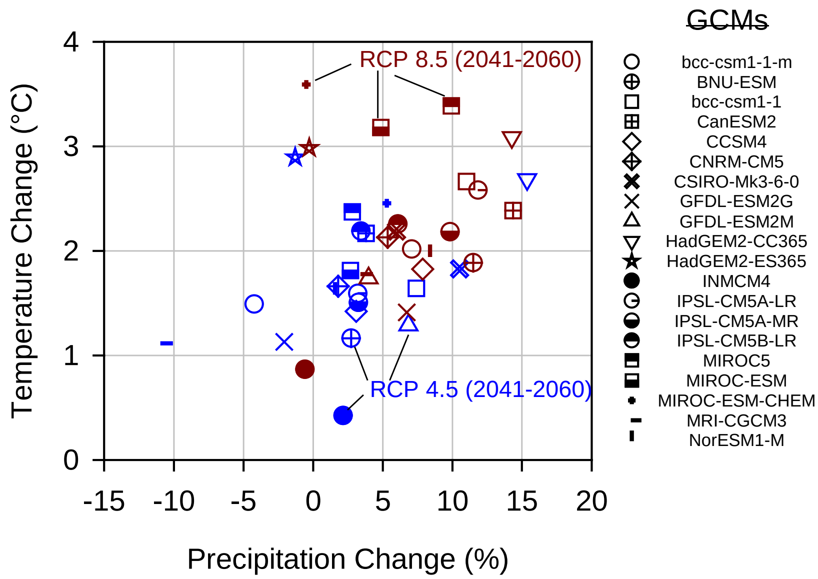


Figure 6.12 Change in annual average temperature (°C) and precipitation (%) from 2001-2020 to 2041-2060 under climate scenarios of RCP 4.5 and RCP 8.5 for Ashokan Reservoir watershed, as projected by 20 GCMs.

Annual changes in inflow, release, spill, diversion, and storage components of the water balance for the Delaware and Catskill systems of reservoirs are presented in Table 6.6.

Table 6.6. Annual average and percent change in components of reservoir water budget from baseline (2001-2020) to future (2041-2060) conditions using climate projections from an ensemble of 20 GCMs under climate scenario of RCP 8.5.

	Delaware System			Catskill System		
	Baseline	Future	% Change	Baseline	Future	% Change
Inflow ($m^3\ s^{-1}$)	52.68	55.68	6	31.44	33.43	6
Release ($m^3\ s^{-1}$)	23.51	24.28	3	3.09	4.00	30
Spill ($m^3\ s^{-1}$)	3.82	3.53	-8	11.15	12.52	12
Diversion ($m^3\ s^{-1}$)	24.12	26.40	9	16.39	15.94	-3
Storage ($10^9\ m^3$)	1.03	1.05	1	0.453	0.460	2

$10^9\ m^3$ = 264.17 billion gallons; 1 $m^3\ s^{-1}$ = 22.8245 million gallons per day

Notable differences between the current and future operations on an annual basis are reduced diversion from Catskill System (–3%) and increased use of Ashokan Release Channel (+30%) to release water from the West Basin (Table 6.6). Reduced diversion from Catskill System is due to increase in turbidity in the future. In response to a warming climate, stream temperatures are projected to rise by about 1.4 degrees Celsius on average in the WOH watershed for 2041-2060. The combined effect of warmer streams and warmer air temperature will be increased in-reservoir and diversion temperatures. Monthly average temperatures of the diversion from Schoharie Reservoir via Shandaken Tunnel is expected to rise by 1 degrees Celsius. We have not yet evaluated the impact of warmer discharges from Shandaken Tunnel on the health of ecosystem of Esopus Creek, particularly habitat for coldwater fishery.

Computed turbidity values for the baseline and future periods from 20 GCMs were analyzed to discern changes in frequency and magnitude of extreme events. Daily turbidities in excess of 100 NTU are slightly more likely to occur for the future conditions than for the baseline conditions in Rondout, Schoharie, and Esopus creeks (Table 6.7). Furthermore, extreme turbidity levels, such as 99.9th percentile (corresponding to approximately once every 33 years) will likely increase by varying magnitudes (typically 50%) in all WOH watersheds, with the possibility of a decrease in Rondout Creek during January-February.

Table 6.7. Recurrence interval (years) of selected threshold levels of turbidities in three tributaries for baseline (2001-2020) and future (2041-2060) conditions using climate projections from an ensemble of 20 GCMs under climate scenario of RCP 8.5.

Turbidity Level	Rondout Creek		Schoharie Creek		Esopus Creek	
(NTU)	Baseline	Future	Baseline	Future	Baseline	Future
50	1.4	1.2	0.2	0.2	0.2	0.1
100	5.3	2.8	0.6	0.5	0.4	0.3
200	13.8	8.4	1.6	1.2	1.0	0.7
500	44.4	28.2	5.3	4.0	3.7	2.5
1000	80.0	131.7	15.4	10.4	9.1	6.8

Impact on Reservoir Diversion Water Quality: Assessment of turbidity in the diversion waters under future conditions not only reflect the impact of climate but also the impact of dynamically adapting reservoir operations to those changing conditions. Results from the linked reservoir operations and water quality model runs within OST indicate that there may be modestly higher frequency of exceedances of selected turbidity levels, though none of these reach a level of concern (Figure 6.13). For example, Rondout Reservoir diversion turbidity may exceed 2 NTU 43 days y^{-1} in the future as compared to 30 days y^{-1} under the current baseline conditions, and 5 NTU 4 days y^{-1} from 3 days y^{-1}. Turbidity in the diversion from Kensico Reservoir is simulated to exceed 5 NTU 1 day y^{-1} for both the current and future climate conditions suggesting that updating of operating rules will be required in OST as, other than instances caused by short, localized events, 5 NTU has never been exceeded during actual historical operations in the baseline period.

System Performance Indicators: The NYC water supply system is a within-year system meaning that it refills each year, in contrast to over-year systems which contain multi-year drawdown periods and are seldom full. The current study found an average standardized net inflow index (Vogel 1999) m = 2.4 (range 1.6 – 3.6) for the future climate as compared to m = 2.3 (range 1.5 – 3.4) for the current climate, signifying that the NYC system remains a within-year system and that is consistent with the 6% increase in average inflow. The probability of the system delivering its stated yield in a year following failure, designated r, remained very high (median r = 0.98; Figure 6.14a). The steady-state probability of delivering its yield without failure in a giver year, designated Ra, was also very high (median Ra = 0.993; Figure 6.14b). Vulnerability remained substantially less than unity, suggesting that the system will always recover within a year (Figure 6.14c).

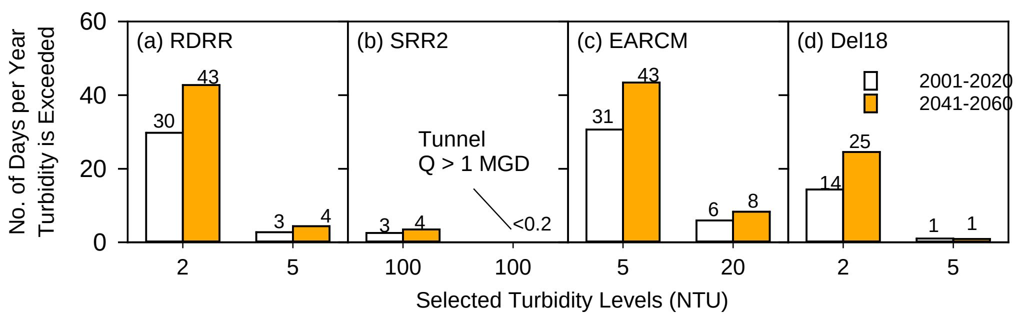


Figure 6.13 Predicted number of days per year when turbidity is exceeded by specific levels at (a) Rondout Reservoir diversion, RDRRCM, (b) Schoharie Reservoir diversion, SRR2CM, (c) Ashokan Reservoir diversion, EARCM, and (d) Kensico Reservoir diversion, DEL18DT, for the baseline (2001-2020) and future (2041-2060) climate scenarios (20 GCMs; RCP 8.5).

Average number of days when the water supply system is under watch, warning or emergency drought conditions remain generally unchanged for the future conditions (8–10 days per year; Figure 6.14d). However, the variability resulting from different scenarios is reduced for the future conditions is likely due to increased inflow and absence of any prolonged multi-year dry periods in the future. An important water quality metric for the NYC system is the use of alum to reduce turbidity. On average, alum may be required for < 2 days/year (range 0–8 days/year) under all, baseline and future, climate scenarios investigated here (Figure 6.14e). Overall, all future climate scenarios continue to project high resiliency, reliability, and low vulnerability of the system with minimal impact on water quality.

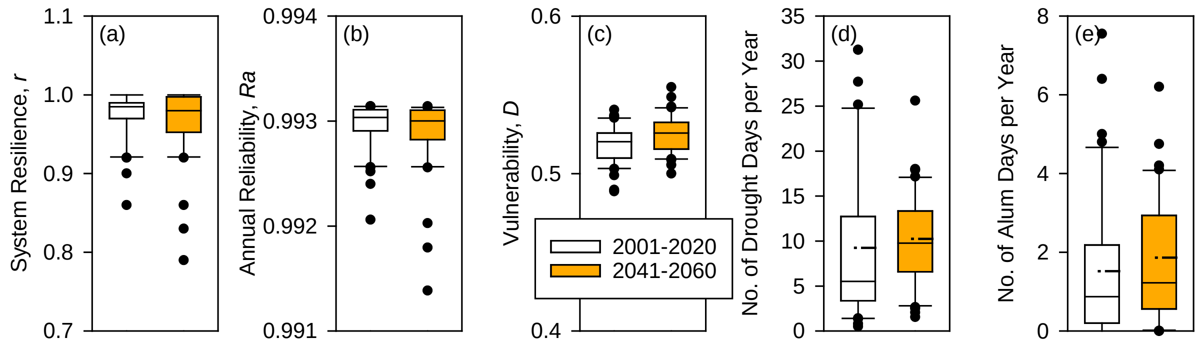


Figure 6.14. Performance indices of NYC water supply system for the baseline (2001-2020) and future (2041-2060) climate scenarios (20 GCMs; RCP 4.5 and RCP 8.5 combined): (a) system resilience, (b) annual reliability, (c) vulnerability, (d) drought days, and (e) alum addition days.

6.8. Operations Support Tool (OST)

6.8.1. OST Database Extension

During 2019, as recommended by OST Expert Panel (NASEM 2018), the meteorological data set underlying OST was extended up to 2018 to include recent climate change and associated hydrologic conditions. This resulted in an additional 20 traces, bringing the total to 68 traces for a typical position analysis run. Hourly meteorological data from the National Weather Service (NWS) locations in the region were adjusted to reflect conditions at the reservoir locations according to regression coefficients previously developed and presented here in Table 6.8. Models for Ashokan and Kensico reservoirs worked best with the unadjusted data. Further, solar radiation data was kept as derived from the cloud cover observed at the NWS sites as no reliable relationships could be developed with the observations at the reservoir locations.

Table 6.8. Multipliers to adjust meteorological data from NWS airport sites to reservoir locations.

Reservoir	NWS Airport Site	Multiplier				
		Air Temp.	Dewpoint	Solar Radiation	Wind X-component	Wind Y-component
Cannonsville	Binghamton	0.959	1.01	1	0.774	-0.072
Pepacton	Binghamton	0.958	0.999	1	0.482	-0.035
Neversink	Binghamton	0.965	0.995	1	0.779	0.53
Rondout	Binghamton	1	1.04	1	1.106	0.456
Schoharie	Albany	0.9207	0.9528	1	0.631	0.631
Ashokan	Albany	1	1	1	1	1
Kensico	White Plains	1	1	1	1	1

6.8.2. Global Ensemble Forecast System Weather Data Verification

The Modeling Section also began to explore and verify the forecasts of weather variables (minimum and maximum temperatures, and precipitation) provided by Global Ensemble Forecast System (GEFS) of NOAA. The GEFS forecast consist of 11 equal-probability members of an ensemble at a 3-hour interval for days 1-8 and half degree spatial resolution, and at a 4-hour interval for days 8-16 at two-thirds degree spatial resolution. One common approach of ensemble verification is the uniformity of a rank histogram. Figure 6.15 shows an example of verification of predictions of daily maximum temperature in the format of a rank histogram at the Schoharie Reservoir site. The ensemble members produce a U-shaped rank histogram indicating that the observations are too frequently outliers among the collection of 12 (11 ensemble members predictions + 1 observation) values. In other words, there is systematic under or over prediction bias in the forecasts. Similar bias was present at other sites in the watershed and for other weather variables. In the future, the group plans to develop bias correction procedures for these forecasts.

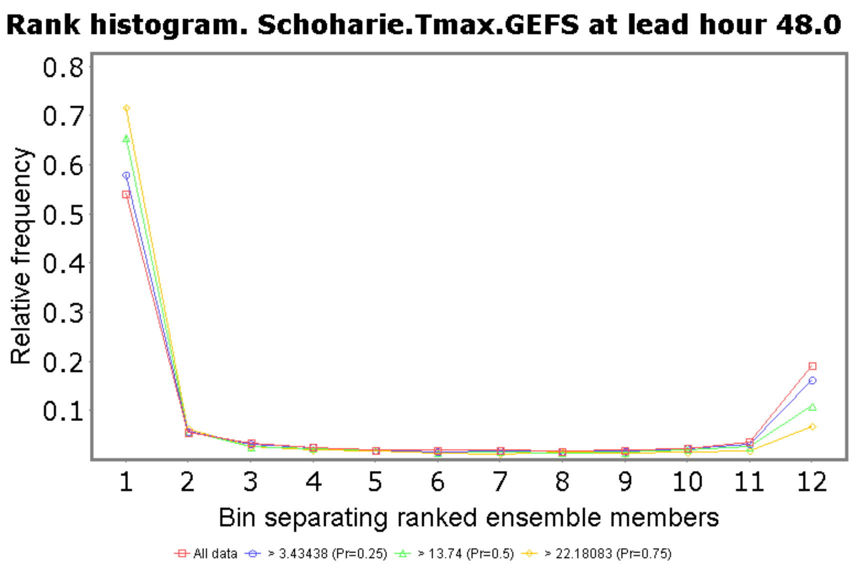


Figure 6.15. Verification rank histogram for ensemble of 11 GEFS forecasts of daily maximum temperature at lead hour 48 for Schoharie Reservoir site. The GEFS forecasts are for 1984-2018 and the corresponding observations are obtained from PRISM gridded data set.

6.9. Pepacton Reservoir Turbidity Model

Development and testing of a turbidity model for Pepacton Reservoir is currently ongoing. The model adopted, CE-QUAL-W2 (W2), is a two-dimensional hydrothermal and water quality model developed by the U.S. Army Corps of Engineers. The turbidity model included in W2 for the Pepacton Reservoir model is the same as previously tested turbidity models for Schoharie, Ashokan, Kensico, Rondout, and Neversink reservoirs. Model testing (calibration-validation) is being performed for 1996-2018, the period of most complete available data; however, an extended period of application of the model may also include 1987-1995. Plans call for this model to be integrated into OST in the future.

A proposed model setup is depicted in Figure 6.16. The USGS gage for the primary tributary of the reservoir, East Branch Delaware River at Margaretville, NY, captures runoff from 45% of the watershed. The three other USGS gaged tributaries are Mill Brook, Tremper Kill, and Platte Kill, draining a combined area of 26% of the watershed. The rest of the watershed area (29%) is ungaged. Outflow from the reservoir occurs via an aqueduct (Pepacton Tunnel) that discharges into Rondout Reservoir, through release works (located in the dam) for the purposes of conservation and directed releases to lower Delaware River, and over the spillway also into the lower Delaware River. Inflow turbidity is ≤ 4 NTU 75% of the times in all sources though occasionally it exceeds 100 NTU during extreme runoff events. Outflow turbidity rarely exceeds 3 NTU (< 10% of the times). This modeling work is expected to be completed in 2020.

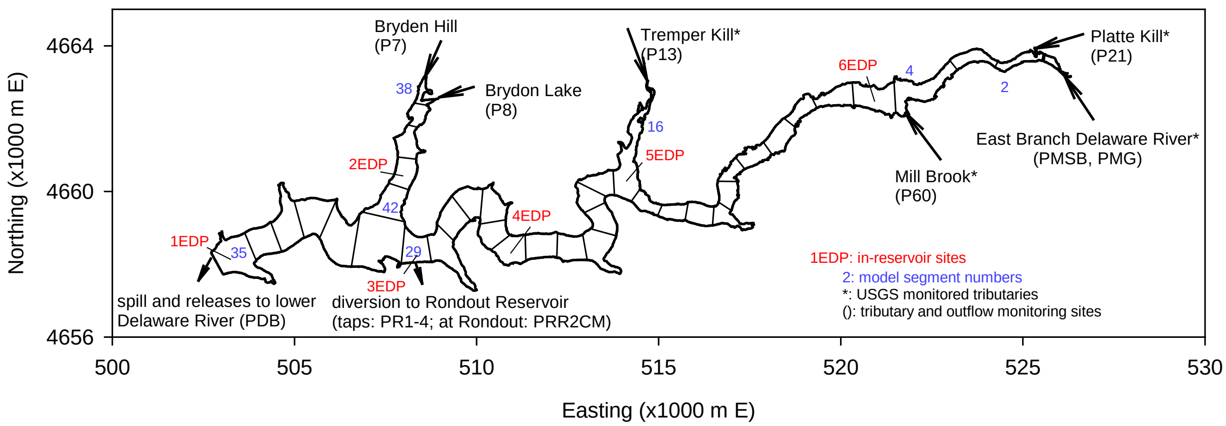


Figure 6.16 Pepacton Reservoir: Inflows, outflows, in-stream and in-reservoir routine water quality monitoring locations, and w2 model segments. Selected model segments are also numbered according to the numbering scheme of w2.

6.10. Testing of GLM-AED for Cannonsville Reservoir

The General Lake Model (GLM), a one-dimensional (vertical) lake and reservoir hydrothermal model, linked with the Aquatic Eco-Dynamic (AED) water quality model, was applied to Cannonsville Reservoir. GLM has the capability to predict vertical profiles of water temperature, the temperature of reservoir outflows (diversion, release, and spill), vertical water motion due to inflow and outflow occurring at different elevations, and vertical diffusion or mixing in the water column of a lake or reservoir. The water quality model AED can predict vertical profiles of the concentration of water quality constituents, and outflow concentrations. In this study, the cycling of various fractions (such as organic/inorganic, dissolved/particulate) of carbon, phosphorus, nitrogen, dissolved oxygen, and phytoplankton were simulated. Hindcasting simulations for the 21-year period, 1995-2015, were made.

6.10.1. Input Data

Data describing features of the reservoir, streamflow, temperature, water quality of reservoir inflows, the reservoir operation, and meteorology, are required to operate the model for historical periods. Cannonsville Reservoir bathymetry data was obtained from the USGS 2015 bathymetry survey. Daily streamflow for the West Branch Delaware River at Walton, NY (WBDR) and Trout Creek inflows were obtained from the USGS. Daily outflows (diversion, release, and spill) were obtained from DEP operating records. Using a simple water balance calculation, the inflow from the ungaged portion of the watershed was computed. When the ungaged inflow from this calculation is used in the model, the predicted and observed water surface elevation and reservoir storage will agree.

Stream (inflow) temperature was obtained from DEP monitoring. For the 1995-2010 interval, the New York State Department of Environmental Conservation (NYSDEC) operated a stream sampling program on the WBDR which measured the concentration of many of the state variables in the water quality model. For this period, and for the constituents measured by NYSDEC, the data alone was sufficient to compute a daily time series of stream concentrations entering the reservoir. For the remaining constituents, and for 2011-2015 (after the NYSDEC program ceased), the FLUX32 loading calculation software was used to estimate daily concentrations. For meteorology, the observations at the station operated by DEP at the Cannonsville Dam were used, with daily average values computed and used as model inputs for the 21-year simulation period. For the application of AED described here, Table 6.9 lists the state variables, these being the constituents for which individual mass balance calculations were computed by the model. Note that three classes of phytoplankton were used in the simulations.

Calibration of the model was undertaken to determine the value of various model coefficients that best represent the conditions in Cannonsville Reservoir, which was determined by minimizing the difference between model predictions and observations from the water column of the reservoir. Calibration was completed first for GLM, the hydrothermal portion of the model. Coefficients that affect the various surface heat transfer processes and the turbulent mixing in the water column of the reservoir were adjusted to minimize the error in predicted water column temperatures. As an example of the model predictions, predicted and observed temperature profiles for each month during the April-October interval of 2005, are shown in Figure 6.17. Daily predictions for the temperature profile were made for each day during the 21-year simulation period.

Table 6.9. State variables used in the application of GLM-AED to Cannonsville Reservoir.

Group	Individual State Variable
Carbon	Algal carbon
	Dissolved organic carbon
	Particulate organic carbon
Phosphorus	Algal phosphorus
	Soluble reactive phosphorus
	Dissolved organic phosphorus
	Particulate organic phosphorus
Nitrogen	Algal nitrogen
	Ammonia
	Nitrate
	Dissolved organic nitrogen
	Particulate organic nitrogen
Oxygen	Dissolved oxygen
Phytoplankton	Green algae
	Blue green algae
	Diatoms

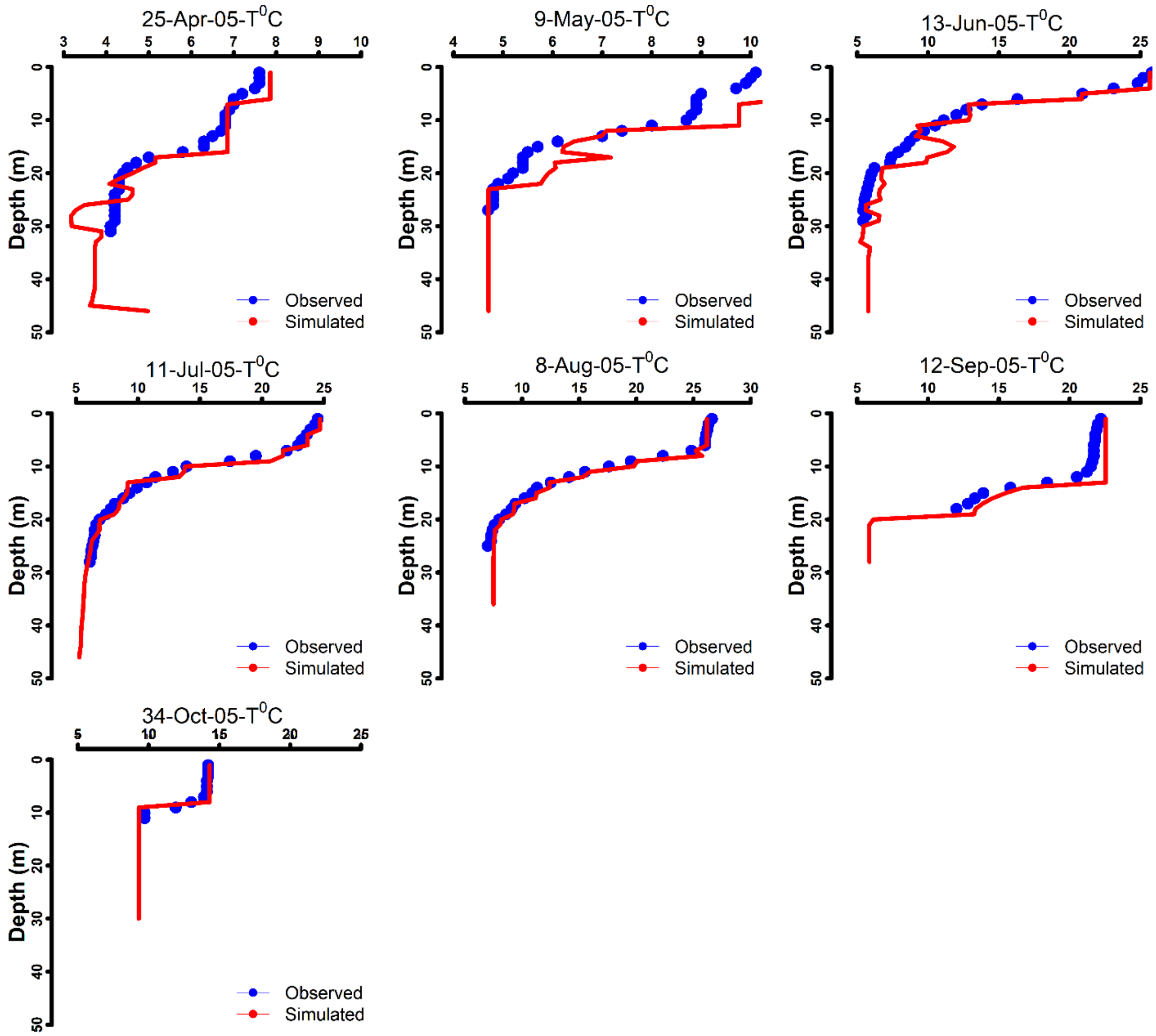


Figure 6.17. Predicted and observed vertical profiles of temperature (°C) in Cannonsville Reservoir, April through October 2005.

Turning to the calibration of the water quality component of the model (AED), model coefficients used in relationships that represent production or loss terms in the various mass balance equations for the state variables (Table 6.9) were adjusted to minimize the difference between predictions and observations in the water column of the reservoir. The model generated predictions of each of the state variables in Table 6.9 for each day of the 21-year simulation period. Example results are shown here in the form of monthly profiles for dissolved oxygen (Figure 6.18), dissolved organic carbon (Figure 6.19), and soluble reactive phosphorus (Figure 6.20) for the April-October interval of 2005. Average error statistics for the mean absolute error (MAE) and root mean square error (RMSE) for each available observation in the water column for the 21-year period are given in

Table 6.10.

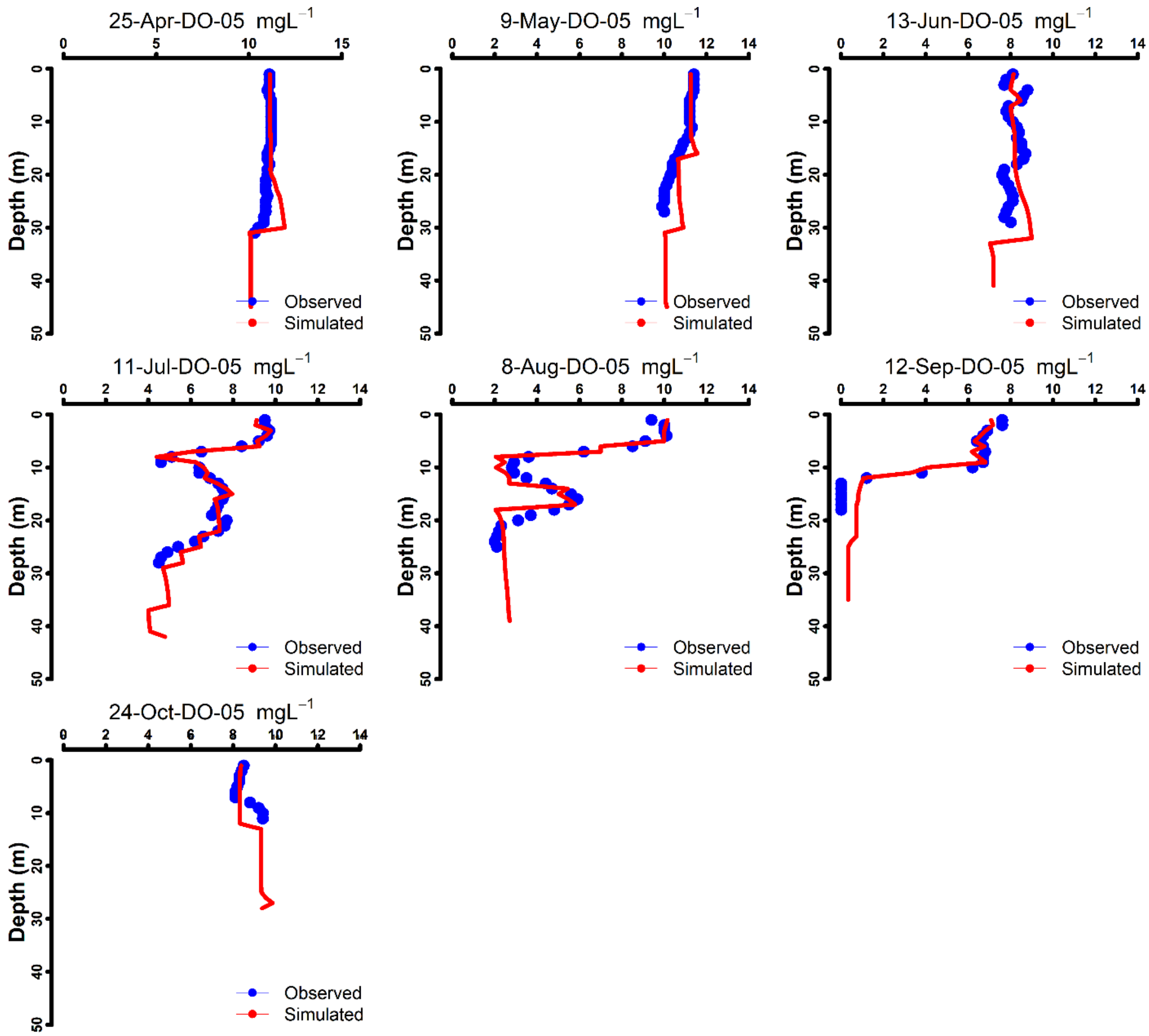


Figure 6.18 Predicted and observed vertical profiles of dissolved oxygen (DO) (mgL^{-1}) in Cannonsville Reservoir, April through October 2005.

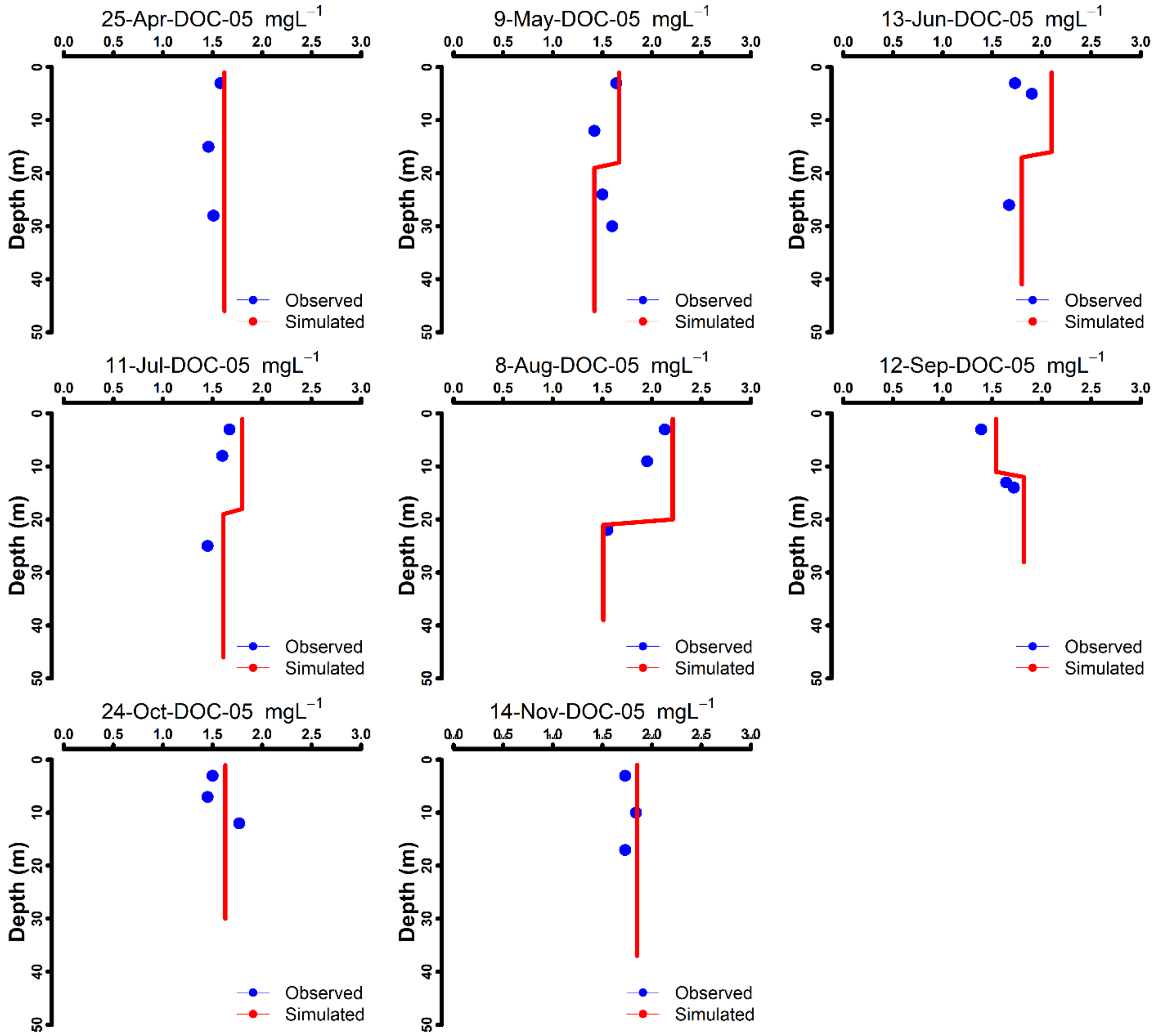


Figure 6.19 Predicted and observed vertical profiles of dissolved organic carbon (DOC) (mgL^{-1}) in Cannonsville Reservoir, April through October 2005.

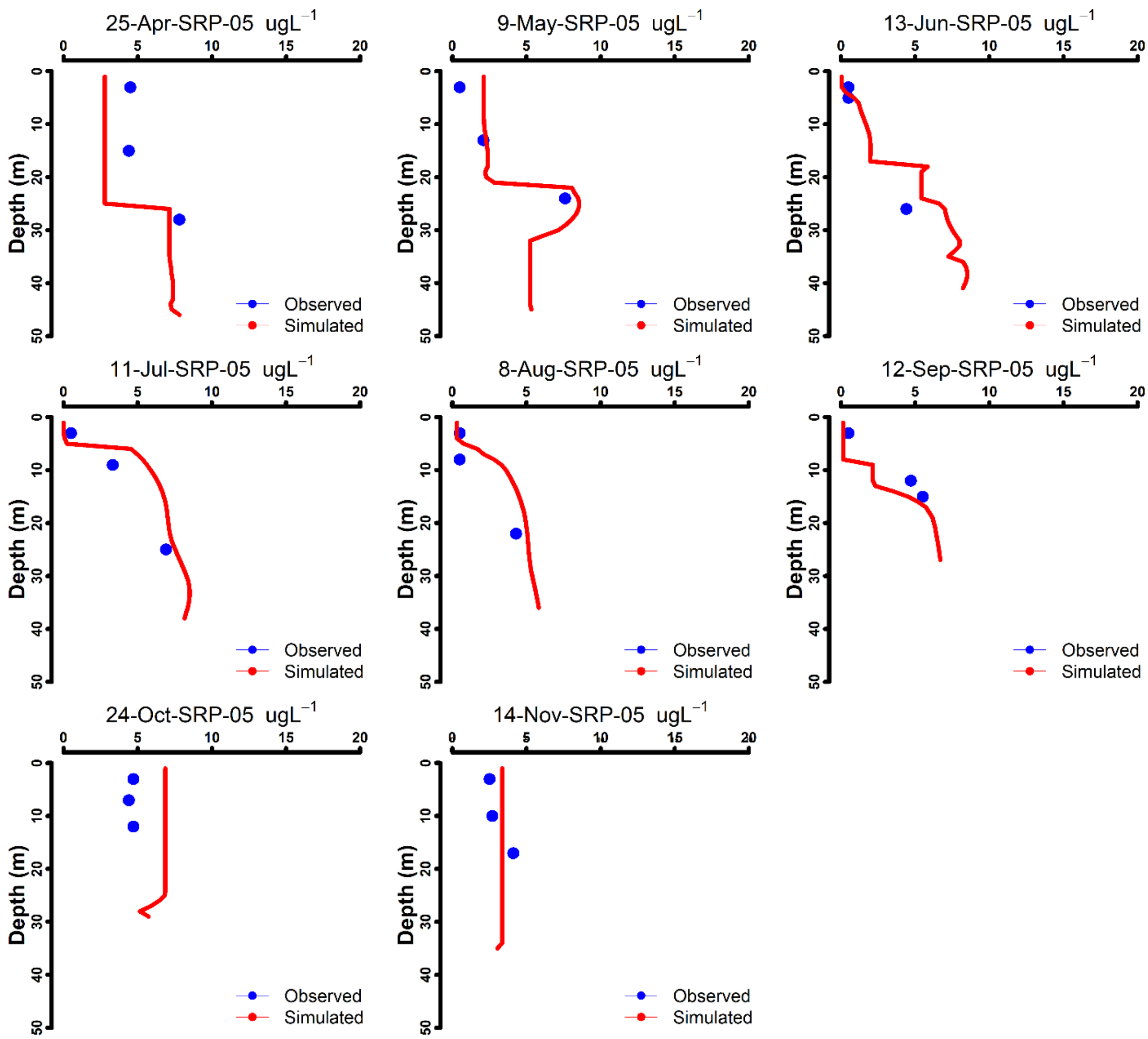


Figure 6.20. Predicted and observed vertical profiles of soluble reactive phosphorus (SRP) (μgL^{-1}) in Cannonsville Reservoir, April through October 2005.

Table 6.10. Average error statistics for the predictions of GLM-AED for Cannonsville Reservoir for the period 1995-2015.

Variable	MAE (mgL^{-1})	RMSE (mgL^{-1})
Ammonium	0.022	0.149
Nitrate	0.15	0.382
Total Nitrogen	0.089	0.294
Soluble Reactive Phosphorus	0.0007	0.027
Total Phosphorus	0.009	0.097
Dissolved Organic Carbon	0.367	0.605
Total Organic Carbon	0.188	0.434
Chlorophyll *a*	0.547	0.739
Dissolved Oxygen	0.194	0.441
Temperature	1.579	1.257

6.11. Development of a Fate and Transport Model for UV_{254} in Cannonsville Reservoir

The development and validation of a model to predict the fate and transport of disinfection byproduct precursors in water supply reservoirs is an ongoing goal of the Water Quality Modeling section. A model to predict the fate and transport of trihalomethane formation potential (THMfp) and haloacetic acid formation potential (HAAfp) is believed to be the best approach to address the disinfection byproduct (DBP) precursor issue in the water supply. As a database for formation potential data from streams, reservoir water columns and keypoints in the Cannonsville and Neversink systems is being assembled, DEP is developing an alternative model to predict levels of an optical proxy or surrogate for formation potential. The optical measurement for which a model is underdevelopment is UV_{254}, the absorption coefficient for ultraviolet light at a wavelength of 254 nm. Such a model is currently under development for a number of reasons including (1) UV_{254} is correlated to formation potential in WOH watersheds, (2) UV_{254} is relatively inexpensive to measure, (3) there is currently a more substantial database of UV_{254} measurements relative to formation potential, and (4) as an optical measurement, UV_{254} observations can be made in situ with minimal maintenance and quickly reported to a server and used together with other information to guide short term operations of the water supply.

The model framework selected is UFILS4, a one-dimensional hydrothermal and water quality model developed by the Upstate Freshwater Institute. UFILS4 has be previously applied and validated for hydrothermal and eutrophication predictions. The hydrothermal simulations of UFILS4 has been validated for Cannonsville Reservoir for 1988-2004 (Owens 1998), while the eutrophication predictions have been validated for 1994-2002 (Doerr et al 1998). The eutrophication component has the ability to simulate cycling of organic carbon (dissolved and particulate), major fractions of phosphorus and nitrogen, dissolved oxygen, and chlorophyll.

UFILS4 has also been applied to simulate THMfp in Cannonsville (Stepczuk et al 1998) and other WOH reservoirs (Effler et al 2005).

This project involves modification of the UFILS4 source code to allow simulation of UV_{254}. The source code is quite flexible and allows addition or deletion of state variables, and modification of the expressions describing internal production or loss in the reservoir water column. Here UV_{254} has been added as a state variable to this model. In the work described here, simulations using this modified model for conditions in Cannonsville Reservoir during 2018 are presented.

UFILS4 was operated for the interval of April 23 – November 14, 2018, the period for which routine limnological monitoring was conducted. The following data for that time interval was used as model inputs. Meteorological data from the NYCDEP station located at the Cannonsville Dam was used; daily averages were computed for air temperature, humidity, wind speed, and incident solar radiation. Daily average streamflow for WBDR at Walton, Trout Creek near Trout Creek, as measured by the USGS was used. Daily average reservoir outflows (diversion, release and spill) as recorded by NYCDEP were used. The inflow and outflow data, together with daily measurements of water storage, were used to compute the inflow from the ungaged portion of the watershed.

The model requires that the UV_{254} of stream inflows be specified on a daily basis. In 2018, 225 individual measurements of UV_{254} were made. Using the FLUX32 software, various relationships between the UV_{254} measurements and other stream properties that are measured on a daily basis were made. For the 2018 data, a relationship between UV_{254} and streamflow Q yielded the most accurate predictions. This relationship is

$$\mathrm{UV}_{254} = 0.0422 + 0.000499Q - 0.015/Q \tag{6-2}$$

where UV_{254} is the absorption coefficient for light at wavelength 254 nm (cm^{-1}), and Q is the daily average Walton streamflow in m^3/sec. The resulting predicted values of UV_{254} for the West Branch Delaware River for each day in 2018 are shown in Figure 6.21. It should be noted that this regression equation is by no means intended to be a final relationship as it is, at this point, simply a good relationship based on the 2018 data only. The UV_{254} predicted by Equation 6-2 was used for all three individual sources of inflow considered by the model: West Branch Delaware R., Trout Creek, and ungaged inflow.

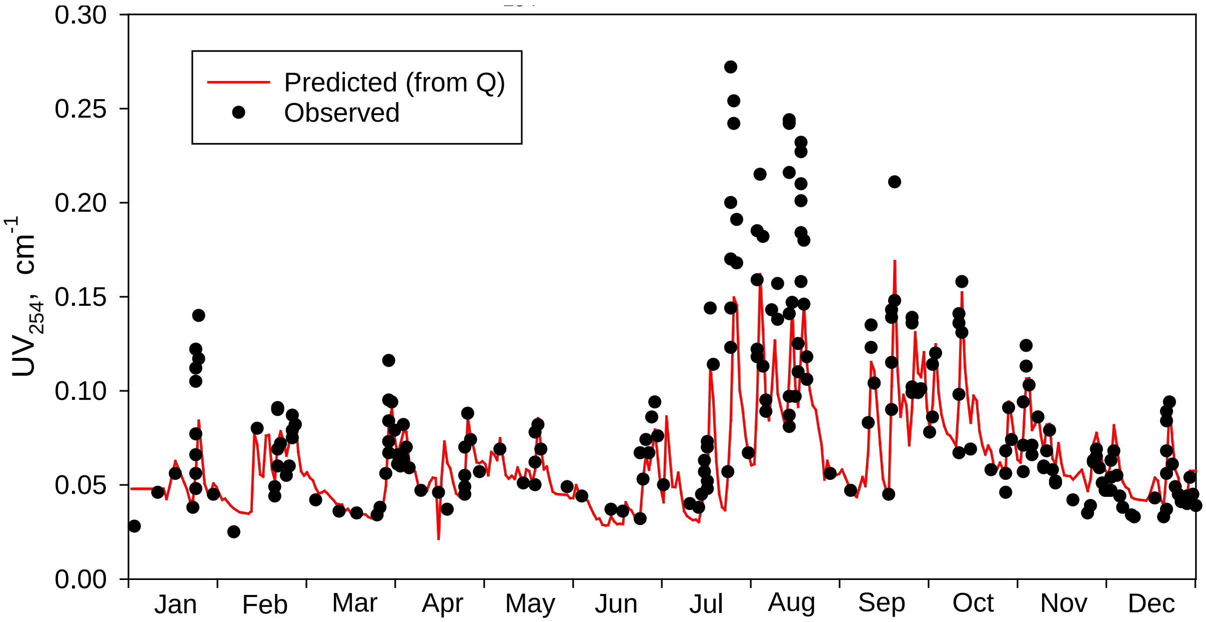


Figure 6.21 Observed and predicted UV_{254} levels for the West Branch Delaware River, 2018. Observations are the black circles (n=225), while the predictions are daily values based on the measured USGS daily average streamflow measured at the Walton gage, and using Equation (6-2).

Other input data used by the model included stream temperature measurements and Secchi disc transparency measurements, which were used to specify the light extinction coefficient in the water column of the reservoir.

The first set of model predictions shown are for the temperature of the water column. The model used in this work for temperature predictions is identical to that described by Owens (1998). High-frequency measurements (four to six profiles per day) of water temperature were made in 2018 using a buoy deployed at site 4WDC. For this application, temperature profiles measured at a weekly time interval were used to validate the predictions of the model. A comparison of selected model predictions (at roughly a two-month interval) and measurements are shown in Figure 6.22. This predictions are excellent, especially considering these were generated with a model that had not previously been tested for conditions after 2004.

UFILS4 did not previously have the capability to simulate UV_{254}, so the model code was modified to enable prediction of this quantity. In the initial model simulations shown here, the simple assumption was made that UV_{254} behaves in a conservative manner in the water column, so that there are no processes that produce or deplete UV_{254} in the water column. This is a simple initial assumption. There is good reason to believe that UV_{254}, like DOC and formation potential, undergoes production associated with algal production, and also experiences biodegradation and photodecay. Under the conservative assumption, UV_{254} levels in the reservoir are driven largely by the loading of UV_{254} from stream inflows, with transport and mixing processes also playing a role. Again, this is a simple initial assumption. A subset of the results from these simulations are shown in Figure 6.23, which show predictions and observations of UV_{254} at roughly a two-month interval. The predictions in Figure 6.23b seem to indicate that UV_{254} may be behaving conservatively over the April-June interval, while the August and October predictions indicate that some sources and sinks. These results indicate that internal production and loss of UV_{254} in the water column must be investigated. That work is ongoing.

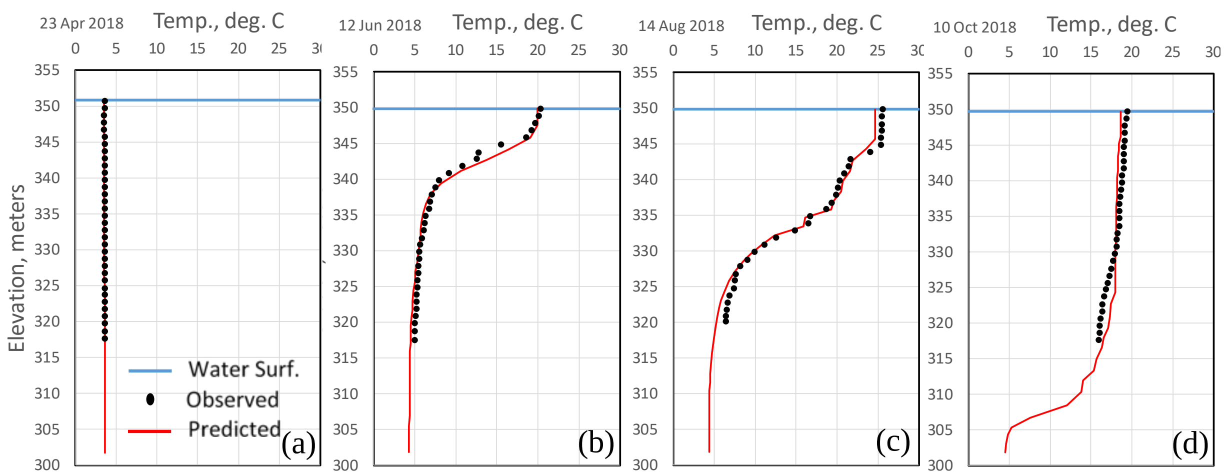


Figure 6.22 Observed and predicted water temperature (°C) in the water column of Cannonsville Reservoir, 2018: (a) April 23 (initial condition), (b) June 12, (c) August 14, and (d) October 10.

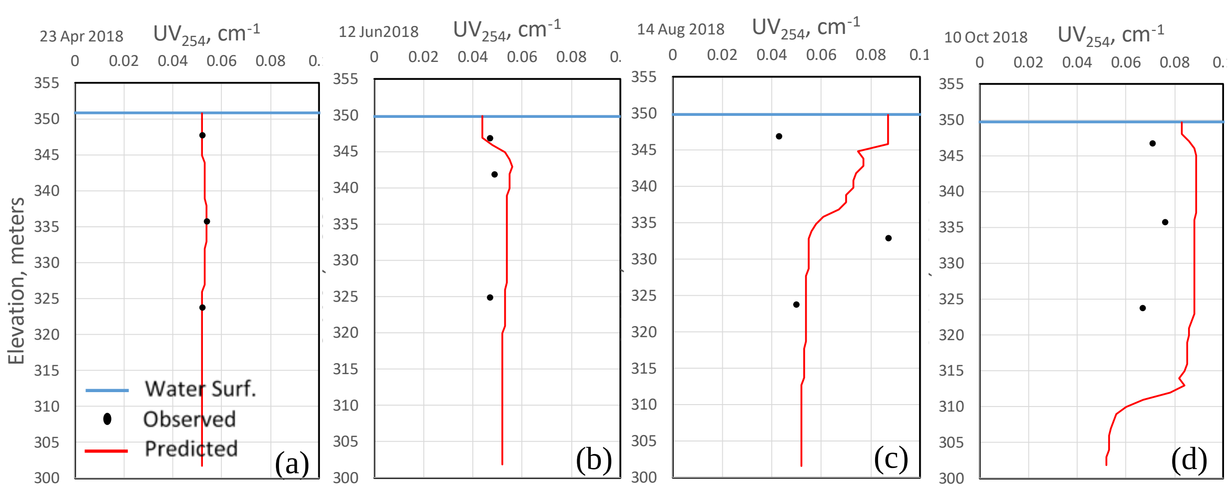


Figure 6.23 Observed and predicted UV_{254} (cm^{-1}) in the water column of Cannonsville Reservoir, 2018: (a) April 23 (initial condition), (b) June 12, (c) August 14, and (d) October 10.

6.12. Review of Watershed Protection Program by National Academy of Sciences, Engineering, and Medicine Expert Panel

The National Academy of Sciences, Engineering, and Medicine Panel (expert panel), which is evaluating the Watershed Protection Program, continued a series of meetings that began in 2018. At the February 4, 2019, meeting, Rajith Mukundan and Rakesh Gelda made presentations on watershed and reservoir modeling conducted by the Water Quality Modeling Section over the years. Modeling staff also attended the expert panel meeting on May 14, 2019. Modeling staff participated in a stress test that involved the hypothetical application of the Operations Support Tool (OST) in responding to a runoff event leading to significant increases in turbidity in the West of Hudson reservoirs. This test was requested and observed by, several members of the expert panel. WQ Modeling also provided data to a member of the expert panel who was interested in setting up a model for Rondout Reservoir, and to another member interested in streamflow, turbidity, and temperature data from Esopus Creek at Coldbrook in the requested format. Modeling staff also responded to a list of follow-up questions and request for a recent journal article from the modeling section.

6.13. Annual Water Quality Modeling Progress Meeting with Regulators

The annual meeting with regulators to present and discuss water quality modeling results was held on October 24, 2019, at DEP's Kingston office. Staff from the New York State Department of Health (NYSDOH) and from United State Environmental Protection Agency (USEPA) attended. This annual meeting is a requirement of the 2017 FAD. The meeting began with an overview of the modeling program and significant events occurring during the previous year, followed by a series of presentations on major modeling projects by DEP staff and CUNY support scientists. There was ample time for questions and discussion. Below is the agenda's meeting.

1. Overview of the Water Quality Modeling Program – Emmet Owens (DEP staff)
    a. Staff and CUNY Post-Doctoral Researcher Introductions
    b. CUNY-NYCDEP contract to support water quality modeling
    c. Upcoming FAD requirements: this meeting; Annual modeling report now a part of Watershed Water Quality Annual Report (next submission July 2020)
    d. National Academy of Sciences Expert Panel Review of the Watershed Protection Program
    e. Status report and future plans for individual models
    f. Peer-reviewed publications
2. Application of a stochastic weather model coupled with SWAT to estimate daily streamflow in the Cannonsville watershed – Chris Yeo (CUNY Support Scientist)
3. Data automation for Water Quality Modeling: From data processing and model execution to describing impacts of climate change – Jordan Gass (DEP staff)
4. Progress Report: Application of SWAT to West of Hudson watersheds – Mahrokh Moknatian (CUNY Support Scientist)

5. Water Quality Responses to Future Climate in the Cannonsville Watershed – Rajith Mukundan (DEP Staff)
6. Assessment of Climate Change Impacts on New York City Water Supply System using Operations Support Tool – Rakesh Gelda (DEP staff)
7. Summary: Application of GLM/AED to Cannonsville Reservoir – Theo Kpodonu (CUNY Support Scientist)
8. Monitoring and modeling of disinfection byproduct precursors: program update – Emmet Owens (DEP staff)

6.14. Water Quality Modeling: Publications and Presentations in 2019

6.14.1. Peer-Reviewed Publications

The following papers written by members of the Water Quality Modeling section were published in peer-reviewed journals in 2019:

Hoang, L., R. Mukundan, K.E. Moore, E.M. Owens and T.S. Steenhuis 2019. Phosphorus reduction in the New York City water supply system: a water-quality success story confirmed with data and modeling. *Ecological Engineering* 135:75-88. doi: 10.1016/j.ecoleng.2019.04.029.

Mukundan, R., N. Acharya, R.K. Gelda, A. Frei, and E.M. Owens, 2019., Modeling streamflow sensitivity to climate change in New York City water supply streams using a stochastic weather generator, *Journal of Hydrology: Regional Studies* 21:147-158, doi: 10.1016/j.ejrh.2019.01.001.

Son, K., L. Lin, L.E. Band and E.M. Owens 2019. Integrating climate, forest ecosystem and hydrology to estimate forested catchment dissolved organic carbon export. *Hydrological Processes* 33(10):1448-1464. doi.org/10.1002/hyp.13412.

Yeo, M.-H., A. Frei, R.K. Gelda, and E.M. Owens 2019. A Stochastic Weather Model for Generating Daily Precipitation Series at Ungauged Locations in the Catskill Mountain Region of New York State. *International Journal of Climatology* 2019:1-19. doi:10.1002/joc.6230.

Du, X., X. Zhang, R. Mukundan, L. Hoang, and E.M. Owens, 2019. Integrating terrestrial and aquatic processes toward watershed scale modeling of dissolved organic carbon fluxes. *Environmental Pollution* 249:125-135. doi:10.1016/j.envpol.2019.03.014.

Gelda, R.K., R. Mukundan, E.M. Owens, and J.T. Abatzoglou, 2019. A Practical Approach to Developing Climate Change Scenarios for Water Quality Models. *Journal of Hydrometeorology* 20(6):1197-1211. doi:10.1175/JHM-D-18-0213.1.

Kelly-Voicu, P., and A. Frei, 2019. Hydrological and temperature variations between 1900 and 2016 in the Catskill Mountains, New York, USA. *International Journal of Climatology* 2019:1-21. DOI:10.1002/joc.6289.

Suriano, Z.J., C.J. Leathers, D.K. Hall, and A. Frei. 2019. Contribution of snowfall from diverse synoptic conditions in the Catskill/Delaware Watershed of New York State. *International Journal of Climatology*. doi: 10.1002/joc.6043.

Steenhuis, T.S., E.M. Schneiderman, R. Mukundan, L. Hoang, M. Moges, and E.M. Owens, 2019. Revisiting SWAT as a Saturation-Excess Runoff Model. *Water* 11(7), 1427; doi: 10.3390/w11071427.

6.14.2. Conference Presentations

R.K. Gelda, A.H. Matonse, R. Mukundan, J. Mead, and E.M. Owens. "Assessment of Climate Change Impacts on New York City Water Supply System using Operations Support Tool: CCIMP Phase II". Watershed Science and Technology Conference, Saugerties NY, Sept. 2019.

A. Frei, P. Kelly-Voicu, E. M. Owens, R. Gelda, and R. Mukundan. "Hydrological and Temperature Variations between 1900 and 2016 in the Catskill Mountains and some discussion of the uncertainty in future drought scenarios". Watershed Science and Technology Conference, Saugerties NY, Sept. 2019.

R. Mukundan. “Watershed Modeling” presented to the National Academy of Sciences, Engineering, and Medicine (NASEM) Committee to Review the New York City Department of Environmental Protection (NYC DEP) Watershed Protection Program, West Harrison, NY, February 4, 2019.

R. Gelda. “Reservoir Water Quality Modeling” presented to the National Academy of Sciences, Engineering, and Medicine (NASEM) Committee to Review the New York City Department of Environmental Protection (NYC DEP) Watershed Protection Program, West Harrison, NY, February 4, 2019.

R. Mukundan, L. Hoang, R.K. Gelda, and E. M. Owens. “Water Quality Responses to Future Climate in a Water Supply Watershed”. Watershed Science and Technical Conference Saugerties, NY, September 12, 2019.

M. Moknatian, R. Mukundan, T.S. Steenhuis, and E.M. Owens “Comparison of Saturation-Excess Runoff Estimated using SWAT-HS and SWAT-wil Models for Mountainous Regions with Humid Climate” Poster Presentation, American Geophysical Union (AGU) Fall Meeting, San Francisco CA, Dec. 2019.

Z. Dong, C.T. Driscoll, E.M. Owens, J.L. Campbell, A. Pourmokhtarian, J. Baron, A. M. K. Stoner7, and K.Hayhoe “Hydrological response of high elevation watersheds in the conterminous United States to climate change under Representative Concentration Pathway scenarios” Poster Presentation, American Geophysical Union (AGU) Fall Meeting, San Francisco CA, Dec. 2019.

7. Further 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). Participation with external groups is an efficient way for DEP to bring specialized expertise into the work of the Water Quality Directorate (WQD) and to remain aware of the most recent developments in the water supply industry. The on-going contracts and projects in which WQD is involved are described in this chapter.

7.1. Contracts Managed by the Water Quality Directorate in 2019

In 2019, the WQD managed nine contracts to enhance its ability to monitor and model the watershed. The contracts supported data collection related to water quantity, water quality, wildlife surveillance, and model development to attain watershed protection and management goals. A brief description of each contract is provided below.

7.1.1. Laboratory Analytical Support Contracts

Eurofins Eaton Analytical Inc. (EEA): This contract is managed by DEP's Distribution Water Quality Operations. EEA conducts various analyses to support the work of DEP laboratories and fill gaps if analyses needed are not done by DEP. In 2019, analyses that were conducted by EEA under this contract covered a wide variety of analytes.

Watershed samples from aqueducts and reservoirs were analyzed for algal toxins, geosmin, methylisoborneol (MIB), and total petroleum hydrocarbons. Volatile organic carbon (VOC), semi-volatile organic carbon (SVOC), and glyphosate analyses on selected aqueduct samples were also done. Wastewater treatment plant effluents were analyzed for total Kjeldahl nitrogen, methylene blue active substance (MBAS), and total dissolved solids (TDS). Regulated and unregulated routine drinking water samples required the analysis of cyanide, fluoride, and a number of organic tests to meet regulatory standards.

There were also a number of special projects, including the Emerging Contaminant Monitoring Project (ECMP), to monitor aqueduct and stream samples for personal care protection products (PCPPs), radionuclides, UCMR3 analytes (i.e., chlorate, hexavalent chromium, perfluorinated compounds, 1,4-Dioxane, and metals), and UCMR4 analytes (i.e., pesticides, alcohols, SVOCs, metals and algal toxins). In another study designed to improve our understanding of disinfection byproduct formation potential, reservoir and stream samples were chlorinated and then analyzed for THMs and HAAs. In another special investigation, *Bacteroides* analyses were important in tracking to find the source of *Giardia* in the watershed.

EnviroTest Laboratories, Inc.: A special investigation was performed at Shaft 7 in the Town of Moodna to determine the water quality of a large amount of stagnant water that needed to be removed from the shaft. Redox, salinity and total dissolved solids (TDS) samples were sent to Envirotest Laboratory for analyses to inform the removal procedure.

York Analytical Laboratories, Inc.: York was equipped to analyze total petroleum hydrocarbons (TPH), both diesel range organics (DRO) and gasoline range organics (GRO) on Titicus Reservoir samples that were used to track the impact of a fuel truck spill on the reservoir. This contract was managed by DEP's Hawthorne Laboratory.

Source Molecular Laboratories: As part of studying the sources of fecal coliforms and protozoans in the watershed, samples were collected as grab samples, or with autosamplers during storm events, on streams in the Kensico watershed and sent to this laboratory for microbial source tracking analysis. Analysis includes the search for *Bacteroidales* genetic markers, which are specific to humans, through use of polymerase chain reaction (PCR) and other molecular techniques. The goal was to determine if sources are human or animal so they can be isolated and managed to prevent future contamination. As in past years, the majority of samples were negative for the human marker.

Watershed Assessment Associates: Samples of benthic macroinvertebrates collected in Croton, Catskill, and Delaware system streams were sent to this laboratory for identification to levels that meet the taxonomic targets set forth in the New York State Stream Biomonitoring Unit's Standard Operating Procedure. The benthic monitoring program was transferred to the Watershed Protection Program (WPP) in 2019.

7.1.2. Water Quality Operation, Maintenance and Assessment for the Hydrological Monitoring Network

DEP contracts with the United States Geological Survey (USGS) to operate and maintain a hydrological monitoring network in the NYC watershed. Under the current agreement, which runs from October 1, 2018 to September 30, 2023, the USGS measures stage and discharge at 60 stream gages throughout the Croton, Catskill, and Delaware watersheds along with turbidity at two gages and water temperature at four gages. The operation and maintenance of the gages involves (1) retrieving the stage, water temperature, and/or turbidity data; measuring streamflow; and/or collecting sediment samples at specified gages, (2) ensuring the integrity of the data, (3) maintaining the automatic monitoring equipment used to collect the data, (4) preparing selected data for real-time distribution over the internet, (5) analyzing stage, water temperature, turbidity, and streamflow data, and (6) preparing online annual Water-Year Summary reports. The data support DEP's development of multi-tiered water quality models, which is a requirement of the 2017 Filtration Avoidance Determination (FAD) (NYSDOH 2017). The data also provide support to the following FAD watershed protection programs: Land Acquisition, the Watershed Agricultural Program, the Watershed Forestry Program, the Stream Management Program, the Wetlands Protection Program, and Catskill Turbidity Control.

7.1.3. CUNY Postdoctoral Modeling Support Contract

A new four-year modeling support contract between DEP and CUNY was executed on April 1, 2019. As in the previous modeling support contract, an important component of this contract is financing for four post-doctoral modeling support scientists who are employed by CUNY and who work full time in the office of the DEP Water Quality Modeling section in Kingston. The contract also provides financing for three program advisors. In the new contract, these advisors are Dr. Allan Frei (Department of Geography and Institute for Sustainable Cities, Hunter College), Dr. Tammo Steenhuis (Department of Biological and Agricultural Engineering, Cornell University), and Dr. David Reckhow (Department of Civil and Environmental Engineering, University of Massachusetts-Amherst). In addition, Dr. Reckhow is overseeing a program of sampling from streams, reservoirs, and keypoints in the water supply system, and analysis of samples for disinfection byproduct (DBP) precursors and related chemical and optical properties. This program is generally intended to support and enhance DEP’s in-house sampling and analysis program for DBP precursor-related parameters. It also brings Dr. Reckhow’s expertise to bear in the effort to characterize these compounds in the water supply, and to provide data to support model development, testing, and validation.

Support for the four post-docs began on April 1 and continued through the year. Initial appointments to these positions is for 18 months, with extensions in some cases. Two post-doc vacancies occurred in the second half of 2019, with one of those vacancies filled by year’s end. In summer 2019, subcontracts between CUNY and Cornell, and CUNY and UMass-Amherst, were executed. Sampling using an automatic sampler deployed on the Neversink River, and analysis of those samples at the UMass laboratory, was completed for two storm events in mid- and late October 2019. In addition, the post docs joined the Water Quality Modeling section staff in presenting DEP’s progress on water quality model development and testing at a FAD-required meeting with state and federal regulators in October 2019.

7.1.4. Waterfowl Management

The Waterfowl Management Program (WMP) was developed in response to seasonal elevations of fecal coliform bacteria counts first identified at Kensico Reservoir from the late 1980s to the early 1990s. In 1993, DEP identified a direct relationship between the waterfowl populations present and the concentrations of fecal coliforms in Kensico Reservoir. Subsequently, a highly effective management program was developed based on this scientific finding. A contract was first let in 1995 to a private environmental consulting firm and has been rebid every three to four years since to help meet the requirements of the federal Surface Water Treatment Rule for fecal coliform bacteria (USEPA 1989). The current WMP contract (WMP-16-Renewal), with Henningson, Durham & Richardson, requires staffing of up to 25 contractor personnel annually to cover waterfowl management activities at several upstate reservoirs. It will run through July 29, 2020, with an option to extend the contract for another year through July 29, 2021, under the same terms.

7.1.5. Bathymetric Surveys of Reservoirs

An inter-governmental agreement was initiated in 2017 with United States Geological Survey (USGS) to conduct bathymetric surveys of the 13 East of Hudson (EOH) reservoirs and 3 controlled lakes. The USGS currently uses a multibeam echosounder to improve the accuracy and spatial resolution of the surveys compared to previous single-beam transect surveys. The USGS will provide DEP with GIS surfaces of the reservoirs, maps, and elevation tables.

The majority of fieldwork was conducted in 2017 and 2018. In 2019, the USGS completed secondary surveys of shallow and weedy areas that were inaccessible during earlier surveys, as well as other areas that required supplemental surveys to improve data quality. USGS has been working to clean the raw survey point clouds of noise and erroneous points, and to convert the data from depth measurements beneath the survey boat to elevations in the local vertical datum. The USGS is expected to deliver draft products and reports in 2020.

7.1.6. WISKI Software Support Contract

DEP has continued to expand and enhance usage of the WISKI (Water Information Systems KISTERS) software to collect and view fixed point as well as continuous online data on a web portal, in an effort to provide a management tool that tracks water from rainfall in the watershed, through the streams and reservoirs, and into the distribution system that supplies drinking water to New York City. To date, data are collected from keypoints on the aqueducts, stream monitoring locations from both USGS and DEP sites, as well as sites throughout the distribution system. The software was updated to WISKI 7.4.5, and the new ESRI portal is operational. Work continues on the development of heat maps for select data sets on the portal. The weather stations in the watershed aid in evaluating possible flooding events. In the distribution system along with Doppler radar, the data aid in tracking flooding and scheduling of BWSO crew assignments during heavy rain events. Build-out of harbor buoy monitoring is nearing completion and is expected to be available on the portal web page by 2020. Finally, data from the FDNY hydrant flushing and NYC Department of Buildings has been integrated into the portal to better understand phantom 311 water quality clusters of complaints.

7.2. Water Research Foundation Project Participation

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 members and as a participating utility, in order to remain current with cutting-edge research for the benefit of the City's drinking water. DEP participated in six 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 WQD is involved are described below.

7.2.1. WRF#5032 Analysis of Corrosion Control Treatment for Lead and Copper Control (S. Schindler)

The objective of this project is to create a guidance document based on science and utility experience for state regulators and water systems recommending when and how to conduct a corrosion control study in anticipation of a treatment change, water quality change, or a requirement and desire to lower lead levels. The approach will include outreach to utilities and states on use of the guidance materials. DEP is serving as a participating utility.

7.2.2. WRF#4911 Sampling and Monitoring Strategies for Opportunistic Pathogens in Drinking Water Distribution Systems (A. Szczerba)

Opportunistic pathogens (OPs) pose a significant health impact but are primarily an issue in premise plumbing systems, which are outside the water utility's jurisdiction. Nonetheless, water utilities may be able to proactively assist their customers and minimize the risks of exposure. This research project seeks to optimize sampling and detection methodologies for OPs (specifically *Legionella pneumophila*, *Pseudomonas aeruginosa*, and non-tuberculous mycobacteria) and devise suitable monitoring strategies to understand their occurrence in bulk water, biofilms, and sediments 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.

7.2.3. WRF#4910 Evaluating Key Factors that Affect the Accumulation and Release of Lead from Galvanized Pipes (C. Glaser)

The objective of this project is to better understand the conditions under which galvanized pipes can contribute to lead at the tap, the magnitude of lead release from galvanized pipes, and factors that can impact accumulation and release of lead from galvanized pipes. To accomplish this, the project will develop cutting edge tools that will evaluate links between galvanized iron pipe (GIP) and lead (Pb) release, by (1) scientifically assessing customers' concerns related to GIP corrosion and possible association with Pb in water, (2) characterizing the nature of iron (Fe) and Pb release to drinking water from known sources, and (3) examining Fe and Pb release from GIP using bench-scale testing. In addition, public education materials will be developed related to GIP and Pb release.

7.2.4. WRF#4721 Opportunistic Pathogens in Premise Plumbing (A. Capetanakis)

The incidence of waterborne infectious disease outbreaks attributed to opportunistic pathogens (OPs), which are not regulated by the USEPA, appears to be increasing. Although many studies have surveyed premise plumbing and distribution systems for OPs, there is no unified method to monitor drinking water systems for all OPs of interest. This lack of unified methodology stems from differences in life cycle stages and physiologies of different OPs.

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. Additionally, they collectively encompass the physiological and ecological traits of all known OPs in premise plumbing that make their detection and quantification particularly challenging.

The research team will also develop guidelines for utilities with different levels of expertise and resources on how to implement OP monitoring. The team will also examine the effectiveness of several mitigation strategies to reduce the abundance of Ops, with a focus on in-home premise plumbing modifications.

7.2.5. WRF#4713 Full Lead Service Line Replacement Guidance (C. Glaser)

Removing an entire lead service line (LSL) eliminates one significant potential source of lead. However, even after full LSL replacement, lead sources can still be present that can contribute to lead levels at the tap. Following a full LSL replacement, lead exposure can come from lead scale that has built up over time within premise plumbing, brass components that contain lead, and lead-based solder.

The objective of this project is to evaluate strategies to reduce lead exposure after conducting full lead service line replacements (FLSLRs). The research will provide accurate and easily understood guidance and reference materials for staff at any U.S. or Canadian water system to use when planning and implementing FLSLRs.

The research team will conduct a literature review of current information related to limiting lead release following lead service line disturbances and evaluate the effectiveness of flushing to reduce lead exposure following FLSLRs at single-family homes. The research will also identify lessons learned from case studies, if any are available, of utilities that have monitored lead release following FLSLR.

7.2.6. WRF#4616 Hospital Discharge Practices and Contaminants of Emerging Concern (S. Neuman)

This project aimed to provide a holistic view to water utility and healthcare facility practitioners on management of compounds of emerging concern (CECs) in hospital wastewater. Emphasis was placed on identifying information gaps for future research on CEC management at these facilities, with the ultimate goal of establishing practices to improve the protection of both human health and ecosystems.

More specifically, researchers will investigate hospital discharge practices to better understand current best management practices associated with CECs, what actions hospitals are taking to mitigate or reduce that loading, if any, and what actions are feasible beyond what's already being done. It will also investigate what regulations exist regarding such discharge practices and how they are communicated.

7.3. Water Utility Climate Alliance (WUCA)

In 2019, DEP continued as one of 12 members of the Water Utility Climate Alliance (WUCA). This is a group of 12 large water utilities from around the country who collaborate on water supply issues related to climate change. The Bureau of Environmental Policy and Analysis (represented by Alan Cohn) continued as DEP's official representative to WUCA in 2019 and the Bureau of Water Supply (represented by Emmet Owens, PE) contributed to various WUCA technical activities. On January 16, BWS made a webinar presentation to other WUCA members as a part of the "Learning from Each Other" series, where DEP's use of models to evaluate the impact of climate change was described. On July 17, a meeting was convened in New York City that was attended by several WUCA members, including representatives of Austin (Texas) Water. Information was shared about DEP's development and use of a stochastic weather generator to produce time series of precipitation data that contain extreme events (floods and droughts) that have not been captured in historic monitoring.

7.4. 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. DEP staff have attended the following GLEON "All-Hands" meetings since 2014: GLEON16, Orford, Québec; GLEON17, Chuncheon, South Korea; GLEON18, Gaming, Austria; GLEON19, New Paltz, New York; and GLEON20, Rottnest Island, Australia. Information about GLEON research can be found at: http://gleon.org/research/projects/. The two projects in which DEP staff participated in 2019 are described below.

7.4.1. GLEON Project: Long-term Dissolved Oxygen (DO) Concentrations in Lakes and Reservoirs

A study on the effects of climate on dissolved oxygen concentrations (DO) in lakes and reservoirs around the globe was initiated in 2016 with GLEON partners. DEP contributed Cannonsville and Neversink reservoir temperature, DO, nutrient, and chlorophyll data and expertise. Following is a summary of the research:

Oxygen within freshwater systems influences the cycling of biologically essential elements carbon, nitrogen, and phosphorus. DO concentrations in lakes are temperature dependent due to gas solubility, and influenced by lake mixing and other biogeochemical mechanisms. Long-term declines in DO in marine waters have been linked to climate warming and increases in nutrient loading, however, little is known about how the DO content of lakes has changed. Using a long-term, globally distributed data set compiled from 400 lakes and 22,983 DO and temperature profiles, it was found that decreases in DO are widespread in surface and deep waters of lakes. Deep-water DO declines are associated with reduced water clarity and changes in thermal stratification, but not gas solubility. In contrast, surface water DO declines were driven mainly by reduced solubility under warmer temperatures. In 22% of the lakes, however, surface DO increased despite reduced solubility, likely as the result of increased algal biomass in highly productive warm lakes. Results demonstrate that lake ecosystems are being modified by complex and synergistic effects of temperature change and eutrophication.

In 2019, Stephen Jane at Rensselaer Polytechnic Institute and GLEON collaborators submitted a paper on deoxygenation of lakes due to the combined effects of eutrophication and climate change to the journal Nature. However, it was rejected and will be revised and resubmitted in 2020.

7.4.2. GLEON Project: Before the Pipe: Monitoring and Modeling DBP Precursors in Drinking Water Sources

Collaboration on a project to identify important questions and research gaps on disinfection byproduct (DBP) precursors and water supply concerns continued in 2019. Efforts included reaching an agreement with project participants at the GLEON21 meeting in November 2019 on an outline for a systematic review paper. Leading up to that meeting, the project co-leaders (Karen Moore, DEP; and Elias Munthali, ICRA-Barcelona) worked on understanding and planning the process for conducting a systematic literature review. This included virtual meetings to gain insights on the review process from Ilya Fischhoff, a post-doctoral scientist and Amy Schuler, Director of Information Services and Library, both on staff at the Cary Institute of Ecosystem Studies in Millbrook, New York. Dr. Fischhoff had successfully completed two systematic reviews in ecology and was willing to share his experience and insights on how to approach this process with multiple collaborators. Systematic reviews are more common in medical research and require that a predetermined protocol be developed prior to conducting a literature search and review. The process includes careful articulation of the research question, development of inclusion and exclusion criteria, and predetermined decision rules for steps in the review that evaluate bias and make the review reproducible. The review will be conducted in 2020 with GLEON project partners.

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DEP. 2019a. Stream Management Program Upper Esopus Creek Watershed Turbidity/Suspended-Sediment Monitoring Study: Biennial Status Report. Valhalla, NY. 44 p.

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DEP. 2019c. Results from a Comparison Study between Foamstream® and Conventional Herbicides: A Study on Efficacy. Valhalla, NY. 37 p.

DEP. 2019d. Special Investigation Report: Elevated *Giardia* at Rondout Reservoir, November 2018 – October 2019 (SI19RR1). Valhalla, NY. 57 p.

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

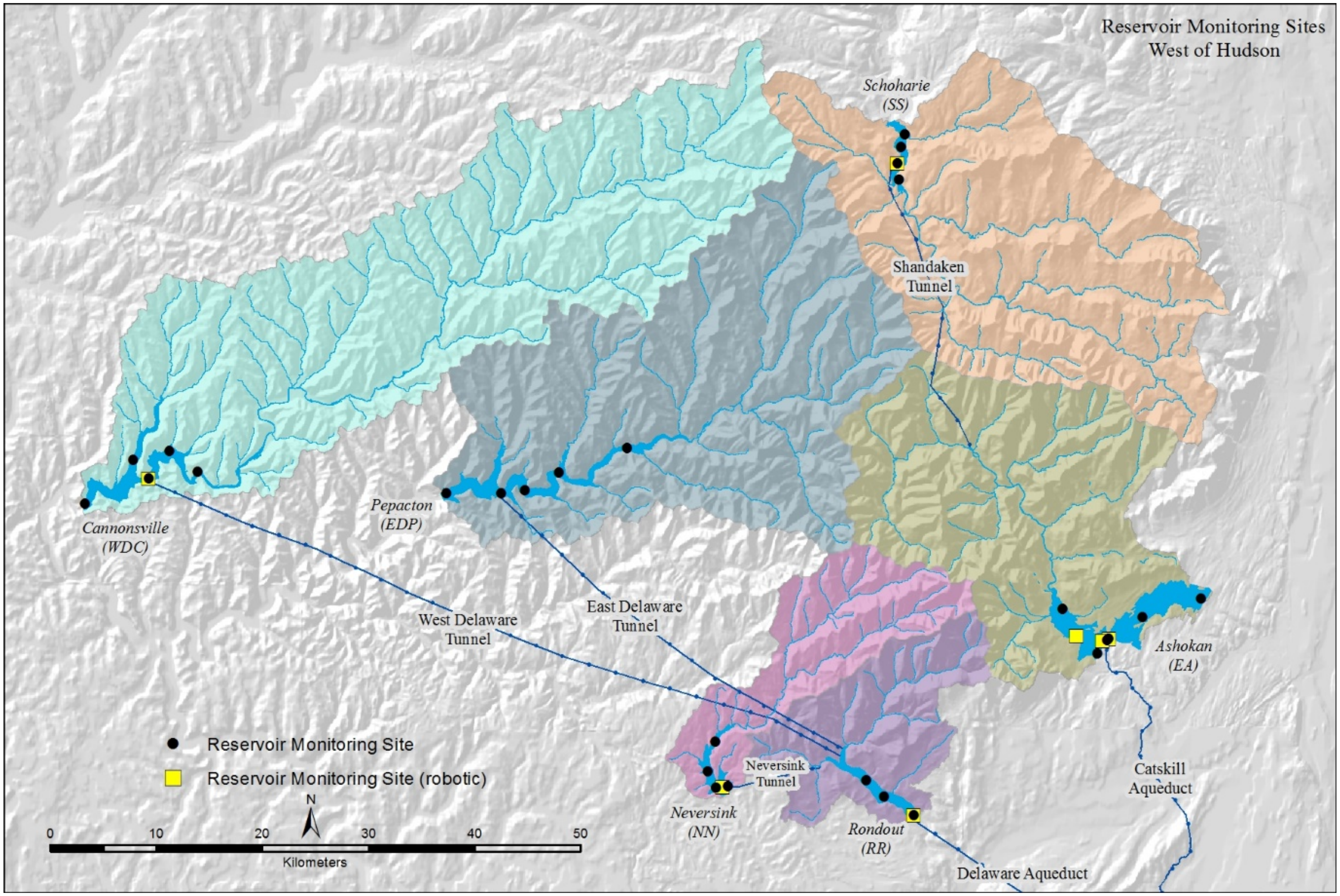
List of sites for Watershed Water Quality Operations (WWQO) Early Warning Remote Monitoring (EWRM).

Site	Location	System	Water Type	Parameters
SRR1CM	Schoharie Intake Chamber	Catskill	Raw	Turb, pH, Temp, SpCond
SRR2CM	Shandaken Tunnel Outlet	Catskill	Raw	Turb, pH, Temp, SpCond
EARCM	Catskill Aqueduct	Catskill	Raw	Turb, pH, Temp, SpCond,
M-1	Ashokan Release Channel	Catskill	Raw	Turb
AEAP	Esopus Creek Upstream STO	Catskill	Raw	Turb
RDRRCM	Delaware Aqueduct (REC)	Delaware	Raw	Turb, pH, Temp, SpCond
NRR2CM	Neversink Tunnel Outlet	Delaware	Raw	Turb, pH, Temp, SpCond
PRR2CM	East Delaware Tunnel Outlet	Delaware	Raw	Turb, pH, Temp, SpCond
WDTOCM	West Delaware Tunnel Outlet	Delaware	Raw	Turb, pH, Temp, SpCond
RR1-RR4	All Taps	Delaware	Raw	Turb
CDIS4-DEL	Cat/Del Interconnect at Shaft 4 (Delaware)	Delaware	Raw	pH, Temp, TCR, Turb
CDIS4-CAT	Cat/Del Interconnect at Shaft 4 (Catskill)	Catskill	Raw	Turb
CDIS4-Combined	Cat/Del Interconnect at Shaft 4 (Catskill)	Catskill	Raw	pH, Temp, Turb
CWB1.5	Croton West Branch Reservoir	Delaware	Raw	Pump used to collect grab samples.
DEL9	Delaware Shaft 9	Delaware	Raw	Turb, pH, Temp, SpCond, TCR, Dechlor, DO
DEL10	Delaware Shaft 10	Delaware	Raw	Turb, pH, Temp, SpCond, Elev

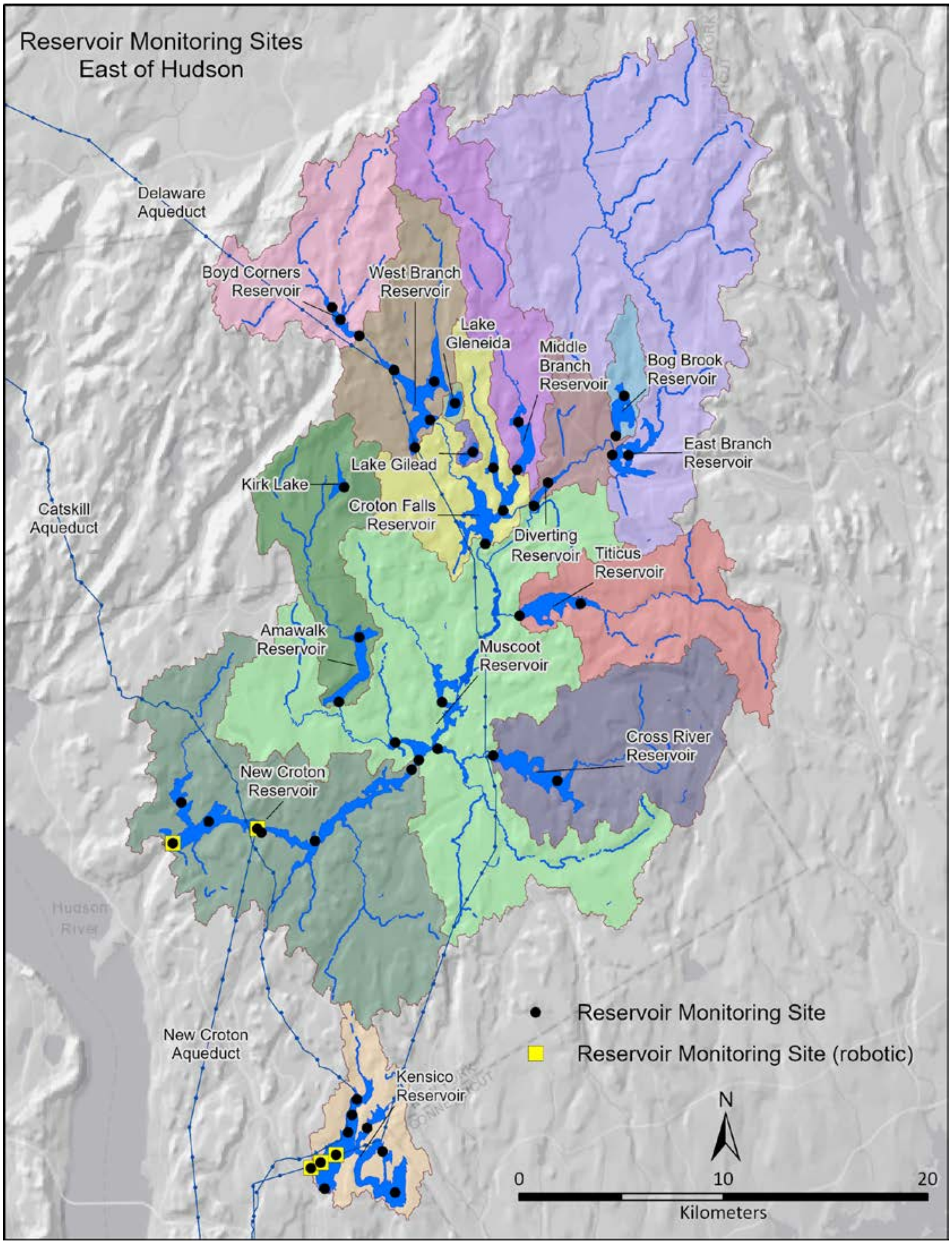
List of sites for Watershed Water Quality Operations (WWQO) Early Warning Remote Monitoring (EWRM).

Site	Location	System	Water Type	Parameters
DEL17	Delaware Shaft 17	Delaware	Raw	Turb, pH, Temp, SpCond, TCR, Dechlor, DO
DEL18DT	Delaware Shaft 18 Downtake	Cat/Del	Raw	Turb, pH, Temp, SpCond, Flow, Elev
DEL19	Delaware Shaft 19	Cat/Del	Pre-Treated	Turb, pH, Temp, SpCond, FCR, F
DEL19LAB	Delaware Shaft 19 Lab	Cat/Del	Pre-Treated	Turb, pH, Temp, SpCond, FCR, F
DELSFB	Delaware South Forebay	Cat/Del	Pre-Treated	Turb, pH, Temp, SpCond, FCR, F
DELSFBLAB	Delaware South Forebay Lab	Cat/Del	Pre-Treated	Turb, pH, Temp, SpCond, FCR, F
CCC	Catskill Connection Chamber	Cat/Del	Pre-Treated	Turb, pH, Temp, SpCond, FCR, F
CCCLAB	Catskill Connection Chamber Lab	Cat/Del	Pre-Treated	Turb, pH, Temp, SpCond, FCR, F
CROFALLSVC	Croton Falls Valve Chamber	Croton	Raw	Turb
CROSSRVVC	Cross River Valve Chamber	Croton	Raw	Turb
CATALUM	Catskill Alum Plant	Catskill	Raw	Turb
CATIC	Catskill Influent Chamber	Catskill	Raw	pH, Temp
CROGH	CLGH Raw Water	Croton	Raw	Turb, pH, Temp, SpCond, DO
CRO1T	New Croton Dam	Croton	Raw	Turb, pH, Temp, SpCond,
CRO1B	New Croton Dam	Croton	Raw	Turb, pH, Temp, SpCond, DO
CRO183	CLGH	Croton	Raw	Turb, pH, Temp, SpCond,
CRO163	CLGH	Croton	Raw	Turb, pH, Temp, SpCond,
CRO143	CLGH	Croton	Raw	Turb, pH, Temp, SpCond, DO

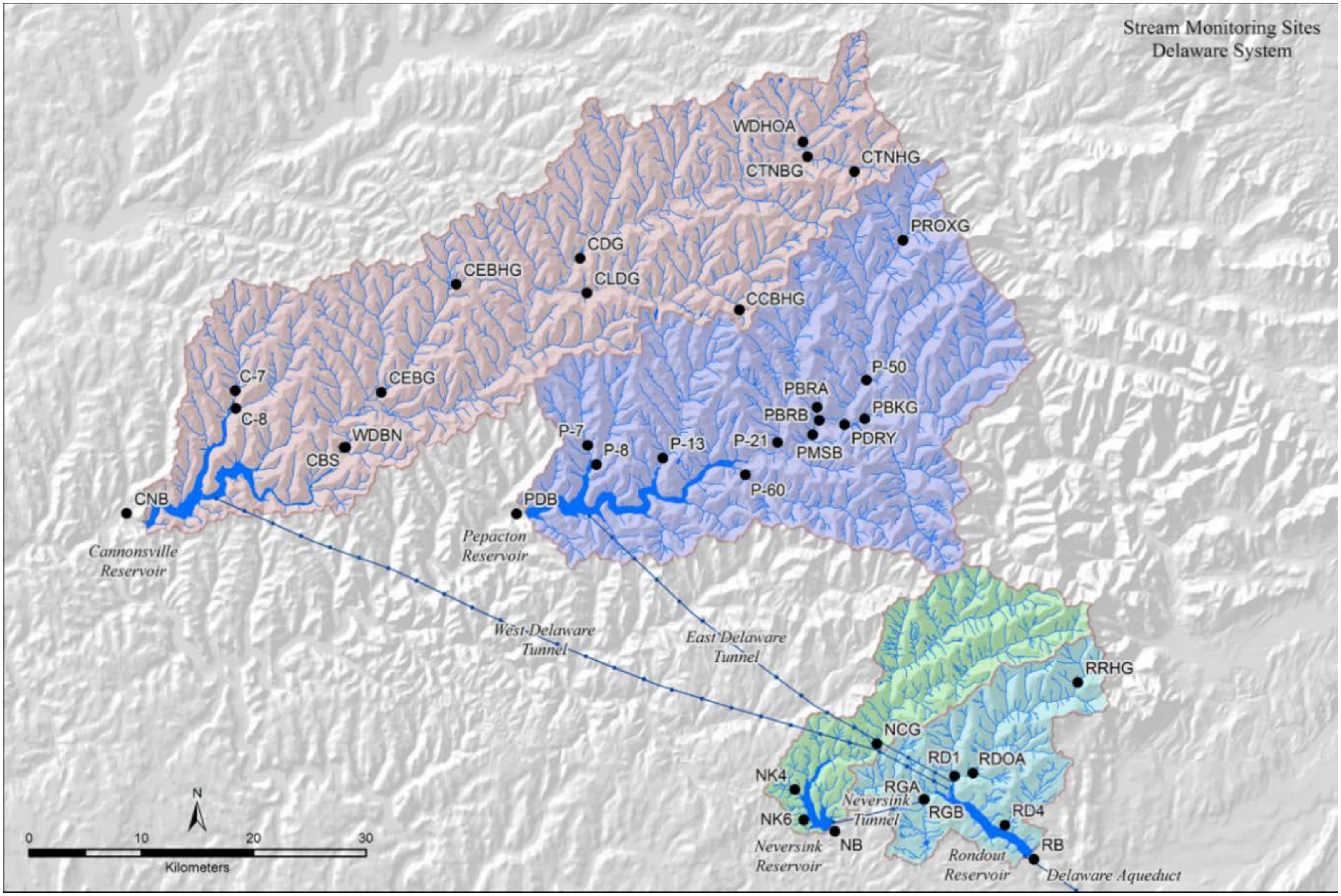
Appendix B. Sampling Locations



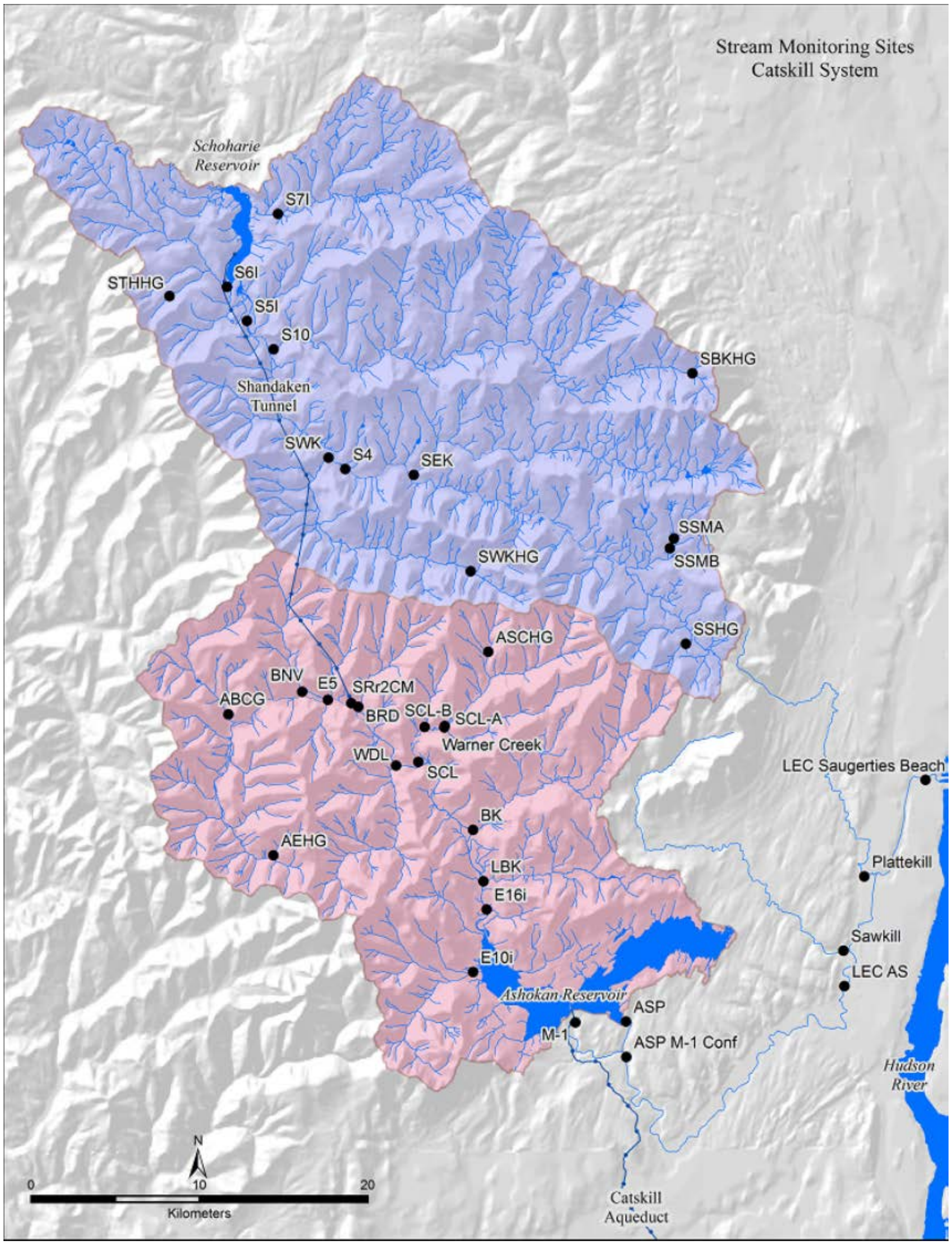
Appendix Figure 1 WOH reservoir monitoring sites [see WWQMP (DEP 2018) for detailed maps].



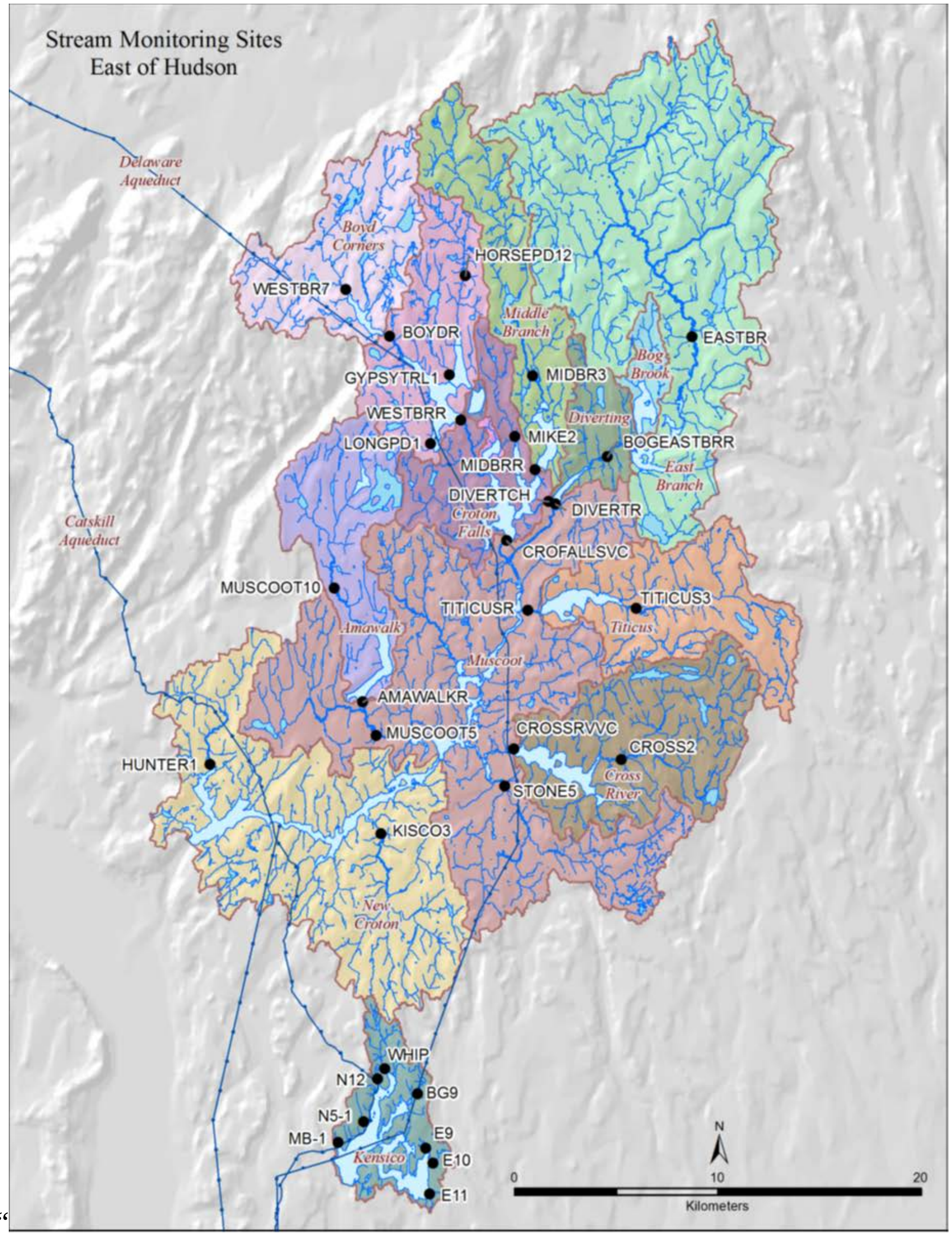
Appendix Figure 2 EOH reservoir monitoring sites [see WWQMP (DEP 2018) for detailed maps].



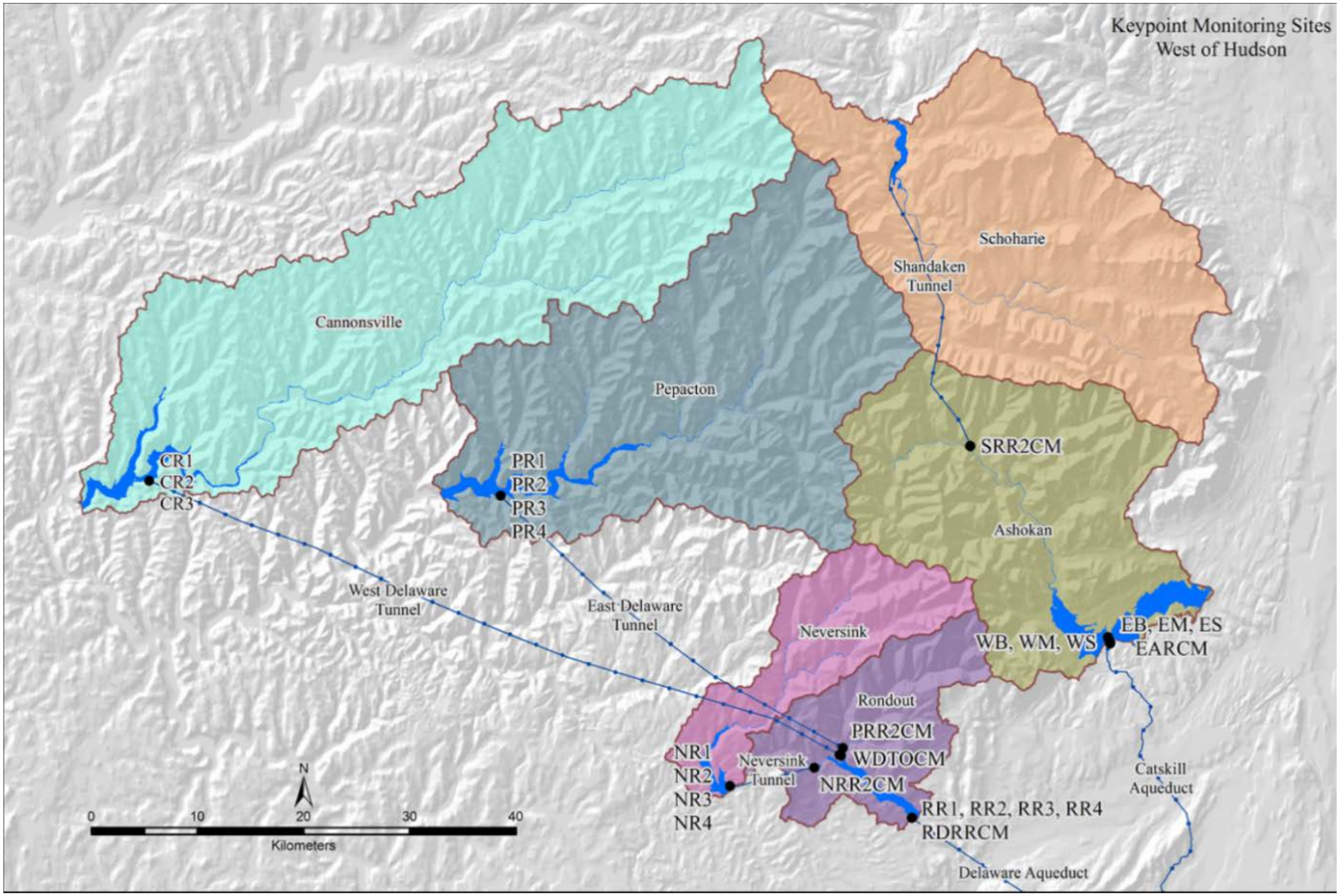
Appendix Figure 3 Delaware System stream monitoring sites [see WWQMP (DEP 2018) for detailed maps].



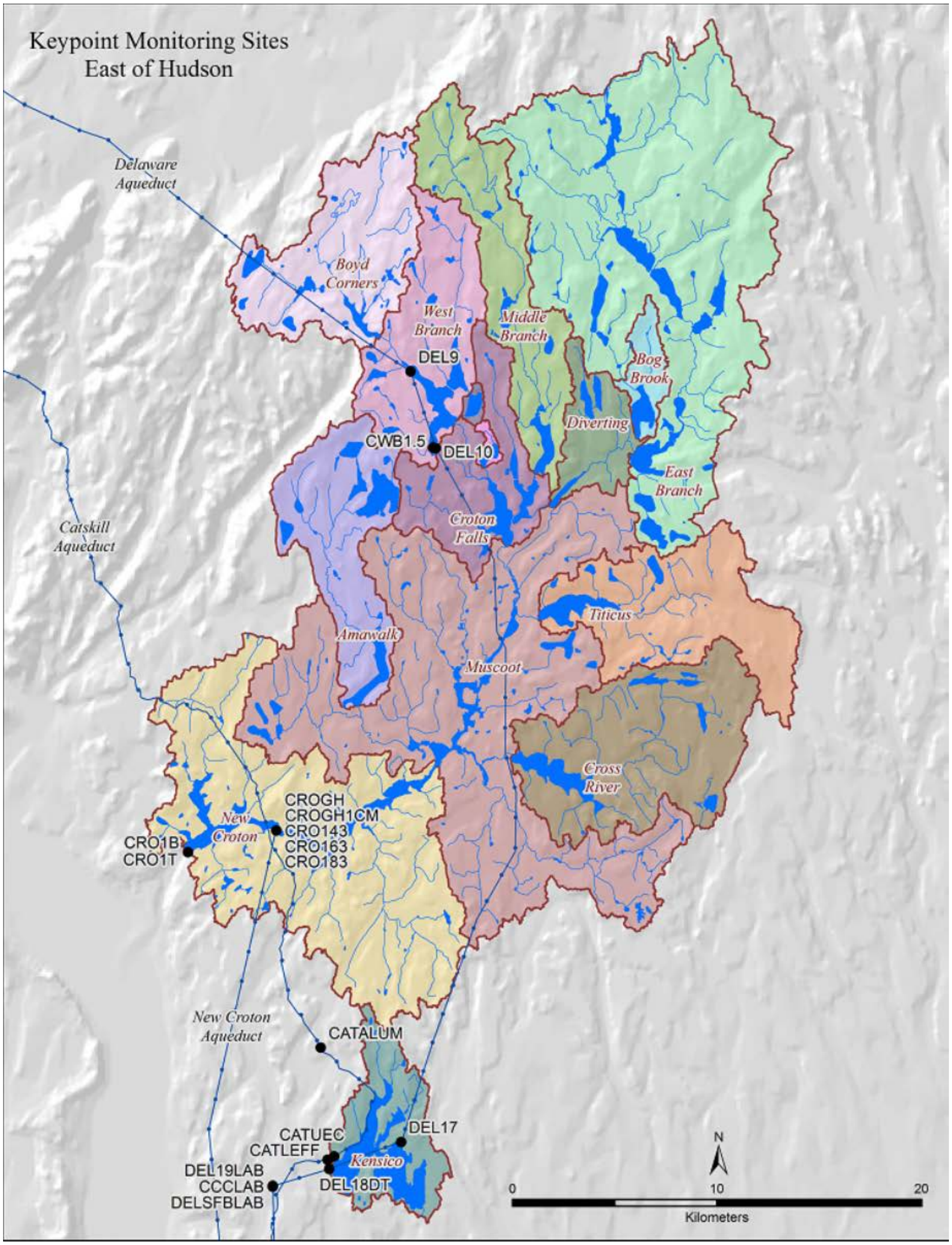
Appendix Figure 4 Catskill System stream monitoring sites [see WWQMP (DEP 2018) for detailed maps].



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

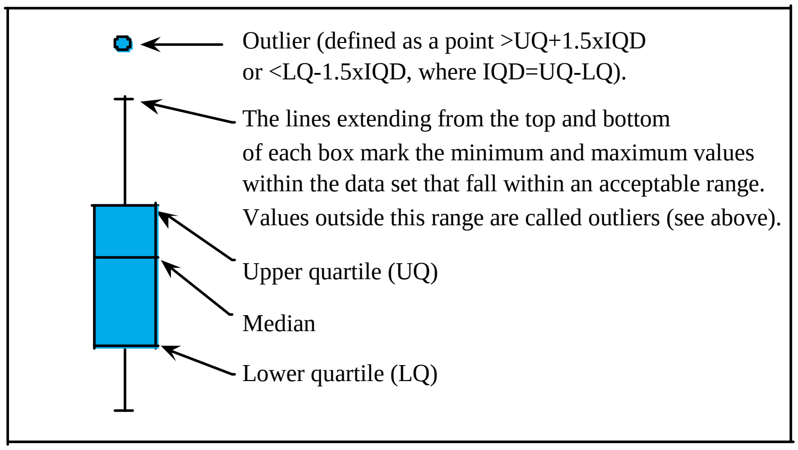


Appendix Figure 6 WOH aqueduct keypoint monitoring sites [see WWQMP (DEP 2018) for detailed maps].



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

Appendix C. 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 D. Monthly Coliform-Restricted Calculations used for Non-Terminal Reservoirs

Monthly coliform-restricted calculations for total coliform counts on non-terminal reservoirs.

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF[1]	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
Amawalk	A (2400, 5000)	Apr-19	5	0	E45	0
		May-19	5	0	E70	0
		Jun-19	5	0	E30	0
		Jul-19	5	0	<10	0
		Aug-19	5	0	E10	0
		Sep-19	5	0	E10	0
		Oct-19	5	0	E50	0
		Nov-19	5	0	E550	0
Bog Brook	AA (50, 240)	Apr-19	5	0	E5	0
		May-19	5	0	E15	0
		Jun-19	5	0	E10	0
		Jul-19	5	0	E40	0
		Aug-19	6	0	E10	0
		Sep-19	5	0	<10	0
		Oct-19	5	0	E10	0
		Nov-19	5	0	E10	0
Boyd Corners	AA (50, 240)	Apr-19	6	0	E28	0
		Jun-19	6	0	>=E15	0
		Jul-19	6	0	E50	0
		Aug-19	7	0	<50	0
		Sep-19	6	0	E125	17
		Oct-19	6	0	E100	33
		Nov-19	6	0	E250	50
Cross River	A/AA (50, 240)	Apr-19	6	0	E22	0
		May-19	6	0	E5	0
		Jun-19	6	0	E42	0
		Jul-19	6	0	E10	0

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF[1]	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
		Aug-19	6	0	E10	0
		Sep-19	6	0	E48	0
		Oct-19	6	0	>=E5	0
		Nov-19	6	0	E15	0
Croton Falls	A/AA (50, 240)	Apr-19	8	0	E20	0
		May-19	8	0	E30	0
		Jun-19	8	0	E40	38
		Jul-19	8	0	E50	0
		Aug-19	8	0	<50	12
		Sep-19	8	0	E100	50
		Oct-19	8	0	E50	0
		Nov-19	8	0	<50	0
Diverting	AA (50, 240)	Apr-19	4	0	E72	0
		May-19	5	0	E50	0
		Jun-19	5	0	180	20
		Jul-19	5	0	E100	0
		Aug-19	5	0	E100	20
		Sep-19	5	0	E30	0
		Oct-19	5	0	E90	0
		Nov-19	5	0	E30	0
East Branch	AA (50, 240)	Apr-19	5	0	E10	0
		May-19	6	0	>=E18	0
		Jun-19	5	0	E20	0
		Jul-19	5	0	<20	0
		Aug-19	6	0	E20	0
		Sep-19	6	0	E20	0
		Oct-19	6	0	E60	0
		Nov-19	6	0	E20	0
Kirk Lake	B (2400, 5000)	Apr-19	5	0	E20	0
		May-19	5	0	E10	0

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF[1]	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
		Jun-19	5	0	E5	0
		Jul-19	5	0	E8	0
		Aug-19	5	0	E10	0
		Sep-19	5	0	E10	0
		Oct-19	5	0	E30	0
		Nov-19	5	0	E200	0
Lake Gilead	A (2400, 5000)	Apr-19	5	0	E15	0
		May-19	5	0	<5	0
		Jun-19	5	0	E15	0
		Jul-19	5	0	<50	0
		Aug-19	5	0	E15	0
		Sep-19	5	0	E5	0
		Oct-19	5	0	E5	0
		Nov-19	5	0	E20	0
Lake Gleneida	AA (50, 240)	Apr-19	5	0	<5	0
		Jun-19	5	0	E10	0
		Jul-19	5	0	<5	0
		Aug-19	5	0	E20	0
		Sep-19	5	0	E5	0
		Oct-19	5	0	E5	0
		Nov-19	5	0	<20	0
Middle Branch	A (2400, 5000)	Apr-19	5	0	E30	0
		May-19	5	0	100	0
		Jun-19	5	0	E65	0
		Jul-19	5	0	<10	0
		Aug-19	5	0	>=<10	0
		Sep-19	5	0	<10	0
		Oct-19	5	0	<10	0
		Nov-19	5	0	E10	0
	A (2400, 5000)	Apr-19	6	0	E28	0

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF[1]	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
Muscoot		May-19	6	0	315	0
		Jun-19	7	0	780	0
		Jul-19	6	0	540	17
		Aug-19	6	0	E20	0
		Sep-19	7	0	E60	0
		Oct-19	7	0	1100	0
		Nov-19	6	0	E20	0
Titicus	AA (50, 240)	Apr-19	5	0	<5	0
		May-19	5	0	E30	0
		Jun-19	5	0	E20	0
		Jul-19	5	0	E50	40
		Aug-19	5	0	E10	0
		Sep-19	5	0	<10	0
		Oct-19	5	0	E40	20
		Nov-19	5	0	E50	0
Cannonsville	A/AA (50, 240)	Apr-19	12	0	E63	8
		May-19	12	0	E15	0
		Jun-19	15	0	>=<20	7
		Jul-19	15	0	3800	100
		Aug-19	14	0	50	7
		Sep-19	13	0	600	62
		Oct-19	12	0	E170	42
		Nov-19	9	0	E220	44
Pepacton	A/AA (50, 240)	Apr-19	16	0	E5	0
		May-19	15	0	E2	0
		Jun-19	16	0	<20	6
		Jul-19	15	0	E40	0
		Aug-19	15	0	2600	93
		Sep-19	14	0	385	57
		Oct-19	13	0	E45	0

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF[1]	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
		Nov-19	14	0	E17	7
Neversink	AA (50, 240)	Apr-19	12	1	E12	0
		May-19	13	0	E6	0
		Jun-19	13	0	<20	0
		Jul-19	13	0	<10	0
		Aug-19	11	0	E10	0
		Sep-19	11	0	E30	0
		Oct-19	10	1	E105	10
		Nov-19	12	0	95	0
Schoharie	AA (50, 240)	Apr-19	12	0	E58	0
		May-19	12	0	120	42
		Jun-19	12	0	E108	8
		Jul-19	4	8	>=E20	0
		Aug-19	11	0	E20	0
		Sep-19	10	0	>=5	0
		Oct-19	9	0	>=E380	89
		Nov-19	11	0	E20	18

[1]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 E. 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 µg 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 NYS guidance value of 20 µg L^{-1} (15 µg 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 µg L^{-1} (15 µg 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 μg L^{-1} (15 μg 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 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	2014 $\mu g\ L^{-1}$	2015 $\mu g\ L^{-1}$	2016 $\mu g\ L^{-1}$	2017 $\mu g\ L^{-1}$	2018 $\mu g\ L^{-1}$	2019 $\mu g\ L^{-1}$
Non-Source Waters (Delaware System)						
Cannonsville Reservoir	13.1	14.9	17.0	15.4	14.3	15.6
Pepacton Reservoir	7.8	9.0	10.8	10.3	10.1	9.8
Neversink Reservoir	6.2	6.5	8.0	7.3	6.5	6.5
Non-Source Waters (Catskill System)						
Schoharie Reservoir	15.3	11.9	12.5	12.2	14.9	12.3
Non-Source Waters (Croton System)						
Amawalk Reservoir	19.4	19.3	29.8	26.3	25.4	17.3
Bog Brook Reservoir	14.4	19.4	28.4	27.8	19.4	14.1
Boyd Corners Reservoir	9.0	9.0	11.3	15.1	14.0	11.5
Diverting Reservoir	29.1	25.8	37.4	31.6	28.7	23.2
East Branch Reservoir	24.2	21.3	23.5	25.1	27.5	21.6
Middle Branch Reservoir	35.3	27.4	34.1	28.4	29.4	18.3
Muscoot Reservoir	28.7	28.5	30.6	36.5	30.6	28.9
Titicus Reservoir	24.8	19.5	23.7	25.2	25.0	23.1
Lake Gleneida	19.8	35.0	27.0	25.5	21.5	14.9
Lake Gilead	32.8	27.1	34.6	33.6	32.7	20.5
Kirk Lake	32.8	30.8	27.3	23.3	20.9	18.4
Source Waters (all systems)						
Ashokan West Basin	8.1	8.8	12.6	8.2	8.3	7.8
Ashokan East Basin	7.5	7.9	10.3	8.1	7.6	7.4
Cross River Reservoir	17.6	15.7	19.0	23.2	21.1	16.8
Croton Falls Reservoir	19.9	19.4	18.0	23.2	21.5	15.3
Kensico Reservoir	5.7	7.4	7.6	8.8	7.9	6.8
New Croton Reservoir	16.0	16.8	22.1	22.5	26.2	19.5
Rondout Reservoir	6.6	7.9	10.0	9.0	8.1	7.8
West Branch Reservoir	11.2	11.3	13.4	14.2	11.8	9.5

Appendix F. Comparison of Reservoir Water Quality Results to Benchmarks

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Croton System						
Amawalk Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	3	na	na	≥40	79
Chloride (mg L^{-1})	40	0			30	
Chlorophyll *a* (µg L^{-1})	15	10	0	0	10	9.5
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7.0	0			6	
Fecal coliforms (coliform $100mL^{-1}$)	20	40	3	8	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	0			0.3	
pH (units)	6.5-8.5	40	9	23	na	na
Dissolved sodium (mg L^{-1})	20	0			15	
Soluble reactive phosphorus (µg L^{-1})	15	0			na	na
Sulfate (mg L^{-1})	25	0			15	
Total ammonia-N (mg L^{-1})	0.10	0			0.05	
Total dissolved phosphorus (µg L^{-1})	15	0			na	na
Total dissolved solids (mg L^{-1})[2]	175	25	25	100	150	380
Total phosphorus (µg L^{-1})	15	40	28	70	na	na
Total phytoplankton (ASU mL^{-1})	2000	10	0	0	na	na
Primary genus (ASU mL^{-1})	1000	10	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	10	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	3	0	0	5	2.1
Turbidity (NTU)	5	25	0	0	na	na
Bog Brook Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	5	na	na	≥40	73
Chloride (mg L^{-1})	40	5	5	100	30	70.9
Chlorophyll *a* (µg L^{-1})	15	5	0	0	10	4.9
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7.0	12	0	0	6	3.7
Fecal coliforms (coliform $100mL^{-1}$)	20	40	1	3	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	12	0	0	0.3	0.05
pH (units)	6.5-8.5	25	6	24	na	na
Dissolved sodium (mg L^{-1})	20	5	5	100	15	36.9

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Soluble reactive phosphorus (µg L^{-1})	15	12	0	0	na	na
Sulfate (mg L^{-1})	25	5	0	0	15	8.7
Total ammonia-N (mg L^{-1})	0.10	12	0	0	0.05	0.01
Total dissolved phosphorus (µg L^{-1})	15	12	0	0	na	na
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	260
Total phosphorus (µg L^{-1})	15	18	10	56	na	na
Total phytoplankton (ASU mL^{-1})	2000	5	0	0	na	na
Primary genus (ASU mL^{-1})	1000	5	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	5	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	5	0	0	5	1.9
Turbidity (NTU)	5	12	0	0	na	na
Boyd Corners Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	6	na	na	≥40	39
Chloride (mg L^{-1})	40	6	0	0	30	35.5
Chlorophyll *a* (µg L^{-1})	15	7	2	29	10	10.8
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7.0	14	0	0	6	3.3
Fecal coliforms (coliform 100mL^{-1})	20	43	1	2	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	14	0	0	0.3	0.02
pH (units)	6.5-8.5	15	0	0	na	na
Dissolved sodium (mg L^{-1})	20	6	6	100	15	22.8
Soluble reactive phosphorus (µg L^{-1})	15	14	0	0	na	na
Sulfate (mg L^{-1})	25	6	0	0	15	5.6
Total ammonia-N (mg L^{-1})	0.10	14	0	0	0.05	0.01
Total dissolved phosphorus (µg L^{-1})	15	14	0	0	na	na
Total dissolved solids (mg L^{-1})[2]	175	14	0	0	150	136
Total phosphorus (µg L^{-1})	15	14	4	29	na	na
Total phytoplankton (ASU mL^{-1})	2000	7	1	14	na	na
Primary genus (ASU mL^{-1})	1000	7	1	14	na	na
Secondary genus (ASU mL^{-1})	1000	7	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	6	0	0	5	1.1
Turbidity (NTU)	5	14	0	0	na	na
Cross River Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	≥40	51
Chloride (mg L^{-1})	40	8	7	88	30	41.4

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Chlorophyll *a* (µg L^{-1})	15	16	2	13	10	10.5
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7.0	27	0	0	6	3.5
Fecal coliforms (coliform 100mL^{-1})	20	48	1	2	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	26	0	0	0.3	<u>0.10</u>
pH (units)	6.5-8.5	48	8	17	na	na
Dissolved sodium (mg L^{-1})	20	9	9	100	15	21.6
Soluble reactive phosphorus (µg L^{-1})	15	26	1	4	na	na
Sulfate (mg L^{-1})	25	8	0	0	15	7.6
Total ammonia-N (mg L^{-1})	0.10	27	9	33	0.05	<u>0.11</u>
Total dissolved phosphorus (µg L^{-1})	15	27	4	15	na	na
Total dissolved solids (mg L^{-1})[2]	175	48	1	2	150	166
Total phosphorus (µg L^{-1})	15	48	32	67	na	na
Total phytoplankton (ASU mL^{-1})	2000	16	1	6	na	na
Primary genus (ASU mL^{-1})	1000	16	1	6	na	na
Secondary genus (ASU mL^{-1})	1000	16	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	9	0	0	5	2.7
Turbidity (NTU)	5	48	3	6	na	na
Croton Falls Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	18	na	na	≥40	65
Chloride (mg L^{-1})	40	18	18	100	30	66.6
Chlorophyll *a* (µg L^{-1})	15	22	8	33	10	22.9
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7.0	64	0	0	6	3.3
Fecal coliforms (coliform 100mL^{-1})	20	64	2	3	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	64	5	8	0.3	<u>0.18</u>
pH (units)	6.5-8.5	63	18	29	na	na
Dissolved sodium (mg L^{-1})	20	18	18	100	15	38.9
Soluble reactive phosphorus (µg L^{-1})	15	64	3	5	na	na
Sulfate (mg L^{-1})	25	18	0	0	15	8.7
Total ammonia-N (mg L^{-1})	0.10	64	11	17	0.05	<u>0.06</u>
Total dissolved phosphorus (µg L^{-1})	15	62	5	8	na	na
Total dissolved solids (mg L^{-1})[2]	175	64	63	98	150	276
Total phosphorus (µg L^{-1})	15	62	24	39	na	na
Total phytoplankton (ASU mL^{-1})	2000	22	6	27	na	na

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Primary genus (ASU mL^{-1})	1000	22	8	36	na	na
Secondary genus (ASU mL^{-1})	1000	22	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	9	0	0	5	2.3
Turbidity (NTU)	5	64	15	23	na	na
Diverting Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	5	na	na	≥40	81
Chloride (mg L^{-1})	40	0			30	
Chlorophyll *a* (µg L^{-1})	15	10	4	40	10	17.4
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7	0			6	
Fecal coliforms (coliform 100mL^{-1})	20	39	4	10	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	0			0.3	
pH (units)	6.5-8.5	32	0	0	na	na
Dissolved sodium (mg L^{-1})	20	0			15	
Soluble reactive phosphorus (µg L^{-1})	15	0			na	na
Sulfate (mg L^{-1})	25	0			15	
Total ammonia-N (mg L^{-1})	0.1	0			0.05	
Total dissolved phosphorus (µg L^{-1})	15	0			na	na
Total dissolved solids (mg L^{-1})[2]	175	22	22	100	150	247
Total phosphorus (µg L^{-1})	15	34	32	94	na	na
Total phytoplankton (ASU mL^{-1})	2000	10	0	0	na	na
Primary genus (ASU mL^{-1})	1000	10	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	10	0	0	na	na
Total suspended solids (mg L^{-1})	8	5	0	0	5	3.7
Turbidity (NTU)	5	22	2	9	na	na
East Branch Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	6	na	na	≥40	82
Chloride (mg L^{-1})	40	6	6	100	30	51.2
Chlorophyll *a* (µg L^{-1})	15	5	2	40	10	16.9
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7	15	0	0	6	3.8
Fecal coliforms (coliform 100mL^{-1})	20	45	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	15	0	0	0.3	0.12
pH (units)	6.5-8.5	30	1	3	na	na
Dissolved sodium (mg L^{-1})	20	6	6	100	15	27.7

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Soluble reactive phosphorus (µg L^{-1})	15	15	0	0	na	na
Sulfate (mg L^{-1})	25	6	0	0	15	8.3
Total ammonia-N (mg L^{-1})	0.1	15	1	7	0.05	<u>0.04</u>
Total dissolved phosphorus (µg L^{-1})	15	15	2	13	na	na
Total dissolved solids (mg L^{-1})[2]	175	15	15	100	150	229
Total phosphorus (µg L^{-1})	15	24	19	79	na	na
Total phytoplankton (ASU mL^{-1})	2000	5	0	0	na	na
Primary genus (ASU mL^{-1})	1000	5	1	20	na	na
Secondary genus (ASU mL^{-1})	1000	5	0	0	na	na
Total suspended solids (mg L^{-1})	8	6	0	0	5	<u>2.1</u>
Turbidity (NTU)	5	15	2	13	na	na
Kirk Lake						
Alkalinity (mg $CaCO_3$ L^{-1})	na	1	na	na	≥40	64
Chloride (mg L^{-1})	40	1	1	100	30	88.1
Chlorophyll *a* (µg L^{-1})	15	1	1	100	10	24.0
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7	1	0	0	6	4.7
Fecal coliforms (coliform 100mL^{-1})	20	40	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	1	0	0	0.3	<0.02
pH (units)	6.5-8.5	15	4	27	na	na
Dissolved sodium (mg L^{-1})	20	1	1	100	15	45.7
Soluble reactive phosphorus (µg L^{-1})	15	1	0	0	na	na
Sulfate (mg L^{-1})	25	1	0	0	15	8.1
Total ammonia-N (mg L^{-1})	0.1	1	0	0	0.05	<0.02
Total dissolved phosphorus (µg L^{-1})	15	1	0	0	na	na
Total dissolved solids (mg L^{-1})[2]	175	1	1	100	150	282
Total phosphorus (µg L^{-1})	15	2	2	100	na	na
Total phytoplankton (ASU mL^{-1})	2000	1	0	0	na	na
Primary genus (ASU mL^{-1})	1000	1	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	1	0	0	na	na
Total suspended solids (mg L^{-1})	8	1	0	0	5	5.6
Turbidity (NTU)	5	1	0	0	na	na
Lake Gilead						
Alkalinity (mg $CaCO_3$ L^{-1})	na	6	na	na	≥40	46
Chloride (mg L^{-1})	40	6	6	100	30	65.5

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Chlorophyll *a* (µg L^{-1})	15	2	0	0	10	3.1
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7	6	0	0	6	3.3
Fecal coliforms (coliform 100mL^{-1})	20	40	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	6	0	0	0.3	0.08
pH (units)	6.5-8.5	15	2	13	na	na
Dissolved sodium (mg L^{-1})	20	6	6	100	15	34.6
Soluble reactive phosphorus (µg L^{-1})	15	6	2	33	na	na
Sulfate (mg L^{-1})	25	6	0	0	15	8.1
Total ammonia-N (mg L^{-1})	0.1	6	1	17	0.05	<0.02
Total dissolved phosphorus (µg L^{-1})	15	6	2	33	na	na
Total dissolved solids (mg L^{-1})[2]	175	6	6	100	150	214
Total phosphorus (µg L^{-1})	15	9	4	44	na	na
Total phytoplankton (ASU mL^{-1})	2000	2	0	0	na	na
Primary genus (ASU mL^{-1})	1000	2	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	2	0	0	na	na
Total suspended solids (mg L^{-1})	8	6	0	0	5	1.1
Turbidity (NTU)	5	6	0	0	na	na
Lake Gleneida						
Alkalinity (mg $CaCO_3$ L^{-1})	na	6	na	na	≥40	66
Chloride (mg L^{-1})	40	6	6	100	30	114.3
Chlorophyll *a* (µg L^{-1})	15	2	0	0	10	2.3
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7	6	0	0	6	2.8
Fecal coliforms (coliform 100mL^{-1})	20	35	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	6	0	0	0.3	0.02
pH (units)	6.5-8.5	15	2	13	na	na
Dissolved sodium (mg L^{-1})	20	6	6	100	15	58.9
Soluble reactive phosphorus (µg L^{-1})	15	6	0	0	na	na
Sulfate (mg L^{-1})	25	6	0	0	15	6.6
Total ammonia-N (mg L^{-1})	0.1	6	2	33	0.05	<0.02
Total dissolved phosphorus (µg L^{-1})	15	6	0	0	na	na
Total dissolved solids (mg L^{-1})[2]	175	6	6	100	150	341
Total phosphorus (µg L^{-1})	15	9	3	33	na	na
Total phytoplankton (ASU mL^{-1})	2000	2	0	0	na	na

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Primary genus (ASU mL^{-1})	1000	2	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	2	0	0	na	na
Total suspended solids (mg L^{-1})	8	6	0	0	5	1.3
Turbidity (NTU)	5	6	0	0	na	na
Middle Branch Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	6	na	na	≥40	62
Chloride (mg L^{-1})	40	0			30	
Chlorophyll *a* (µg L^{-1})	15	10	4	40	10	12.4
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7	0			6	
Fecal coliforms (coliform 100mL^{-1})	20	40	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	0			0.3	
pH (units)	6.5-8.5	38	4	11	na	na
Dissolved sodium (mg L^{-1})	20	0			15	
Soluble reactive phosphorus (µg L^{-1})	15	0			na	na
Sulfate (mg L^{-1})	25	0			15	
Total ammonia-N (mg L^{-1})	0.1	0			0.05	
Total dissolved phosphorus (µg L^{-1})	15	0			na	na
Total dissolved solids (mg L^{-1})[2]	175	25	25	100	150	290
Total phosphorus (µg L^{-1})	15	40	26	65	na	na
Total phytoplankton (ASU mL^{-1})	2000	10	2	20	na	na
Primary genus (ASU mL^{-1})	1000	10	4	40	na	na
Secondary genus (ASU mL^{-1})	1000	10	0	0	na	na
Total suspended solids (mg L^{-1})	8	6	0	0	5	2.7
Turbidity (NTU)	5	25	2	8	na	na
Muscoot Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	4	na	na	≥40	75
Chloride (mg L^{-1})	40	0			30	
Chlorophyll *a* (µg L^{-1})	15	20	9	45	10	19.2
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7	6	0	0	6	3.0
Fecal coliforms (coliform 100mL^{-1})	20	51	11	22	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	6	1	17	0.3	0.49
pH (units)	6.5-8.5	45	3	7	na	na
Dissolved sodium (mg L^{-1})	20	0			15	

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Soluble reactive phosphorus (µg L^{-1})	15	6	0	0	na	na
Sulfate (mg L^{-1})	25	0			15	
Total ammonia-N (mg L^{-1})	0.1	6	0	0	0.05	<0.02
Total dissolved phosphorus (µg L^{-1})	15	6	0	0	na	na
Total dissolved solids (mg L^{-1})[2]	175	31	31	100	150	257
Total phosphorus (µg L^{-1})	15	51	50	98	na	na
Total phytoplankton (ASU mL^{-1})	2000	20	5	25	na	na
Primary genus (ASU mL^{-1})	1000	20	4	20	na	na
Secondary genus (ASU mL^{-1})	1000	20	0	0	na	na
Total suspended solids (mg L^{-1})	8	4	0	0	5	3.9
Turbidity (NTU)	5	31	5	16	na	na
New Croton Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	30	na	na	≥40	66
Chloride (mg L^{-1})	40	30	30	100	30	68.5
Chlorophyll *a* (µg L^{-1})	15	56	12	21	10	11.6
Color (Pt-Co units)	15	10	10	100	na	na
Dissolved organic carbon (mg L^{-1})	7	168	0	0	6	3.3
Fecal coliforms (coliform 100mL^{-1})	20	168	6	4	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	168	4	2	0.3	<u>0.18</u>
pH (units)	6.5-8.5	168	19	11	na	na
Dissolved sodium (mg L^{-1})	20	30	30	100	15	36.5
Soluble reactive phosphorus (µg L^{-1})	15	168	7	4	na	na
Sulfate (mg L^{-1})	25	30	0	0	15	8.8
Total ammonia-N (mg L^{-1})	0.1	168	36	21	0.05	<u>0.12</u>
Total dissolved phosphorus (µg L^{-1})	15	168	21	13	na	na
Total dissolved solids (mg L^{-1})[2]	175	168	168	100	150	246
Total phosphorus (µg L^{-1})	15	168	89	53	na	na
Total phytoplankton (ASU mL^{-1})	2000	56	4	7	na	na
Primary genus (ASU mL^{-1})	1000	56	4	7	na	na
Secondary genus (ASU mL^{-1})	1000	56	0	0	na	na
Total suspended solids (mg L^{-1})	8	56	0	0	5	<u>1.8</u>
Turbidity (NTU)	5	168	11	7	na	na
Titicus Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	3	na	na	≥40	78
Chloride (mg L^{-1})	40	0			30	

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Chlorophyll *a* (µg L^{-1})	15	10	3	30	10	13.6
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	7	0			6	
Fecal coliforms (coliform 100mL^{-1})	20	40	4	10	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	0			0.3	
pH (units)	6.5-8.5	40	8	20	na	na
Dissolved sodium (mg L^{-1})	20	0			15	
Soluble reactive phosphorus (µg L^{-1})	15	0			na	na
Sulfate (mg L^{-1})	25	0			15	
Total ammonia-N (mg L^{-1})	0.1	0			0.05	
Total dissolved phosphorus (µg L^{-1})	15	0			na	na
Total dissolved solids (mg L^{-1})[2]	175	25	25	100	150	199
Total phosphorus (µg L^{-1})	15	40	33	83	na	na
Total phytoplankton (ASU mL^{-1})	2000	10	1	10	na	na
Primary genus (ASU mL^{-1})	1000	10	1	10	na	na
Secondary genus (ASU mL^{-1})	1000	10	0	0	na	na
Total suspended solids (mg L^{-1})	8	3	0	0	5	3.5
Turbidity (NTU)	5	25	1	4	na	na
Catskill System						
Ashokan East Basin Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	10	na	na	≥10	12
Chloride (mg L^{-1})	12	6	0	0	8	7.8
Chlorophyll *a* (µg L^{-1})	12	24	0	0	7	2.8
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	4	64	1	2	3	1.8
Fecal coliforms (coliform 100mL^{-1})	20	64	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	64	0	0	0.3	0.04
pH (units)	6.5-8.5	48	15	31	na	na
Dissolved sodium (mg L^{-1})	16	10	10	100	3	5.0
Soluble reactive phosphorus (µg L^{-1})	15	64	0	0	na	na
Sulfate (mg L^{-1})	15	6	0	0	10	2.9
Total ammonia-N (mg L^{-1})	0.1	64	0	0	0.05	0.03
Total dissolved phosphorus (µg L^{-1})	15	64	0	0	na	na
Total dissolved solids (mg L^{-1})[2]	50	64	0	0	40	38
Total phosphorus (µg L^{-1})	15	64	3	5	na	na

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Total phytoplankton (ASU mL^{-1})	2000	24	0	0	na	na
Primary genus (ASU mL^{-1})	1000	23	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	22	0	0	na	na
Total suspended solids (mg L^{-1})	8	64	1	2	5	<u>1.6</u>
Turbidity (NTU)	5	64	4	6	na	na
Ashokan West Basin Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	11	na	na	≥10	12
Chloride (mg L^{-1})	12	11	0	0	8	7.7
Chlorophyll *a* (µg L^{-1})	12	24	1	4	7	4.2
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	4	72	0	0	3	<u>1.7</u>
Fecal coliforms (coliform 100mL^{-1})	20	72	5	7	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	72	0	0	0.3	<u>0.13</u>
pH (units)	6.5-8.5	72	9	13	na	na
Dissolved sodium (mg L^{-1})	16	10	10	100	3	4.8
Soluble reactive phosphorus (µg L^{-1})	15	72	0	0	na	na
Sulfate (mg L^{-1})	15	11	0	0	10	2.8
Total ammonia-N (mg L^{-1})	0.1	72	0	0	0.05	<u>0.03</u>
Total dissolved phosphorus (µg L^{-1})	15	72	1	1	na	na
Total dissolved solids (mg L^{-1})[2]	50	72	5	7	40	39
Total phosphorus (µg L^{-1})	15	72	6	8	na	na
Total phytoplankton (ASU mL^{-1})	2000	24	0	0	na	na
Primary genus (ASU mL^{-1})	1000	24	1	4	na	na
Secondary genus (ASU mL^{-1})	1000	24	0	0	na	na
Total suspended solids (mg L^{-1})	8	72	6	8	5	3.2
Turbidity (NTU)	5	72	21	29	na	na
Schoharie Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	≥10	17
Chloride (mg L^{-1})	12	9	0	0	8	9.4
Chlorophyll *a* (µg L^{-1})	12	32	0	0	7	2.9
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	4	89	0	0	3	2.5
Fecal coliforms (coliform 100mL^{-1})	20	84	24	29	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	65	0	0	0.3	<u>0.14</u>
pH (units)	6.5-8.5	89	5	6	na	na

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Dissolved sodium (mg L^{-1})	16	9	9	100	3	6.1
Soluble reactive phosphorus (µg L^{-1})	15	65	0	0	na	na
Sulfate (mg L^{-1})	15	9	0	0	10	2.8
Total ammonia-N (mg L^{-1})	0.1	65	0	0	0.05	0.03
Total dissolved phosphorus (µg L^{-1})	15	65	1	2	na	na
Total dissolved solids (mg L^{-1})[2]	50	89	45	51	40	52
Total phosphorus (µg L^{-1})	15	89	38	43	na	na
Total phytoplankton (ASU mL^{-1})	2000	32	0	0	na	na
Primary genus (ASU mL^{-1})	1000	32	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	32	0	0	na	na
Total suspended solids (mg L^{-1})	8	89	28	31	5	6.4
Turbidity (NTU)	5	89	61	69	na	na
Delaware System						
Cannonsville Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	18	na	na	≥10	18
Chloride (mg L^{-1})	12	18	6	33	8	11.5
Chlorophyll *a* (µg L^{-1})	12	35	5	14	7	7.8
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	4	102	0	0	3	1.9
Fecal coliforms (coliform 100mL^{-1})	20	100	4	4	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	102	24	24	0.3	0.32
pH (units)	6.5-8.5	102	23	23	na	na
Dissolved sodium (mg L^{-1})	16	18	18	100	3	7.6
Soluble reactive phosphorus (µg L^{-1})	15	102	2	2	na	na
Sulfate (mg L^{-1})	15	18	0	0	10	4.0
Total ammonia-N (mg L^{-1})	0.1	102	7	7	0.05	0.04
Total dissolved phosphorus (µg L^{-1})	15	102	4	4	na	na
Total dissolved solids (mg L^{-1})[2]	50	102	101	99	40	62
Total phosphorus (µg L^{-1})	15	101	62	61	na	na
Total phytoplankton (ASU mL^{-1})	2000	36	4	11	na	na
Primary genus (ASU mL^{-1})	1000	36	6	17	na	na
Secondary genus (ASU mL^{-1})	1000	36	0	0	na	na
Total suspended solids (mg L^{-1})	8	39	2	5	5	3.0
Turbidity (NTU)	5	102	24	24	na	na

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Neversink Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	11	na	na	≥10	4
Chloride (mg L^{-1})	12	11	0	0	8	3.7
Chlorophyll *a* (µg L^{-1})	12	24	0	0	7	3.8
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	4	73	0	0	3	1.9
Fecal coliforms (coliform 100mL^{-1})	20	73	1	1	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	73	0	0	0.3	<u>0.19</u>
pH (units)	6.5-8.5	63	44	70	na	na
Dissolved sodium (mg L^{-1})	16	11	0	0	3	2.2
Soluble reactive phosphorus (µg L^{-1})	15	73	0	0	na	na
Sulfate (mg L^{-1})	15	11	0	0	10	2.3
Total ammonia-N (mg L^{-1})	0.1	73	1	1	0.05	<u>0.03</u>
Total dissolved phosphorus (µg L^{-1})	15	73	0	0	na	na
Total dissolved solids (mg L^{-1})[2]	50	73	0	0	40	19
Total phosphorus (µg L^{-1})	15	73	1	1	na	na
Total phytoplankton (ASU mL^{-1})	2000	24	0	0	na	na
Primary genus (ASU mL^{-1})	1000	24	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	24	0	0	na	na
Total suspended solids (mg L^{-1})	8	24	0	0	5	<u>1.1</u>
Turbidity (NTU)	5	73	2	3	na	na
Pepacton Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	21	na	na	≥10	14
Chloride (mg L^{-1})	12	21	0	0	8	8.1
Chlorophyll *a* (µg L^{-1})	12	35	3	9	7	6.8
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	4	103	0	0	3	1.7
Fecal coliforms (coliform 100mL^{-1})	20	103	1	1	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	103	0	0	0.3	<u>0.17</u>
pH (units)	6.5-8.5	103	15	15	na	na
Dissolved sodium (mg L^{-1})	16	21	21	100	3	5.0
Soluble reactive phosphorus (µg L^{-1})	15	103	0	0	na	na
Sulfate (mg L^{-1})	15	21	0	0	10	2.9
Total ammonia-N (mg L^{-1})	0.1	102	0	0	0.05	<u>0.03</u>
Total dissolved phosphorus (µg L^{-1})	15	103	0	0	na	na

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Total dissolved solids (mg L^{-1})[2]	50	103	14	14	40	45
Total phosphorus (µg L^{-1})	15	103	17	17	na	na
Total phytoplankton (ASU mL^{-1})	2000	34	2	6	na	na
Primary genus (ASU mL^{-1})	1000	34	5	15	na	na
Secondary genus (ASU mL^{-1})	1000	34	0	0	na	na
Total suspended solids (mg L^{-1})	8	50	0	0	5	0.9
Turbidity (NTU)	5	103	9	9	na	na
Rondout Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	12	na	na	≥10	11
Chloride (mg L^{-1})	12	12	0	0	8	8.0
Chlorophyll *a* (µg L^{-1})	12	24	2	8	7	5.2
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	4	56	0	0	3	1.8
Fecal coliforms (coliform 100mL^{-1})	20	80	2	3	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	56	0	0	0.3	0.19
pH (units)	6.5-8.5	80	14	18	na	na
Dissolved sodium (mg L^{-1})	16	8	8	100	3	5.1
Soluble reactive phosphorus (µg L^{-1})	15	56	0	0	na	na
Sulfate (mg L^{-1})	15	12	0	0	10	3.1
Total ammonia-N (mg L^{-1})	0.1	56	0	0	0.05	0.03
Total dissolved phosphorus (µg L^{-1})	15	56	0	0	na	na
Total dissolved solids (mg L^{-1})[2]	50	80	1	1	40	41
Total phosphorus (µg L^{-1})	15	80	1	1	na	na
Total phytoplankton (ASU mL^{-1})	2000	24	0	0	na	na
Primary genus (ASU mL^{-1})	1000	24	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	24	0	0	na	na
Total suspended solids (mg L^{-1})	8	32	0	0	5	1.0
Turbidity (NTU)	5	80	2	3	na	na
West Branch Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	15	na	na	≥10	23
Chloride (mg L^{-1})	12	15	12	80	8	20.4
Chlorophyll *a* (µg L^{-1})	12	32	1	3	7	6.5
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	4	71	0	0	3	2.2
Fecal coliforms (coliform 100mL^{-1})	20	71	1	1	na	na

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Nitrate+Nitrite-N (mg L^{-1})	0.5	71	0	0	0.3	0.11
pH (units)	6.5-8.5	71	6	8	na	na
Dissolved sodium (mg L^{-1})	16	15	15	100	3	12.6
Soluble reactive phosphorus (µg L^{-1})	15	71	0	0	na	na
Sulfate (mg L^{-1})	15	15	0	0	10	5.0
Total ammonia-N (mg L^{-1})	0.1	71	0	0	0.05	0.02
Total dissolved phosphorus (µg L^{-1})	15	71	0	0	na	na
Total dissolved solids (mg L^{-1})[2]	50	71	47	66	40	77
Total phosphorus (µg L^{-1})	15	71	12	17	na	na
Total phytoplankton (ASU mL^{-1})	2000	32	0	0	na	na
Primary genus (ASU mL^{-1})	1000	32	1	3	na	na
Secondary genus (ASU mL^{-1})	1000	32	0	0	na	na
Total suspended solids (mg L^{-1})	8	9	0	0	5	1.5
Turbidity (NTU)	5	71	0	0	na	na
Terminal Reservoir for Catskill/Delaware System						
Kensico Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	24	na	na	≥10	12
Chloride (mg L^{-1})	12	24	0	0	8	10.1
Chlorophyll *a* (µg L^{-1})	12	60	0	0	7	3.3
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})	4	190	0	0	3	1.7
Fecal coliforms (coliform $100mL^{-1}$)	20	190	1	1	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	190	0	0	0.3	0.13
pH (units)	6.5-8.5	190	19	10	na	na
Dissolved sodium (mg L^{-1})	16	24	24	100	3	6.2
Soluble reactive phosphorus (µg L^{-1})	15	190	0	0	na	na
Sulfate (mg L^{-1})	15	24	0	0	10	3.8
Total ammonia-N (mg L^{-1})	0.1	190	0	0	0.05	0.02
Total dissolved phosphorus (µg L^{-1})	15	190	0	0	na	na
Total dissolved solids (mg L^{-1})[2]	50	190	28	15	40	47
Total phosphorus (µg L^{-1})	15	190	1	1	na	na
Total phytoplankton (ASU mL^{-1})	2000	61	0	0	na	na
Primary genus (ASU mL^{-1})	1000	61	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	61	0	0	na	na
Total suspended solids (mg L^{-1})	8	71	0	0	5	1.0

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Turbidity (NTU)	5	190	0	0	na	na

na = not applicable.

[1]Means were estimated using recommended techniques according to Helsel (2005). For 100% uncensored data the arithmetic mean is reported. For <50% censored data the mean is estimated using the Kaplan-Meier Method. These estimates are underlined with one line. For 50-80% censored data the robust ROS method was used. These estimates are underlined with two lines. The ROS model will not provide an estimate if all detected values are equivalent to the detection limit, if there are two or fewer detections, or if >80% of the data is censored. In these cases we cannot estimate a mean and instead report the detection limit preceded by <.

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

Appendix G. Comparison of Stream Water Quality Results to Benchmarks

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Ashokan Watershed						
E10I (Bushkill at West Shokan)						
Alkalinity (mg L^{-1})	>10.0	12	9	75	na	7.5
Chloride (mg L^{-1})	50	12	0	0	10	3.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	0.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.09
Sulfate (mg L^{-1})	15	5	0	0	10	2.9
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.01
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	24
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.4
E16i (Esopus Brook at Coldbrook)						
Alkalinity (mg L^{-1})	>10.0	12	3	25	na	15.1
Chloride (mg L^{-1})	50	12	0	0	10	10.6
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.16
Sulfate (mg L^{-1})	15	5	0	0	10	2.8
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	5	42	40	49
Dissolved sodium (mg L^{-1})	10	3	1	33	5	8.5
E5 (Esopus Creek at Allaben)						
Alkalinity (mg L^{-1})	>10.0	12	7	58	na	13.4
Chloride (mg L^{-1})	50	12	0	0	10	9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.15
Sulfate (mg L^{-1})	15	4	0	0	10	3
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	3	25	40	43
Dissolved sodium (mg L^{-1})	10	4	0	0	5	5.3

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
Schoharie Watershed						
S5I (Schoharie Creek at Prattsville)						
Alkalinity (mg L^{-1})	>10.0	12	0	0	na	21.4
Chloride (mg L^{-1})	50	12	0	0	10	12.2
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.8
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.18
Sulfate (mg L^{-1})	15	4	0	0	10	3.3
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	9	75	40	63
Dissolved sodium (mg L^{-1})	10	4	1	25	5	7.5
S6I (Bear Kill at Hardenburgh Falls)						
Alkalinity (mg L^{-1})	>10.0	12	0	0	na	29.8
Chloride (mg L^{-1})	50	12	0	0	10	22
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.41
Sulfate (mg L^{-1})	15	4	0	0	10	4.8
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	12	100	40	98
Dissolved sodium (mg L^{-1})	10	4	3	75	5	11.8
S7I (Manor Kill)						
Alkalinity (mg L^{-1})	>10.0	12	0	0	na	27.7
Chloride (mg L^{-1})	50	12	0	0	10	11
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.1
Sulfate (mg L^{-1})	15	4	0	0	10	3.7
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	9	75	40	67
Dissolved sodium (mg L^{-1})	10	4	0	0	5	6.7

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
SRR2CM (Schoharie Reservoir Diversion) [3]						
Alkalinity (mg L^{-1})	>10.0	12	0	0	na	13.5
Chloride (mg L^{-1})	50	12	0	0	10	10.6
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.16
Sulfate (mg L^{-1})	15	4	0	0	10	3
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	7	58	40	53
Dissolved sodium (mg L^{-1})	10	4	0	0	5	6.1
Cannonsville Watershed						
C-7 (Trout Creek above Cannonsville Reservoir)						
Alkalinity (mg L^{-1})	>10.0	11	1	9	na	17.2
Chloride (mg L^{-1})	50	11	0	0	10	16.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.4
Nitrate+Nitrite-N (mg L^{-1})	1.5	11	0	0	0.4	0.4
Sulfate (mg L^{-1})	15	4	0	0	10	5.2
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	11	92	40	71
Dissolved sodium (mg L^{-1})	10	4	1	25	5	9.7
C-8 (Loomis Brook above Cannonsville Reservoir						
Alkalinity (mg L^{-1})	>10.0	12	1	8	na	16.3
Chloride (mg L^{-1})	50	12	0	0	10	15.2
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.34
Sulfate (mg L^{-1})	15	4	0	0	10	4.5
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.01
Total dissolved solids (mg L^{-1})[2]	50	12	12	100	40	67
Dissolved sodium (mg L^{-1})	10	4	2	50	5	9.6

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
CBS (formerly WDBN, West Branch Delaware River at Beerston Bridge)						
Alkalinity (mg L^{-1})	>10.0	12	0	0	na	20.4
Chloride (mg L^{-1})	50	12	0	0	10	14.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.61
Sulfate (mg L^{-1})	15	4	0	0	10	4.8
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	10	83	40	73
Dissolved sodium (mg L^{-1})	10	4	1	25	5	9.8
Neversink Watershed						
NCG (Neversink River near Claryville)						
Alkalinity (mg L^{-1})	>10.0	12	12	100	na	3.9
Chloride (mg L^{-1})	50	12	0	0	10	3.8
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.23
Sulfate (mg L^{-1})	15	1	0	0	10	2.3
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.01
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	20
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.2
NK4 (Aden Brook above Neversink Reservoir)						
Alkalinity (mg L^{-1})	>10.0	12	9	75	na	7.3
Chloride (mg L^{-1})	50	12	0	0	10	4.0
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.2
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.21
Sulfate (mg L^{-1})	15	1	0	0	10	2.8
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	27
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.3

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
NK6 (Kramer Brook above Neversink Reservoir)						
Alkalinity (mg L^{-1})	>10.0	12	6	50	na	10.9
Chloride (mg L^{-1})	50	12	1	8	10	36
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.35
Sulfate (mg L^{-1})	15	1	0	0	10	4.5
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<u>0.04</u>
Total dissolved solids (mg L^{-1})[2]	50	12	12	100	40	107
Dissolved sodium (mg L^{-1})	10	4	4	100	5	18.7
Pepacton Watershed						
P-13 (Tremper Kill above Pepacton Reservoir)						
Alkalinity (mg L^{-1})	>10.0	12	0	0	na	17.5
Chloride (mg L^{-1})	50	12	0	0	10	11.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.7
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.34
Sulfate (mg L^{-1})	15	3	0	0	10	3.9
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	7	58	40	59
Dissolved sodium (mg L^{-1})	10	4	1	25	5	7.2
P-21 (Platte Kill at Dunraven)						
Alkalinity (mg L^{-1})	>10.0	12	0	0	na	19.1
Chloride (mg L^{-1})	50	12	0	0	10	9.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.8
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.3
Sulfate (mg L^{-1})	15	3	0	0	10	3.7
Total Ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<u>0.02</u>
Total dissolved solids (mg L^{-1})[2]	50	12	6	50	40	56
Dissolved sodium (mg L^{-1})	10	4	1	25	5	6.2

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
P-60 (Mill Brook near Dunraven)						
Alkalinity (mg L^{-1})	>10.0	12	5	42	na	11.8
Chloride (mg L^{-1})	50	12	0	0	10	1.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.3
Sulfate (mg L^{-1})	15	3	0	0	10	3.1
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	27
Dissolved sodium (mg L^{-1})	10	4	0	0	5	1.4
P-7 (Terry Clove above Pepacton Reservoir)						
Alkalinity (mg L^{-1})	>10.0	12	2	17	na	15.2
Chloride (mg L^{-1})	50	12	0	0	10	1.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.4
Sulfate (mg L^{-1})	15	3	0	0	10	3.7
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	32
Dissolved sodium (mg L^{-1})	10	4	0	0	5	1.3
P-8 (Fall Clove above Pepacton Reservoir)						
Alkalinity (mg L^{-1})	>10.0	12	2	17	na	14.3
Chloride (mg L^{-1})	50	12	0	0	10	2.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.47
Sulfate (mg L^{-1})	15	3	0	0	10	3.8
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	35
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.2

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
PMSB (East Branch Delaware River near Margaretville)						
Alkalinity (mg L^{-1})	>10.0	12	0	0	na	19.1
Chloride (mg L^{-1})	50	12	0	0	10	12.4
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.34
Sulfate (mg L^{-1})	15	3	0	0	10	3.5
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	9	75	40	61
Dissolved sodium (mg L^{-1})	10	4	0	0	5	7.3
Rondout Reservoir						
RD1 (Sugarloaf Brook near Lowes Corners)						
Alkalinity (mg L^{-1})	>10.0	12	12	100	na	5.5
Chloride (mg L^{-1})	50	12	0	0	10	6.7
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.18
Sulfate (mg L^{-1})	15	3	0	0	10	3.4
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	31
Dissolved sodium (mg L^{-1})	10	4	0	0	5	3.7
RD4 (Sawkill Brook near Yagerville)						
Alkalinity (mg L^{-1})	>10.0	12	12	100	na	5.8
Chloride (mg L^{-1})	50	12	0	0	10	5.7
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.7
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.10
Sulfate (mg L^{-1})	15	3	0	0	10	4.2
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	30
Dissolved sodium (mg L^{-1})	10	4	0	0	5	3.4

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
RDOA (Rondout Creek near Lowes Corners)						
Alkalinity (mg L^{-1})	>10.0	12	12	100	na	4.1
Chloride (mg L^{-1})	50	12	0	0	10	4.3
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.2
Sulfate (mg L^{-1})	15	3	0	0	10	2.9
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	22
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.4
RGB (Chestnut Creek below Grahamsville STP)						
Alkalinity (mg L^{-1})	>10.0	12	8	67	na	9.3
Chloride (mg L^{-1})	50	12	0	0	10	17
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.4
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.35
Sulfate (mg L^{-1})	15	1	0	0	10	3.4
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	8	67	40	62
Dissolved sodium (mg L^{-1})	10	4	1	25	5	9.5

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
East of Hudson						
AMAWALKR (Amawalk Reservoir Release)						
Alkalinity (mg L^{-1})	>40.0	12	0	0	na	78.9
Chloride (mg L^{-1})	100	12	12	100	35	123.2
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.7
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	<u>0.34</u>
Sulfate (mg L^{-1})	25	4	0	0	15	9.5
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.1	<u>0.05</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	380
Dissolved sodium (mg L^{-1})	20	4	4	100	15	66.7
BOGEASTBRR (Combined release for Bog Brook and East Branch Reservoirs)						
Alkalinity (mg L^{-1})	>40.0	12	0	0	na	81.9
Chloride (mg L^{-1})	100	12	0	0	35	54.8
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.13
Sulfate (mg L^{-1})	25	4	0	0	15	9.6
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.1	<u>0.05</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	236
Dissolved sodium (mg L^{-1})	20	4	4	100	15	29.6
BOYDR (Boyd Corners Release) [3]						
Alkalinity (mg L^{-1})	>40.0	12	9	75	na	35.8
Chloride (mg L^{-1})	100	12	0	0	35	33.2
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	<u>0.06</u>
Sulfate (mg L^{-1})	25	4	0	0	15	5.8
Total ammonia-N (mg L^{-1})	0.20	12	1	8	0.1	<u>0.04</u>
Total dissolved solids (mg L^{-1})[2]	175	12	0	0	150	128
Dissolved sodium (mg L^{-1})	20	4	3	75	15	21.6

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
CROFALLSVC (Croton Falls Reservoir Release)						
Alkalinity (mg L^{-1})	>40.0	11	0	0	na	61.8
Chloride (mg L^{-1})	100	11	0	0	35	69.2
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	2.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	11	0	0	0.35	0.28
Sulfate (mg L^{-1})	25	4	0	0	15	9.5
Total ammonia-N (mg L^{-1})	0.20	11	0	0	0.1	0.06
Total dissolved solids (mg L^{-1})[2]	175	11	11	100	150	246
Dissolved sodium (mg L^{-1})	20	4	4	100	15	38.2
CROSS2 (Cross River above Cross River Reservoir)						
Alkalinity (mg L^{-1})	>40.0	12	1	8	na	58.5
Chloride (mg L^{-1})	100	12	0	0	35	40.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.17
Sulfate (mg L^{-1})	25	4	0	0	15	8.3
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.1	0.02
Total dissolved solids (mg L^{-1})[2]	175	12	8	67	150	177
Dissolved sodium (mg L^{-1})	20	4	4	100	15	22.9
CROSSRVVC (Cross River Reservoir Release)						
Alkalinity (mg L^{-1})	>40.0	12	0	0	na	49.7
Chloride (mg L^{-1})	100	12	0	0	35	41.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.12
Sulfate (mg L^{-1})	25	4	0	0	15	7.3
Total ammonia-N (mg L^{-1})	0.20	12	4	33	0.1	0.19
Total dissolved solids (mg L^{-1})[2]	175	12	1	8	150	169
Dissolved sodium (mg L^{-1})	20	4	4	100	15	22.2

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
DIVERTR (Diverting Reservoir Release)						
Alkalinity (mg L^{-1})	>40.0	12	0	0	na	81.7
Chloride (mg L^{-1})	100	12	0	0	35	63.8
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.8
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.2
Sulfate (mg L^{-1})	25	4	0	0	15	9.3
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.1	0.05
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	255
Dissolved sodium (mg L^{-1})	20	4	4	100	15	35.9
EASTBR (East Branch Croton River above East Branch River)						
Alkalinity (mg L^{-1})	>40.0	12	0	0	na	101
Chloride (mg L^{-1})	100	12	0	0	35	49
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.09
Sulfate (mg L^{-1})	25	4	0	0	15	9.1
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.1	0.02
Total dissolved solids (mg L^{-1})[2]	175	12	11	92	150	246
Dissolved sodium (mg L^{-1})	20	4	3	75	15	26.1
GYPSYTRL1 (Gypsy Trail Brook above West Branch Reservoir)						
Alkalinity (mg L^{-1})	>40.0	12	9	75	na	34.2
Chloride (mg L^{-1})	100	12	1	8	35	37.3
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.06
Sulfate (mg L^{-1})	25	4	0	0	15	6.3
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.1	<0.02
Total dissolved solids (mg L^{-1})[2]	175	12	2	17	150	137
Dissolved sodium (mg L^{-1})	20	4	2	50	15	19.6

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
HORSEPD12 (Horse Pound Brook above West Branch Reservoir)						
Alkalinity (mg L^{-1})	>40.0	12	5	42	na	44.3
Chloride (mg L^{-1})	100	12	0	0	35	43.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.36
Sulfate (mg L^{-1})	25	4	0	0	15	8.6
Total Ammonia-N (mg L^{-1})	0.20	12	0	0	0.1	<0.02
Total dissolved solids (mg L^{-1})[2]	175	12	4	33	150	168
Dissolved sodium (mg L^{-1})	20	4	4	100	15	26.1
KISCO3 (Kisco River above New Croton Reservoir)						
Alkalinity (mg L^{-1})	>40.0	12	0	0	na	79.4
Chloride (mg L^{-1})	100	12	7	58	35	100.7
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.57
Sulfate (mg L^{-1})	25	4	0	0	15	14
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.1	0.02
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	338
Dissolved sodium (mg L^{-1})	20	4	4	100	15	51
LONGPD1 (Long Pond outflow above West Branch Reservoir)						
Alkalinity (mg L^{-1})	>40.0	12	0	0	na	59.8
Chloride (mg L^{-1})	100	12	3	25	35	98.6
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.8
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.27
Sulfate (mg L^{-1})	25	4	0	0	15	8.4
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.1	0.02
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	305
Dissolved sodium (mg L^{-1})	20	4	4	100	15	43.2

Comparison of stream water quality results to benchmarks.

Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
MIKE2 (Michael Brook above Croton Falls Reservoir)						
Alkalinity (mg L^{-1})	>40.0	12	6	50	na	84.7
Chloride (mg L^{-1})	100	12	12	100	35	217.8
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	6	50	0.35	3.70
Sulfate (mg L^{-1})	25	4	1	25	15	19.7
Total ammonia-N (mg L^{-1})	0.20	12	1	8	0.1	0.08
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	546
Dissolved sodium (mg L^{-1})	20	4	4	100	15	92.4
MUSCOOT10 (Muscoot River above Amawalk Reservoir)						
Alkalinity (mg L^{-1})	>40.0	12	0	0	na	85.7
Chloride (mg L^{-1})	100	12	12	100	35	145.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.54
Sulfate (mg L^{-1})	25	4	0	0	15	12
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.1	0.04
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	445
Dissolved sodium (mg L^{-1})	20	4	4	100	15	74.7
TITICUSR (Titicus Reservoir Release)						
Alkalinity (mg L^{-1})	>40.0	12	0	0	na	73.8
Chloride (mg L^{-1})	100	12	0	0	35	45.7
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.25
Sulfate (mg L^{-1})	25	4	0	0	15	7.6
Total ammonia-N (mg L^{-1})	0.20	12	4	33	0.1	0.14
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	207
Dissolved sodium (mg L^{-1})	20	4	4	100	15	23.5

Comparison of stream water quality results to benchmarks.

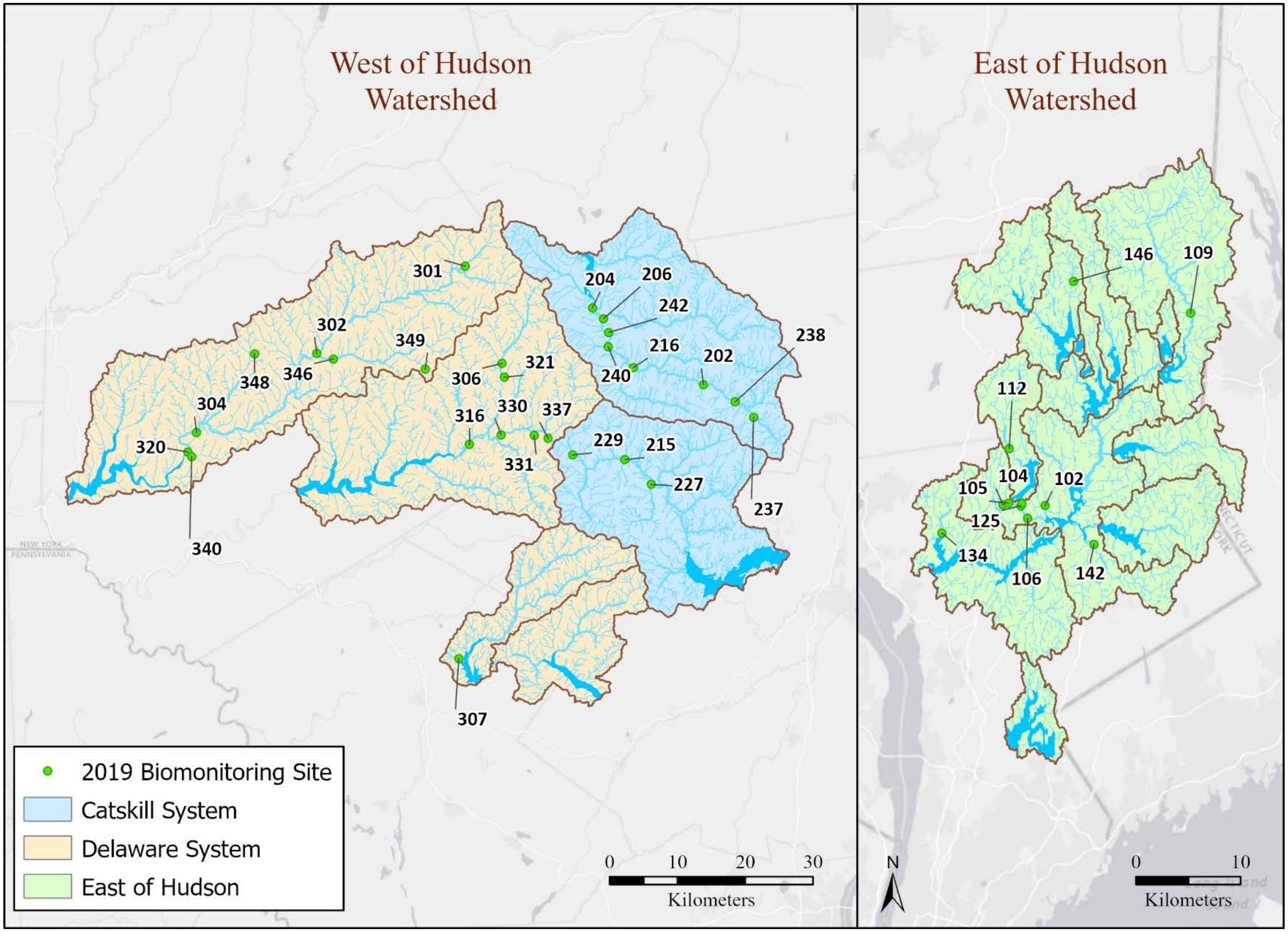
Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2019 Mean[1]
WESTBR7 (West Branch Croton River above Boyd Corners Reservoir)						
Alkalinity (mg L^{-1})	>40.0	12	8	67	na	38.2
Chloride (mg L^{-1})	100	12	0	0	35	33.2
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.8
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.04
Sulfate (mg L^{-1})	25	4	0	0	15	5.5
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.1	0.01
Total dissolved solids (mg L^{-1})[2]	175	12	1	8	150	131
Dissolved sodium (mg L^{-1})	20	4	2	50	15	20
WESTBRR (West Branch Reservoir Release)						
Alkalinity (mg L^{-1})	>10.0	12	0	0	na	18.9
Chloride (mg L^{-1})	50	12	0	0	10	16.8
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.13
Sulfate (mg L^{-1})	15	4	0	0	10	4.5
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.05	0.02
Total dissolved solids (mg L^{-1})[2]	50	12	10	83	40	71
Dissolved sodium (mg L^{-1})	10	4	2	50	5	10

na = not applicable.

[1]Means were estimated using recommended techniques according to Helsel (2005). For 100% uncensored data the arithmetic mean is reported. For <50% censored data the mean is estimated using the Kaplan-Meier Method. These estimates are underlined with one line. For 50-80% censored data the robust ROS method was used. These estimates are underlined using two lines. The ROS model will not provide an estimate if all detected values are equivalent to the detection limit, if there are two or fewer detections, or if >80% of the data is censored. In these cases we cannot estimate a mean and instead report the detection limit preceded by <.

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

Appendix H. Biomonitoring Sampling Sites



2019 Biomonitoring Sites and their Water Quality (WQ) Status

SYSTEM	SITE	WQ STATUS	WQ SITE	STREAM
EOH	102	NA	ANGLE5	Anglefly Brook
EOH	104	NA	HMILL7	Hallocks Mill Brook
EOH	105	NA	HMILL4	Hallocks Mill Brook
EOH	106	NA	MUSCOOT5	Muscoot River
EOH	109	NA	EASTBR	E. Br. Croton River
EOH	112	NA	MUSCOOT9	Muscoot River
EOH	125	NA	HMILL1	Hallocks Mill Brook
EOH	134	NA	HUNTER1	Hunter Brook
EOH	142	NA	STONE5	Stone Hill River
EOH	146	NA	HORSEPD12	Horse Pound Brook
EOH	154	NA	none	Muscoot River
Catskill	202	NA	S3	Schoharie Creek
Catskill	204	NA	S5I	Schoharie Creek
Catskill	206	NA	S10	Batavia Kill
Catskill	215	NA	E5	Esopus Creek
Catskill	216	NA	S4	Schoharie Creek
Catskill	227	NA	AEAWDL	Esopus Creek
Catskill	229	NA	BELLEGIG	Giggle Hollow
Catskill	237	NA	none	Schoharie Creek
Catskill	238	NA	none	Schoharie Creek
Catskill	240	NA	none	Schoharie Creek
Catskill	242	NA	none	Schoharie Creek
Delaware	301	NA	WDHOA	W. Br. Delaware River
Delaware	302	NA	none	W. Br. Delaware River
Delaware	304	NA	WSPB	W. Br. Delaware River
Delaware	306	NA	none	E. Br. Delaware River
Delaware	307	NA	NK4	Aden Brook
Delaware	316	NA	PMSB	E. Br. Delaware River
Delaware	320	NA	WDBN	W. Br. Delaware River
Delaware	321	NA	EDRB	E. Br. Delaware River
Delaware	330	NA	PBKG	Bush Kill
Delaware	331	NA	BELLETOD	Tributary to Bush Kill
Delaware	337	NA	BELLE5	Tributary to Emory Kill
Delaware	340	NA	none	Beer's Brook
Delaware	346	NA	CLDG	Little Delaware River
Delaware	348	NA	CEBHG	East Brook
Delaware	349	NA	CCBHG	Little Delaware River

Appendix I. Semivolatile and Volatile Organic Compounds and Herbicides

EPA 525.2 – Semivolatiles

2,4-Dinitrotoluene, 2,6-Dinitrotoluene, 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), 2,4 DDD, 2,4 DDE, 2,4-DDT

Herbicides

Glyphosate