NYC Department of Environmental Protection

2017 Watershed Water Quality Annual Report

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Bureau of Water Supply

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List of Acronyms

BEPA	Bureau of Environmental Planning and Analysis
CATALUM	Catskill Alum Chamber
CATUEC	Catskill Upper Effluent Chamber
CFR	Code of Federal Regulations
cfs	cubic feet per second
CUNY-RF	City University of New York Research Foundation
DBP	Disinfection Byproducts
DBPFP	Disinfection Byproduct formation potential
DEL17	Delaware Aqueduct Shaft Building 17
DEL18	Delaware Aqueduct Shaft Building 18
DEP	New York City Department of Environmental Protection
DRO	Diesel Range Organics
EOH	East of Hudson
FAD	Filtration Avoidance Determination
fDOM	Fluorescent Dissolved Organic Matter
GLEON	Global Lake Ecological Observatory Network
HEV	Human Enteric Virus
IAR	Inactivation Ratio
$\mu g\ L^{-1}$	microgram per liter
$\mu mhos\ cm^{-1}$	micromhos per centimeter
$mg\ L^{-1}$	milligram per liter
^{o}C	degree Celsius
MPN	Most Probable Number
MST	Microbial Source Tracking
ND	Non-detect
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
RHESSys	Regional Hydro-Ecologic Simulation System
ROS	Regression on order statistics
SSM	single sample maximum
SPDES	State Pollutant Discharge Elimination System
SVOC	Semivolatile Organic Compound
SWAT	Soil Water Assessment Tool
SWTR	Surface Water Treatment Rule
TNTC	too numerous to count
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
WMP	Waterfowl Management Program
WOH	West of Hudson
WQD	Water Quality Directorate
WRF	Water Research Foundation
WR&R	New York City Watershed Rules and Regulations
WUCA	Water Utility Climate Alliance
WWQMP	Watershed Water Quality Monitoring Plan
WWQO	Watershed Water Quality Operations
WQSR	Water Quality Science and Research
WWTP	Wastewater Treatment Plant

Acknowledgements

This report provides a summary of the scientific work conducted in 2017 to manage the water quality of the New York City water supply and to provide information for regulatory agencies and the general public. Commissioner of the Department of Environmental Protection, Vincent Sapienza, P.E., provided oversight of the Department throughout 2017. Paul Rush, P.E., Deputy Commissioner, provided guidance for the Bureau of Water Supply, and Mr. Steven Schindler, Director of Water Quality, continued to provide oversight and direction for the many activities of the Water Quality Directorate (WQD). Dr. Lorraine Janus, Chief of Water Quality Science and Research (WQSR), directed production of this report and her Division was responsible for the data analysis, interpretation, and report production. Ms. Lori Emery, succeeded by Mr. Andrew Bader, Chief of Watershed Water Quality Operations (WWQO), provided oversight of Watershed Field Operations, Watershed Laboratory Operations, Wildlife Studies, and Systems Support. WWQO also manages the database that forms 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. Andrew Bader, Deputy Chief for West of Hudson Water Quality Operations; Mr. Dale Borchert, Deputy Chief for East of Hudson Water Quality Operations; and Mr. John Canning, Section Chief, Early Warning Remote Monitoring (EWRM). Mr. Bader provided the information on Robotic Monitoring, Mr. Canning described EWRM, and Mr. Borchert described the Kensico Reservoir operations. Chapter 2 on Water Quantity was written by Mr. James Mayfield, Mr. Rich Van Dreason, and Mr. Matthew Giannetta with Mr. Alec Fu of Reservoir Operations and Mr. Ken DeRose of Water System Operations providing the operations and rainfall data presented in this chapter. Chapter 3 on Water Quality was written by Dr. Karen Moore and Mr. Rich Van Dreason with contributions from Mr. James Mayfield on streams, Mr. Don Kent on stream biomonitoring, and Mr. David Quentin on Special Investigations with contributions from Mr. Tracy Lawrence, Ms. Kirsten Askildsen, Mr. Andrew Bader, Mr. Dale Borchert, and Mr. James Broderick. Chapter 4 on Kensico Reservoir was written by Mr. Dave Van Valkenburg, Mr. Chris Nadareski, and Mr. Kurt Gabel. Chapter 5 on Pathogens was co-authored by Ms. Kerri Alderisio, Section Chief of Watershed Impacts and Pathogen Assessment, and Mr. Christian Pace. Chapter 6 Water Quality Modeling was written by Emmet Owens, P.E., Section Chief of Water Quality Modeling, Dr. Rakesh Gelda, Mr. Jordan Gass, Dr. Theo Kpodonu, Dr. Kyongho Son, and Dr. Myeong-Ho (Chris) Yeo. This chapter describes ongoing model development and applications conducted by the Modeling Section. Finally, Chapter 7 presents Further Research, which supplements the capabilities of the WQD through contracts and participation in scientific organizations. The chapter was coordinated by Dr. Lorraine Janus with contributions from Mr. Andrew Bader, Ms. Kerri Alderisio, Mr. James Mayfield, Emmet Owens, P.E., Mr. Chris Nadareski, Ms. Sharon Neuman, Mr. Jordan Gass, Mr. James Alair, Ms. Anne Seeley, Mr. Rich Van Dreason, Dr. Karen

Moore, Ms. Aspa Capetenakis, and Ms. Carla Glaser. Other essential database expertise was provided by Mr. Brian O'Malley, Section Chief of Data Management. Most maps in the report were created by Mr. Jordan Gass. Mr. Jim Mayfield and Mr. Dave VanValkenburg were responsible for bringing the chapters of the report together as a single document and polishing the format to make it suitable for printing and posting. Major authors mentioned above edited and proofread chapters of the report to produce the final document for review by the Director and Deputy Commissioner. The cover photograph of the Ashokan Reservoir was taken by Dr. Lorraine Janus on the occasion of the GLEON field trip hosted by DEP to that site in early December 2017. 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 in the Water Quality Directorate 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. This report would not exist without the extensive field work, laboratory analysis, scientific interpretation, and administrative work needed to keep the watershed programs of the Directorate operating. Therefore, thanks are due to all field and laboratory staff who collected and analyzed the thousands of samples required for the watershed monitoring programs; the administrative, computing, health and safety, and quality assurance staff who support them; and the scientific staff responsible for planning, interpreting, and documenting the results of our collective work. Although we could not name everyone, thanks go to all those who contributed directly and indirectly to this report.

Executive Summary

Chapter 1 Introduction

The New York City Water Supply System supplies drinking water to approximately half the population of the State of New York, which includes over 8.5 million people in New York City (NYC) and 1 million people in upstate counties, plus millions of commuters and tourists. New York City's Catskill/Delaware System is one of the largest unfiltered surface water supplies in the world. This report provides summary information about the water quality of the watersheds, streams, and reservoirs that are the sources of New York City's drinking water. It is an annual report that provides the public, regulators, and other stakeholders with a general overview of the City's water resources, their condition during 2017, and compliance with regulatory standards. Field sampling, along with early warning and robotic monitoring equipment, are employed at 458 sites throughout the watershed to measure an array of water quality analytes at various frequencies. These data provide scientific information to guide system operations, for use in water quality models, and for watershed protection policies. Overall, the report illustrates how DEP uses constant surveillance and scientific understanding to protect and maintain high quality source water for the NYC water supply.

Chapter 2 Water Quantity

The NYC Water Supply System is dependent on precipitation and subsequent runoff to supply the reservoirs in each of the three watersheds: Catskill, Delaware, and Croton. Overall, the total precipitation in the watershed for 2017 was 41.6 inches (1,057 mm), which was 3.9 inches (99 mm) below normal (1991-2016). The annual runoff in 2017 was in the normal range (between the 25th and 75th percentile) for the West of Hudson (WOH) sites, with both the East Branch and West Branch of the Delaware River near the 75th percentile. The East of Hudson (EOH) sites were all below the historical median runoff, and most sites were near the 25th percentile. The United States Geological Survey (USGS) reported that New York State had above normal annual runoff (18^{th} highest out of the last 117 years) for the USGS 2017 water year (October 1, 2016-September 30, 2017).

Storage capacity was well below normal levels at the start of the year. Several watershed-wide rain events in January and February allowed the system to exceed normal levels by the end of February. Above average rainfall in March, April and, especially, in May kept capacity at or near 100% heading into the summer months. Typical declines in storage were then observed through the end of October, with September and most of October being especially dry. A large, widespread rain event occurred on October 29, which lifted capacity to about 5 percent above average through the start of November. Extremely dry conditions in November and December caused capacity to end the year approximately 5 percent below normal.

The most recent 1-year, 10-year, and 100-year, 24-hour rainfall events, and the 90% rainfall event maps for New York are presented and are also available in Chapter 4 of the New York State Stormwater Management Design Manual.

Chapter 3 Water Quality

Turbidity levels in 2017 in the Catskill/Delaware and Croton System streams and reservoirs were generally close to or below their historic median levels. Low turbidity levels corresponded with low rainfall amounts observed in 2017.

No changes in coliform restricted basin status occurred in 2017. Fecal coliform levels were generally low as compared with historical ranges in both watershed streams and reservoirs. There were a few exceptions when fecal coliform samples were higher than historical values. These samples were collected soon after rain events in Schoharie, Cannonsville, Cross River, and Muscoot reservoirs. Total coliforms throughout the Catskill/Delaware System were low, but by contrast were higher in Croton System reservoirs and streams during a dry period.

No changes in phosphorus-restricted basin status occurred in 2017. Total phosphorus (TP) levels in most Catskill/Delaware System reservoirs were within 1 µg L^{-1} of their historic median TP concentrations. By contrast, 10 out of 11 Croton System reservoirs had higher median TP concentrations, and streams also had higher TP levels in 2017. Continued monitoring will help to determine if the 2017 increase in TP in EOH reservoirs is a trend or an anomaly.

Trophic state indices (TSI) are commonly used to describe algal productivity of lakes and reservoirs. In 2017, for all Catskill/Delaware System reservoirs on the west side of the Hudson River with the exception of Neversink, median TSI values were higher than historic medians. West Branch receives water from the Catskill/Delaware System and its local drainage area, but had a lower median TSI in 2017. The majority of Croton System reservoirs had lower median TSI values even with increases observed in total phosphorus (TP). The exceptions were Boyd’s Corners and Diverting, with slight increases in median TSI. Kensico Reservoir receives a blend of Catskill/Delaware System water and is typically mesotrophic. In 2017, productivity was very low with a median TSI close to an oligotrophic rating.

Evaluation of additional reservoir and stream analytes in 2017 included chloride. All streams, reservoirs, and controlled lakes in the Croton System exceeded the annual mean chloride benchmarks of 30 mg L^{-1} for reservoirs and 35 mg L^{-1} for streams. This is consistent with previous years and reflects the population and road density for the region. By contrast, there were fewer exceedances of the single sample concentration benchmark of 12.0 mg L^{-1} for the Catskill/Delaware System in 2017. Ashokan West, Ashokan East, Schoharie, Pepacton, and Rondout Reservoirs had no exceedances of the single sample maximum and their annual means were slightly above the benchmark value of 8 mg L^{-1}. Neversink had no exceedances, while Cannonsville was the only WOH reservoir that exceeded chloride benchmark values. All exceedances of benchmark values for chloride were well below the public health standard of 250 mg L^{-1}.

Water quality assessments of watershed streams based on resident benthic macroinvertebrate assemblages continued in 2017. Assessments follow protocols developed by the New York State Stream Biomonitoring Unit. Of the 11 Croton System sites assessed in 2017, only two were considered moderately impaired, while the other nine sites were slightly impaired based on Biological Assessment Profile (BAP) scores. Of the 13 sites assessed in the Catskill System, four were considered slightly impaired and nine sites ranked as non-impaired. Of the 13 assessed in the Delaware System, four were slightly impaired and nine sites ranked as non-impaired.

Surveillance monitoring for metals, a wide range of semivolatile and volatile organic compounds, and the herbicide glyphosate continued at several keypoint locations throughout the water supply system. Most metal sample results were well below state and federal benchmarks. Exceedances of benchmark values occurred for iron, aluminum, and manganese. Although these metals may potentially cause aesthetic concerns (e.g., taste, staining), they were not at levels considered to be a risk to health and occurred well upstream of the NYC distribution system. There were no detections of the monitored semivolatile or volatile compounds or the herbicide glyphosate in 2017.

In 2017, there were four special investigations outside of the Kensico basin. In October 2017, DEP Police investigated reports of raw milk dumping in Dryden Brook, a tributary to Cannonsville Reservoir. A second investigation in October by DEP Police concerning farm manure deposited along Kerr's Creek north of the town of Walton in the Cannonsville watershed was supported with water quality sampling. In both investigations, the analysis results were transmitted to the DEP Police and no exceedances of NYS ambient water quality standards were reported. There was an investigation of a potential Catskill Aqueduct leak in November and water chemistry results indicated that the source was not the Catskill Aqueduct. Follow-up sampling is planned for 2018. The fourth investigation was monitoring for algal toxins that continued in 2017, with samples submitted to a contract laboratory for a comprehensive screening. Algal toxins were detected in four upstate reservoirs. Three reservoirs (New Croton, Croton Falls, and Diverting) had low levels of anatoxin-a; a higher level of anatoxin-a was detected in a remote site in Cannonsville Reservoir. Microcysitn-LA was detected in Croton Falls Reservoir, and microcystin was detected in surface blooms in remote areas of Croton Falls and Cannonsville Reservoirs.

Chapter 4 Kensico Reservoir

Kensico Reservoir is the terminal reservoir for the unfiltered Catskill/Delaware water supply and is the last impoundment prior to entering the City's distribution system. The City's high frequency monitoring ensures that every effort is taken at this key location to meet strict requirements for turbidity and fecal coliform concentrations set forth in the federal Surface Water Treatment Rule (SWTR). Monitoring of the water discharged from Kensico takes place at DEL18DT. All samples from DEL18DT in 2017 had turbidity values less than 5 NTU and fecal coliform values of less than 20 fecal coliforms $100mL^{-1}$, which meant DEP continued to meet the SWTR turbidity and fecal coliform limits. During 2017, DEP replaced the Delaware Shaft 18 cove boat launch. Efforts to minimize any potential impacts to water quality included the installation of additional turbidity curtains and automated monitoring equipment between the construction area and the Shaft 18 intake structure. 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 2017.

In addition to DEP's routine monitoring and the Delaware Shaft 18 boat launch reconstruction, there were two special investigations conducted in the Kensico watershed and video monitoring for Bryozoans continued at the Delaware Shaft 18 sluice gates. There were two special investigations in response to storm events monitored in the Malcom Brook and Stream N5-1 watersheds. For each storm event, there were temporary increases in turbidity and fecal coliforms at the stream sites, but there were no turbidity or fecal coliform issues at DEL18DT. Microbial source tracking (MST) with Bacteroidales were submitted for analysis with each of the two storm events. For N5-1, there were detects for human markers at trace levels for both storm events and MB-1 only reported trace detects for human markers at MB-1 for the October 29 storm. DEL18DT was negative for human marker for the October 29 storm event. The 2017 Bryozoan inspections showed slower growth patterns than the previous three years. The sluiceways were in float mode for part of July and August and closed for a short term in early August, which reduced flow through the area. A report summarizing bryozoan monitoring results from 2014 - 2017 was finalized in 2017 and is available for review.

Chapter 5 Pathogen Monitoring and Research

DEP collected 567 samples for protozoan analysis and 40 samples for human enteric virus (HEV) monitoring in 2017. Most samples were collected at watershed streams (35.7%) and source water keypoint locations (34.1%). Additional samples were collected at Hillview Reservoir, upstate reservoir effluents, and wastewater treatment plants (WWTPs). As a reminder, on April 6, 2015, DEP changed methods for protozoan analysis from Method 1623 to Method 1623.1 with EasyStain to improve *Cryptosporidium* recovery as well as the ability to genotype samples after slide processing, making 2016 – 2017 the first full two-year period of the new method. In many cases, this method change has appeared coincident with a possible shift in data that suggests a potential increased detection of *Cryptosporidium* oocysts and, at times, a decreased detection of *Giardia* cysts. These fluctuations may be a result of the method change and not a variation of prevalence in the environment. Additional data with the new method will be needed to confirm the method change as a cause of the potential shift in the data.

For the two-year period from January 1, 2016, to December 31, 2017, DEP source water results continued to be below the Long Term 2 Enhanced Surface Water Treatment Rule (LT2) *Cryptosporidium* threshold for additional treatment at both the filtered and unfiltered water supplies. The Catskill/Delaware system was below the LT2 unfiltered water supply threshold (0.010 oocysts L^{-1}), with a mean of 0.0016 oocysts L^{-1} at the Delaware outflow. Although a full two-year period was not able to be sampled at 1CR21 due to the Croton System being off-line at times, a value was calculated and the Croton System result was below the filtered system bin threshold (0.075 oocysts L^{-1}) with a mean of 0.0612 oocysts L^{-1}. This result is higher than historical values (as it was last year with a mean value of 0.0541 oocysts L^{-1}), and was mainly driven by one elevated result of 241 oocysts detected in December of 2016.

Overall, protozoan concentrations leaving the upstate reservoirs and Kensico Reservoir were lower than levels at the stream sites that feed these reservoirs, suggesting a reduction as water passes through the system. There were three samples positive for *Giardia* cysts at WWTPs this year, and no WWTPs were positive for *Cryptosporidium*. As per the Hillview Administrative Order, DEP continued weekly protozoan monitoring at the Hillview Reservoir outflow (Site 3) through 2017, with 52 routine samples collected and one sample collected for method studies. Of the 52, there were nine samples positive for *Giardia* and two samples positive for *Cryptosporidium*, possibly related to method changes.

Chapter 6 Water Quality Modeling

The Water Quality Modeling Program protects and improves water quality by developing and applying quantitative tools that relate climate; natural and anthropogenic conditions in watersheds; fate and transport processes in reservoirs; and 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.

Major activities of the Water Quality Modeling Section in 2017 included: (i) reservoir bathymetry measurements, including completion of the West of Hudson bathymetry project and completion of the first year of field measurements for East of Hudson, (ii) creation of software to automate the process of simulations of the Generalized Watershed Loading Function (GWLF) watershed model to forecast streamflows, (iii) testing and validation of a two-dimensional turbidity model for Neversink Reservoir, (iv) development of software to routinely perform position analysis forecasts of reservoir water quality using the Operations Support Tool (OST), (v) participation of Water Quality Modeling staff in a review of OST by a National Academy of Sciences Expert Panel, (vi) an evaluation of the impact of alum addition to inflow to Kensico

Reservoir during the shutdown of the Rondout-West Branch tunnel that is planned to begin in October 2022, (vii) hydrologic modeling of the impact of climate change on streamflow using a stochastic weather generator, (viii) model simulations of the impact of climate change on the turbidity in Esopus Creek, (ix) application of the Regional Hydro-Ecologic Simulation System (RHESSys) to model streamflow and stream water quality in the Biscuit Brook watershed draining to Neversink Reservoir, (x) application of the General Lake Model/Aquatic Ecodynamics reservoir model to Cannonsville Reservoir, (xi) the results of a regionalization analysis of observed precipitation in the West of Hudson watersheds, (xii) application of the SWAT-HS watershed model to evaluate watershed protection programs in the Cannonsville Reservoir watershed, and (xiii) a comparison of the SWAT-HS and RHESSys watershed models in hindcasting of observed streamflow in the Town Brook and Biscuit Brook watersheds. Also, an overview of the first annual meeting with state and federal regulators to present and discuss water quality modeling results, held on November 8, 2017, is given.

Chapter 7 Further Research

The analytical, monitoring, and research activities of DEP are supported through a variety of contracts, 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. In 2017, the WQD managed several water quality-related contracts to enhance its ability to monitor and model the watershed. These included eight different contract types, such as those for laboratory analyses, hydrological monitoring by United States Geological Survey (USGS), modeling support through CUNY-RF, waterfowl management, zebra mussel monitoring, bathymetric surveys by USGS, WISKI Software Support, and *Cryptosporidium* infectivity analyses. The WQD participated in seven WRF projects as both project advisory committee members and as participating utilities. WQSR and the Bureau of Environmental Planning and Analysis (BEPA) staff are part of the Water Utility Climate Alliance (WUCA), a consortium of 10 water utilities across the nation with interest in planning for climate change. In addition, DEP participated in the international Global Lake Ecological Observatory Network (GLEON), with the objectives of adopting software tools developed by GLEON scientists to display and analyze the high-frequency data generated by DEP's Robotic Monitoring project, and to contribute to projects with other scientists. DEP contributed data to four GLEON projects including an exploration of temperature changes related to global weather patterns and a project examining salt and iron concentration trends over several decades. The LAke multi-scaled GeOSpatial and temporal database (LAGOS) was published in GigaScience in 2017 and included DEP data. Additionally, a collaborative project on the relationship between oxygen and chlorophyll and an analysis of long-term trends in oxygen profiles is in progress. These projects allow DEP to see source water quality in a global context and provide insights that may be used to plan for the future.

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 2017, 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 2017 Drinking Water Supply and Quality Report (http://www.nyc.gov/html/dep/pdf/wsstate17.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. As a summary document, topics are not described in depth, but more detailed reports on some of the topics can be found on the DEP website at http://www.nyc.gov/html/dep/html/home/home.shtml.

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 reliably deliver a sufficient quantity of high quality drinking water to protect public health and the quality of life of the City of New York. To gather and

Figure 1.1 The New York City Water Supply System.

process the information needed to meet these goals, there is an ongoing program of water quality data collection (by grab samples and by early warning and robotic monitoring equipment), data display and analysis, modeling runs, and operational responses to changing conditions. Monitoring of the vast watershed is accomplished by Watershed Water Quality Operations based at three upstate locations in Grahamsville, Kingston, and Hawthorne, NY. The data generated by field and laboratory activities are presented here to provide an overview of watershed water quality in 2017 and to show how high quality source water is reliably maintained through constant vigilance and operational changes. DEP also supplements the work of the Water Quality Directorate through contracts and interactions with other organizations as discussed in Chapter 7 Further Research.

1.1.1 Grab Sample Monitoring

Water quality of the reservoirs, streams, and aqueduct keypoints is monitored throughout the watershed for several purposes. Results are used to ensure regulatory compliance, to guide operations, to demonstrate the effectiveness of watershed protection measures, and to provide data for modeling applications. Sampling is specified in the Watershed Water Quality Monitoring Plan (WWQMP; DEP 2016a). This document 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 DEP's needs.

A summary of the number of grab samples and analyses that were processed in 2017 by the three upstate laboratories, and the number of sites that were sampled, 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 2016 WWQMP (DEP 2016a). Samples taken as the result of special investigations (SIs) are also included. The sample numbers for the City's distribution system are also listed for completeness. (However, this report only discusses results from watershed samples.) The number of analyses conducted by DEP's watershed laboratories decreased (by about 6,300) in 2017 due to a decrease in requests for free residential lead test kits by drinking water customers in the City and by a reduction in the frequency of Croton WWTP sampling following the conclusion of the Croton Consent Decree in September 2016. Analyses of the free residential lead test kits were performed at the DEP Kingston Laboratory.

In addition to grab sampling, a great deal of data is recorded by continuous monitoring equipment at keypoints on the aqueducts and by dataloggers at stream sites. Robotic monitoring is deployed at reservoirs as described below.

Table 1.1 Summary of grab samples collected, water quality analyses performed, and sites visited by WQD in 2017.

System	Number of Samples	Number of Analyses	Number of Sites
Watershed	14,200	213,600	458
Distribution	36,100	401,200	~1,000
Total	50,300	614,800	1,460

1.1.2 Robotic Monitoring (RoboMon) Network

DEP's Robotic Monitoring (RoboMon) network provides 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 by water supply modelers to run computational tools, such as the Operational 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. These activities contribute to the safety and reliability of the water supply.

The RoboMon network began in 2012 with four reservoir sites (i.e., three at Ashokan and one at Kensico). The network has continued to grow to its current configuration of 20 sites (Figure 1.2) located in both reservoirs and streams. There has also been enhancement of the sites with additional sensors to obtain data essential for model development.

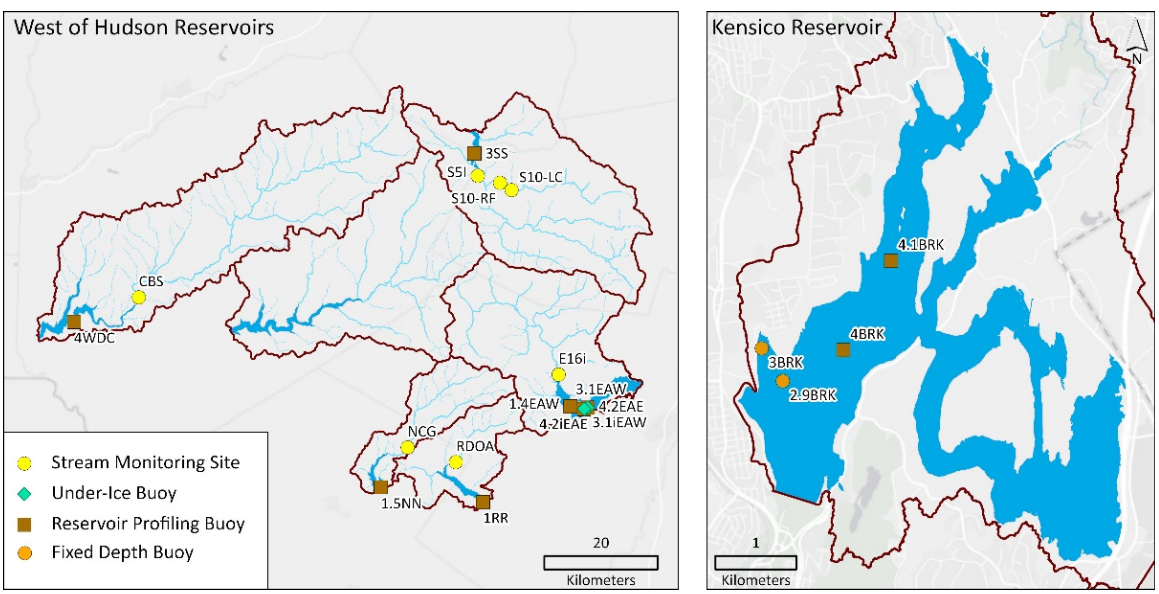

Figure 1.2 Robotic monitoring sites and types in the Catskill and Delaware Systems in 2017.

There are three types of site installations that comprise the RoboMon network: i) profiling buoys in reservoirs, ii) fixed-depth sensors in reservoirs, including under-ice buoys, and iii) 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. Additionally, meteorological stations are located on the Ashokan West Basin (Site 1.4) buoy and the Kensico (Site 4.1) buoy. Fixed-depth buoys are located on Kensico Reservoir at sites 2.9 and 3BRK. Transmissometers or turbidity sensors are suspended in the water column at specific depths (e.g., 5, 10, and 15 meters) to provide near-real-time turbidity data that are recorded in 15-minute intervals. Stream sensors also typically record temperature and turbidity at 15-minute intervals.

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), probes for chlorophyll, phycocyanin (a blue-green algae pigment), dissolved oxygen, and fluorescent dissolved organic matter (fDOM) were added at Cannonsville and Neversink Reservoir buoys in 2015.

To monitor water quality conditions during times of ice-over, two under-ice buoys were deployed on Ashokan Reservoir in December 2017. This is the third year these buoys have been successfully set up and operated. These units consist of fixed depth stick buoys, placed in front of the East and West Basin gatehouses, with turbidity sensors positioned at two discrete depths (at approximate elevations of 555 and 515 feet above sea level).

Recent refinements in reservoir robotic monitoring include the following:

- Temporary relocation of a fixed-depth buoy platform on Kensico to site 2.1 in anticipation of construction of a boat launch near Delaware Shaft Building 18. At the conclusion of that project (August 2017), the platform was repositioned to Site 2.9.
- Deployment of four Forest Technology Systems (FTS) turbidity sensors as a part of the response to turbidity issues at the ramp construction site. These units were set up with data logging and telemetry.
- Replacement in October 2017 of the transmissometers on one of the fixed-depth buoys at Kensico Reservoir (site 2BRK) with FTS turbidity sensors to provide a better estimate of turbidity with less maintenance and calibration effort.

In addition to the reservoir buoy network, there are six automated stream monitoring stations (RoboHuts) operated and maintained year-round. One RoboHut located at Esopus Creek, near Coldbrook, monitors water temperature, specific conductivity, and turbidity at 15-minute intervals and has been in operation since 2012. 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 robotic stream monitoring during 2017 include the following:

- Replacement of the Esopus Creek (Site E16i) YSI multiparameter sonde with a FTS turbidity sensor to reduce labor and maintenance costs. The FTS sensor only measures turbidity and temperature.
- Installation of new monitoring equipment on the Schoharie Creek near Prattsville site (S5I) in September 2017 to assist in modeling and to improve surveillance. This station monitors temperature, specific conductivity, and turbidity.
- Establishment of a new monitoring site in the Schoharie watershed on the Batavia Kill to monitor the effectiveness of a stream improvement project at turbidity reduction. A downstream monitoring site, near Red Falls, had previously been added in 2016. In 2017, an upstream site was added on the Batavia Kill near Lewis Creek to better quantify turbidity reduction due to the stream improvement project.
- Addition of fluorescent dissolved organic matter (fDOM) sensors to existing multiparameter sondes on the Neversink River and the West Branch Delaware River RoboMon stream sites (NCG and CBS, respectively) in February 2017 and July 2017, respectively, as part of a disinfection byproduct formation potential (DBPfp) special investigation study.

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 and made viewable on the DEP intranet through a custom web application. In some cases, near-real-time 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. The Robotic Monitoring program yielded approximately 1.2 million measurements in 2017 at 19 sites (Table 1.2).

Table 1.2 Summary of Robotic Monitoring measurements in 2017.

System/Field Section	**Number of Measurements**	**Number of Sites**
Catskill/Kingston	386,016	9
Delaware/Grahamsville	556,777	6
EOH/Hawthorne	291,744	4
Total	1,234,537	19

1.1.3 Early Warning Remote Monitoring (EWRM)

Aqueduct “keypoint” monitoring is conducted as a means of keeping a “finger on the pulse” of the water supply with respect to the major water flowing through the system and into distribution. Monitoring at these sites is conducted through the use of daily or weekly grab sampling (noted previously) and continuous automated monitoring equipment. The automated equipment at these keypoint sites is operated and maintained by the Early Warning Remote

Monitoring (EWRM) groups. The automated monitoring that is conducted is specific to each site (Appendix A). These sites have some of the highest frequencies of sampling conducted by DEP, the purpose of which is to maintain a high degree of reliability in the quality of water entering the distribution system.

In addition to sites used for operational decisions, keypoint monitoring includes compliance sites for the Surface Water Treatment Rule (SWTR) and are critical for operation of the system to maintain filtration avoidance status. The inactivation ratio (IAR) is computed daily using DEL18DT and DEL19LAB sites as this is required for compliance reporting. DELSFBLAB can be used as an alternate site for the DEL19LAB site. Chlorine monitoring is conducted in compliance with EPA Method 334. For the Croton System, data collected from the Croton Gatehouse (CROGH) are of utmost importance to process control at the Croton Filtration plant.

In addition to the parameters outlined in Appendix A, Intelligent Automated Biological Systems (iABS) using fish are installed at DEL18DT and CROGH sites for rapid detection of water quality changes and contamination events. The purchase of a new fish biological monitoring system, the ToxProtect 64, is currently in progress. The new system is anticipated to reduce the number of false alarms and maintenance expenditures.

In 2017, we continued deployment of instrumentation for the Rondout taps, although they are not yet available in SCADA, and we began to address issues related to construction at the Schoharie Tunnel Intake Chamber (STIC).

1.2 Operations in 2017 to Control Turbidity and Fecal Coliforms

In the Catskill System, the elevation and location (i.e., East and/or West Basin) of withdrawal at Ashokan Reservoir was adjusted throughout the year to draw the best quality water (i.e., low turbidity, low coliforms) from the reservoir. Also, there were several changes to meet operational needs (e.g., lowering the West Basin to create a void to accept more runoff during large storm events and to accommodate repair work). In 2017, the main water quality component driving operational changes was turbidity and not fecal coliform.

In the beginning of the year, the Catskill System diverted water from mid-depth on the East Basin. This configuration continued into March to take advantage of lower turbidity water, with the dividing weir opened as needed to equalize the two basins. In the middle of March the basins equalized, and the diversion out of Ashokan was switched to the West Basin to begin developing a storage void to protect the East Basin from storm event impacts such as turbidity. Rain events soon brought turbid water into the West Basin and the diversion was switched back to the east within a week. The East Basin was utilized exclusively until May, when storage levels approached the target capacity. As before, precipitation moved in after the basin switch to the west and the draw was returned to East Basin after almost a week. The East Basin draw persisted until late June, when Ashokan began drawing down. To allow the East Basin time to refill, the diversion was switched to the West Basin. Drawing down the West Basin had the added benefit of creating space to accommodate future storm flow. In August, the withdrawal level was raised to draw water with the lowest turbidity. The West Basin was utilized until late September, at which time remediation work began on the spillway floor, and an East Basin draw ensured that there would be no flow into the spillway. When the work was completed, the diversion was switched back to West Basin. In October, a large storm impacted the West Basin water quality. In response, the diversion from the West Basin was reduced to minimize the impact on Kensico, and the dividing weir was closed to isolate Ashokan's East Basin. The turbidity in the West Basin diversion eventually increased to the point where the East Basin was selected for withdrawal, and this configuration continued until the end of the year.

In the Delaware System, water quality was very good throughout the year and no operational changes were needed to deliver the best quality water to the distribution system. The chambers at all Delaware System reservoirs were configured for diversion through the mid- or lower-level intakes, and no elevation changes were needed at any of the reservoirs in 2017.

When weather forecasts at Kensico Reservoir predict 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 due to the potential for wave action to resuspend adjacent shoreline sediments. Float mode operation brings water from Rondout (and West Branch) Reservoirs via the Delaware Aqueduct directly to the downtake at Delaware Aqueduct Shaft 18. Since float mode at Kensico Reservoir cannot fully meet demand, water from Rondout Reservoir is supplemented by water drawn from Kensico Reservoir as needed, but in much lesser amounts than would occur during reservoir mode operation. This proactive measure minimizes turbidity that would otherwise enter the distribution system. Float operation in anticipation of strong winds occurred seven times for all or part of 21 days in 2017. In addition, a new boat ramp was built during summer 2017 near Shaft 18 on Kensico Reservoir. To ensure that there would be no impacts to water quality during this construction activity, Kensico Reservoir went on float mode twice for a total of 29 days. There were no impacts to water quality during this construction operation.

The Croton Water Filtration Plant was not in operation for most of the year. The plant was online for a total of 59 days, producing 28 to 229 million gallons per day (MGD) during that period. For the remainder of the year, it remained off-line as there was ample and higher quality water available in the Catskill/Delaware System. This allowed modifications to be made at the plant.

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 affect the nutrient and turbidity loads and the outputs affect the hydraulic residence time, both of which can influence the reservoirs' water quality.

2.2 2017 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 2017 monthly precipitation total for each watershed is plotted along with the historical monthly average (1991-2016) (Figure 2.1).

The total monthly precipitation figures show that precipitation was generally near normal for the first four months of 2017 although Cannonsville, Pepacton, and Ashokan were all more than an inch above normal in April. Precipitation in May was above normal in all watersheds. In June, July, and August most of the watersheds were somewhat below normal, but Pepacton had 2.28 inches of rain on July 13 and 3.66 inches on July 23, and was 4.35 inches above normal for July. In September, all watersheds recorded precipitation below normal. In October all of the watersheds, except Schoharie had above normal precipitation. A storm at the end of October was the largest precipitation event of the year for all watersheds with the exception of Pepacton. Total precipitation amounts for this event ranged from 2.18 inches in Schoharie to 4.31 inches in Ashokan. November and December were very dry throughout the system. Overall, the total precipitation across the watershed for 2017 was 41.6 inches (1057 mm), which was 3.9 inches (99 mm) below normal (1991-2016).

The National Climatic Data Center's (NCDC) climatological rankings (https://www.ncdc.noaa.gov/cag/) were queried to determine the 2017 rankings for New York. Overall total precipitation for New York State in 2017 was 47.36 inches (1202.94 mm), which was 7.07 inches (179.58 mm) above the 20th-century mean (1901-2000) and the twelfth wettest in the last 123 years (1895-2017). However in Climate Division 5, which includes the EOH reservoirs, precipitation was 1.23 inches (31.24 mm) below the 20th-century mean (1901-2000), while in Climate Division 2, which includes the WOH reservoirs, precipitation was 4.87 inches (123.7 mm) above normal. Also, the average temperature for New York State in 2017 was 46.9°F (8.28°C), which was 2.4°F (1.34°C) above normal (1901-2000) and the twelfth warmest in the last 123 years for New York.

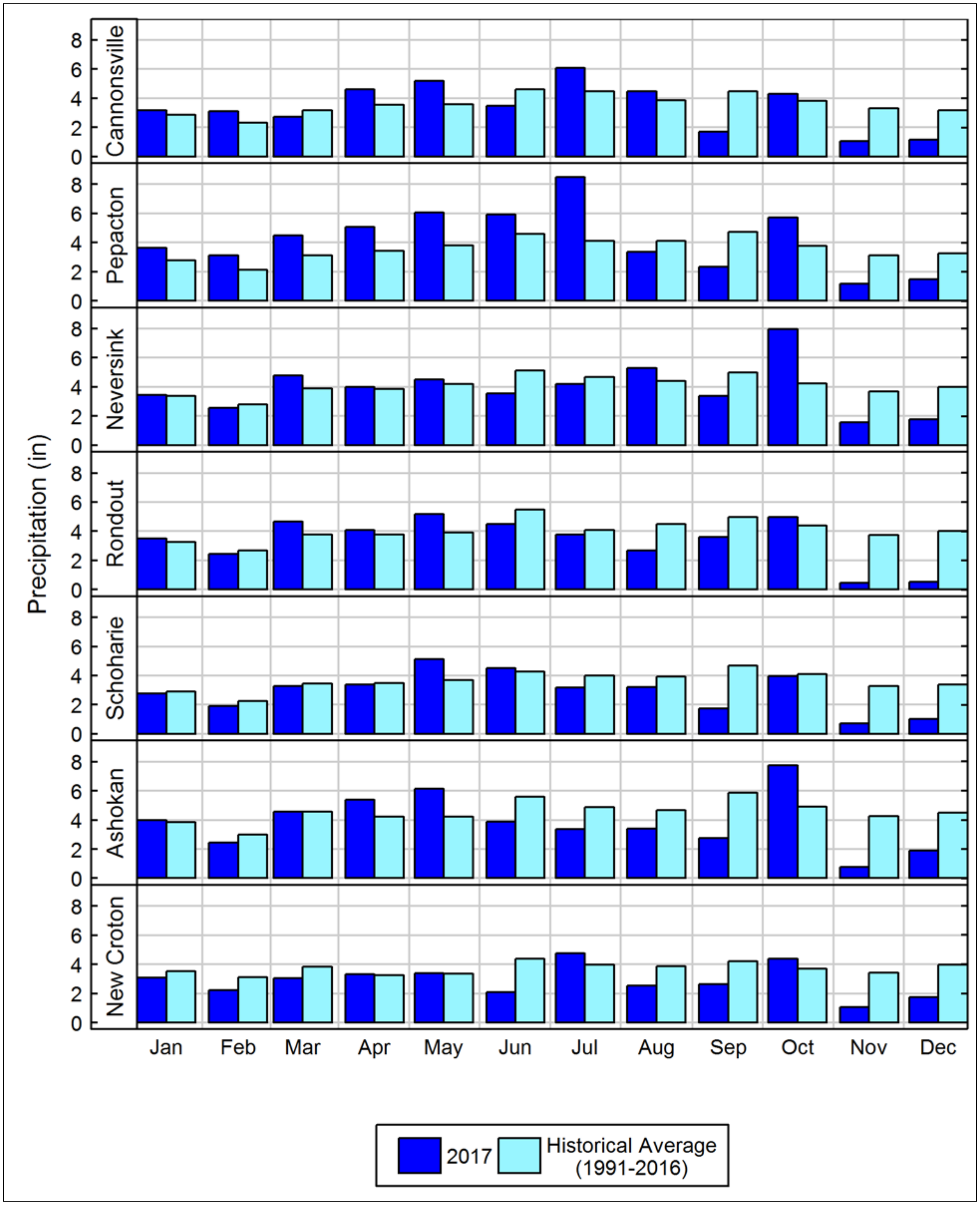

Figure 2.1 Monthly precipitation totals for New York City watersheds, 2017 and historical values.

2.3 2017 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), rainfall intensity, rainfall amount, rainfall duration, spatial distribution of rainfall 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 and 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 to be made of the hydrologic conditions in watersheds of varying sizes.

Selected USGS stations (Figure 3.7) were used to characterize annual runoff in the different NYC watersheds (Figure 2.2). The period of record for the WOH USGS stations ranges from 54 years at the Esopus Creek Allaben station to 115 years at the Schoharie Creek Prattsville gage. The EOH USGS stations have a 22-year period of record, except for the Wappinger Creek site (89-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.) The annual runoff in 2017 was in the normal range (between the 25th and 75th percentile) for the WOH sites, with both the East Branch and West Branch of the Delaware River near the 75th percentile. The EOH sites were all below the historical median runoff, and most sites were near the 25th percentile, indicating relatively low flow for the year. Overall, New York State had above normal runoff (18th highest out of the last 117 years) for the 2017 water year (October 1, 2016-September 30, 2017), as determined by the USGS (http://waterwatch.usgs.gov/index.php?r=ny&m=statesum) (Note the water year ends on September 30, so the USGS annual runoff results do not include the impacts from the latter part of 2017 when it was very dry.)

Figure 2.3 shows the 2017 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. At the WOH gages, mean daily flows were near normal for the first six months of the year with occasional spikes from storms. Several of the WOH sites had somewhat above normal flows from mid-summer into September (e.g. Esopus Creek at Allaben, West Branch Delaware at Walton, East Branch Delaware at Margaretville, and Neversink River, near Claryville). WOH flows from October through December were somewhat below normal except for a spike that was due to a late October rain event. At the EOH gages flows from

January into September were near normal, but also showed occasional spikes from storms. From mid-September until the end of the year, EOH flows were well below normal, except when the late October rain event resulted in above normal flows. From mid-November through the end of the year the EOH flows, except for Wappinger Creek near Wappingers Falls, approached or reached the minimum mean daily flows for the period of record. (The flow in Wappinger Creek was still well below its historic median flow.)

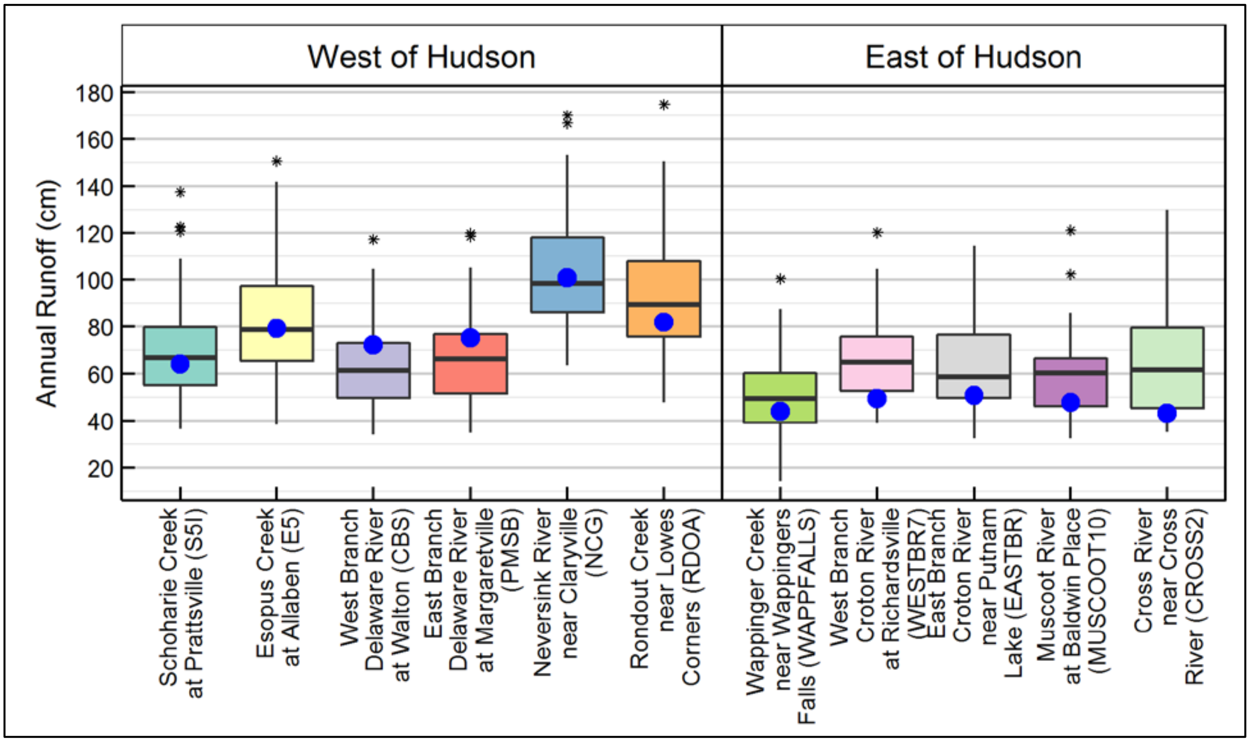

Figure 2.2 Historical annual runoff as boxplots for the WOH and EOH watersheds, with the values for 2017 displayed as a solid blue dot. The asterisks indicate outliers (see Appendix B for a key to the boxplot).

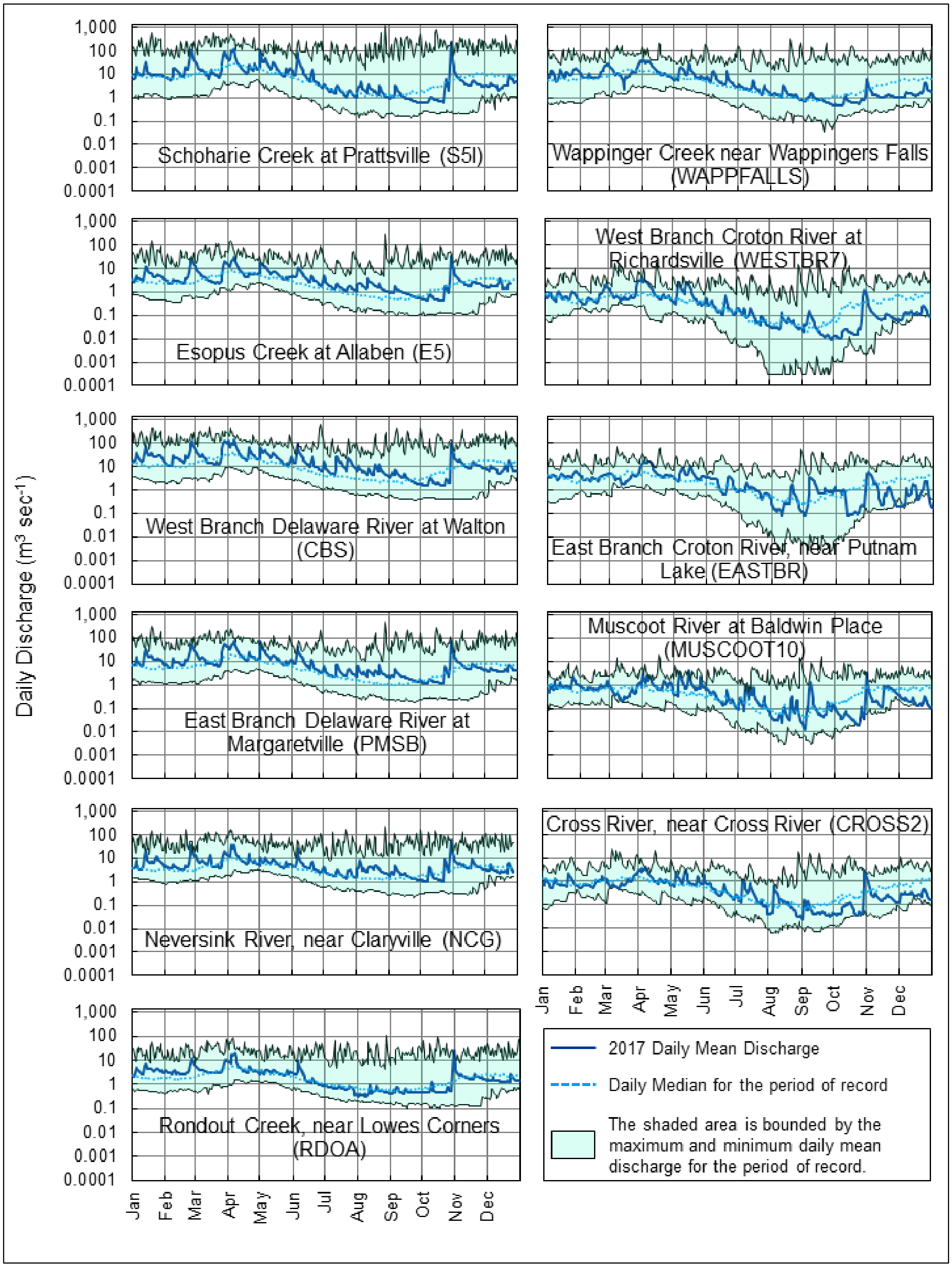

Figure 2.3 Daily mean discharge for 2017 at selected USGS stations. Daily data from October 1-December 31, 2017 are provisional and subject to revision until they have received final approval from the USGS.

2.4 Use of Rainfall Data in the Design of Stormwater Pollution Prevention Plans

DEP is responsible for regulatory oversight of land development activities in the watershed via the review and approval of applications submitted in accordance with Section 18-39 of the New York City Watershed Rules and Regulations (WR&R) (DEP 2010). Section 18-39 established DEP's authority to regulate the management and treatment of stormwater runoff, created standards for the delineation and protection of watercourses, and codified prohibitions regarding the construction of impervious surfaces. This is the section under which Stormwater Pollution Prevention Plans (SWPPPs) are submitted, as well as applications for Individual Residential Stormwater Permits and Stream Crossing, Piping and Diversion Permits. Residential, commercial, institutional, and transportation activities are among the land uses requiring DEP review under this section.

SWPPPs require specific hydrologic modeling and analyses of site runoff conditions prior to and after proposed construction and development activities. Stormwater computer models rely on historical precipitation records to size stormwater management practices, evaluate a variety of runoff conditions, and predict downstream impacts. These records include rainfall data to define the magnitude of a number of storm events, namely the one-year, 10-year, and 100-year, 24-hour events, and the 90% 24-hour rainfall event (Figure 2.4 through Figure 2.7). The one-year, 24-hour storm gives the rainfall depth with a 24-hour duration that statistically has a 100% chance of being equaled or exceeded in any given year. The 10-year, 24-hour storm specifies the rainfall depth with a 24-hour duration that statistically has a 10% chance of being equaled or exceeded in any given year. The 100-year, 24-hour storm is the rainfall depth with a 24-hour duration that statistically has a 1% chance of being equaled or exceeded in any given year. The 90% storm indicates the rainfall depth that is equaled or exceeded during 90% of all events of 24-hour duration. Figure 2.4 through Figure 2.7 are isohyetal maps that present estimates of these four rainfall depths for New York State. Where construction activities require DEP review and approval of a SWPPP in accordance with the WR&R, these maps may be used in the design of stormwater management practices. They are available in Chapter 4 of the New York State Stormwater Management Design Manual (updated January 2015) ("Design Manual") or at http://www.dec.ny.gov/docs/water_pdf/swdm2015chptr04.pdf. Alternatively, as precipitation data are updated, designers may use the most recent rainfall frequency values developed by acceptable sources as noted in the Design Manual.

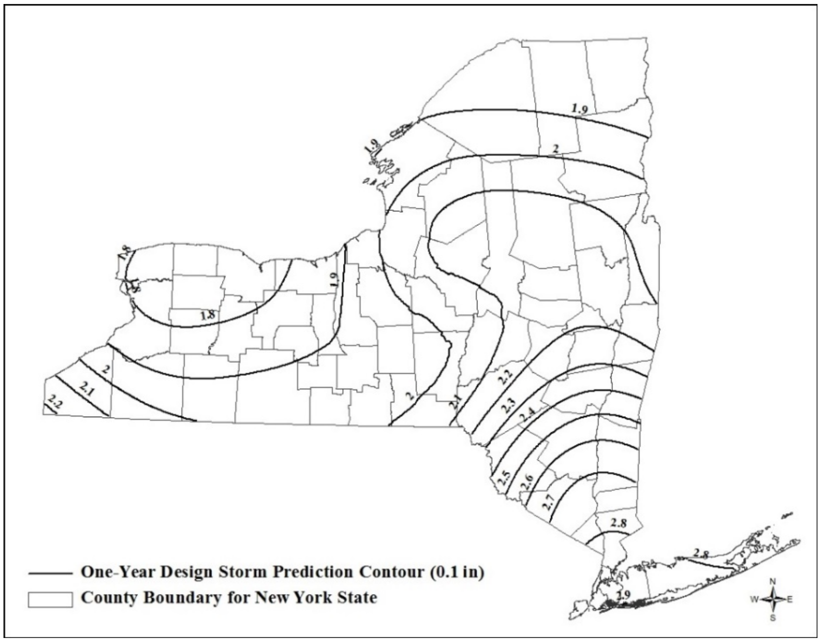

Figure 2.4 The one-year, 24-hour design storm in New York State, from the 2015 Stormwater Management Design Manual.

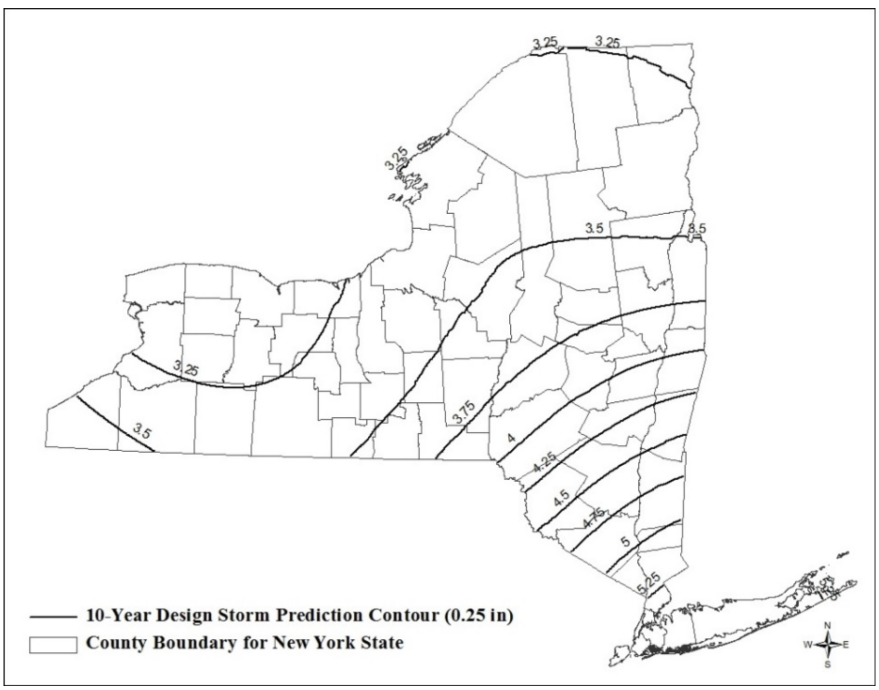

Figure 2.5 The 10-year, 24-hour design storm for New York State, from the 2015 Stormwater Management Design Manual.

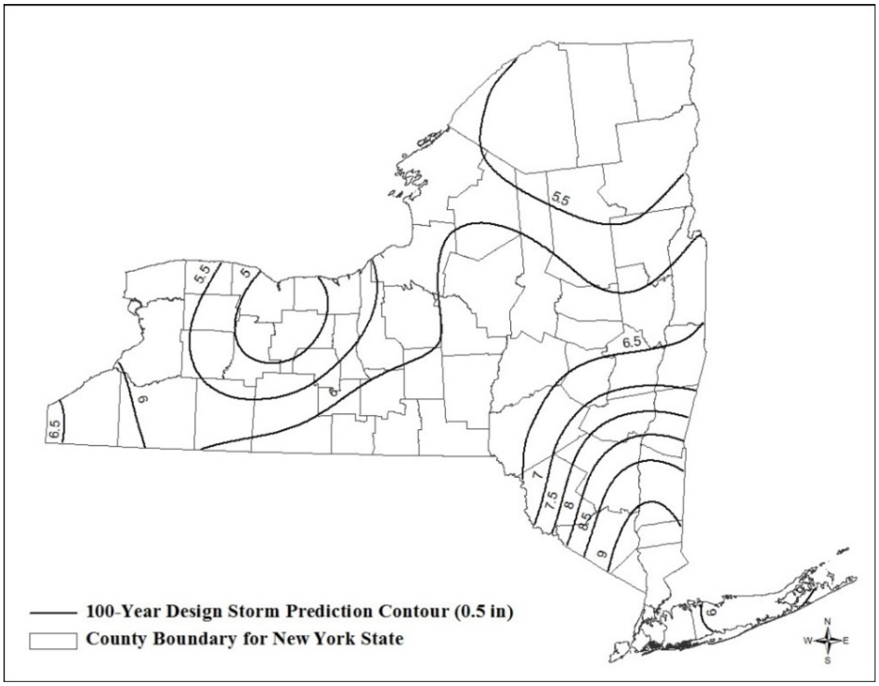

Figure 2.6 The 100-year, 24-hour storm for New York State, from the 2015 Stormwater Management Design Manual.

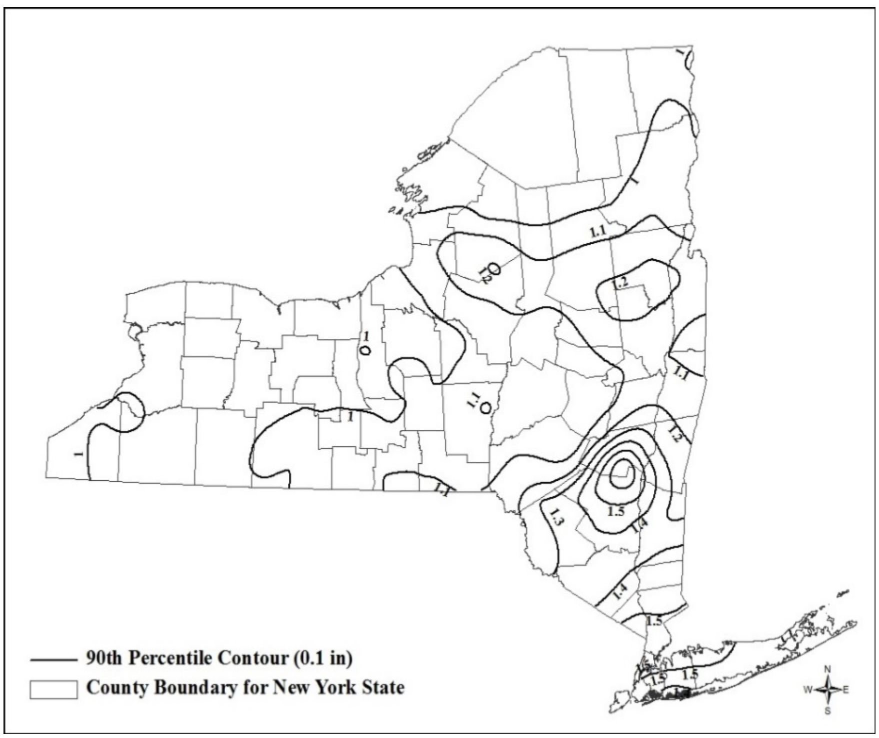

Figure 2.7 90th percentile, 24-hour rainfall for New York State, from the 2015 Stormwater Management Design Manual.

2.5 Reservoir Usable Storage Capacity in 2017

Ongoing daily monitoring of reservoir storage allows DEP to compare the system wide storage in 2017 (including Kensico Reservoir) against average historical values for 1991-2016 for any given day of the year (Figure 2.8). Storage capacity started well below normal levels at the start of the year, a continuation of drought conditions which began in September 2016. Several watershed-wide rain events in January and February allowed the system to exceed normal levels by the end of February. Above average rainfall in March, April and especially in May kept capacity at or near 100 percent heading into the summer months. Typical declines in storage were then observed through the end of October with September and most of October being especially dry. A large widespread rain event occurred on October 29, which lifted capacity to about 5 percent above average through the start of November. Extremely dry conditions in November and December caused capacity to end the year approximately 5 percent below normal.

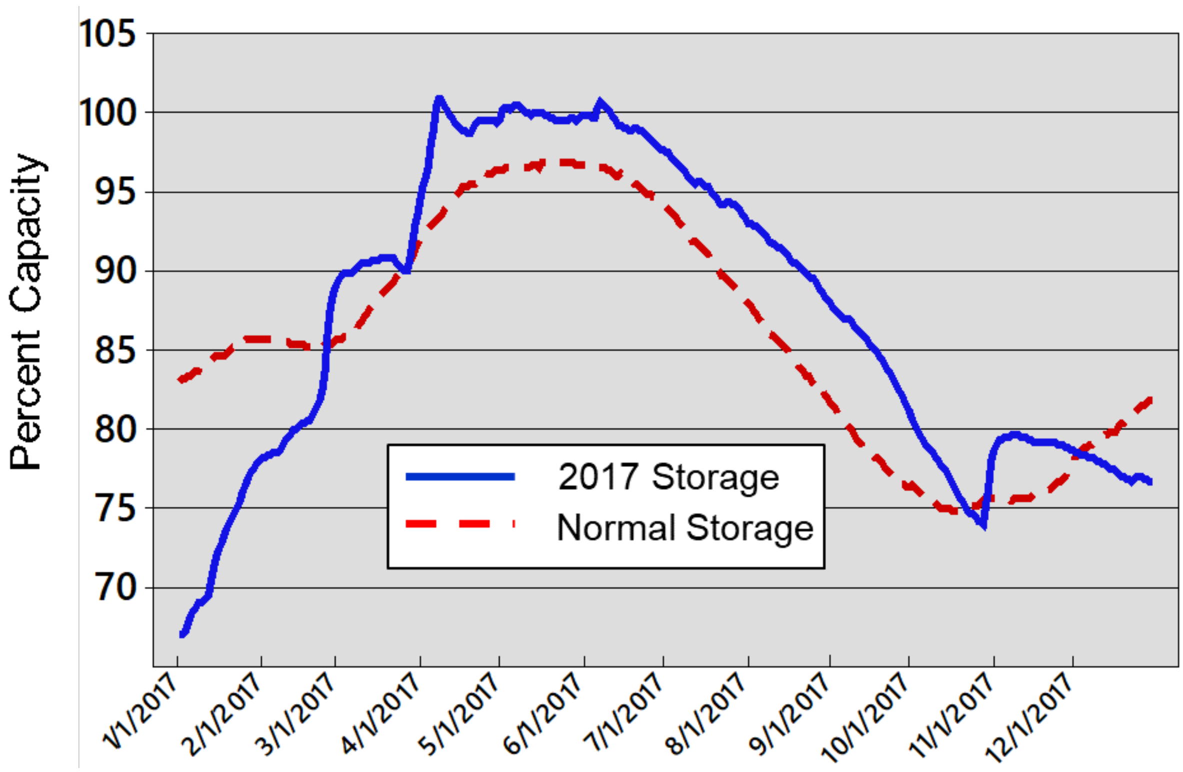

Figure 2.8 Systemwide usable storage in 2017 compared to the average historical value (1991-2016.) Storage greater than 100% occurs when the water surface elevation is greater than the spillway elevation, so that reservoirs are spilling.

3. Water Quality

3.1 Monitoring Overview

Water quality samples are collected from streams, reservoirs, and aqueduct locations throughout the NYC water supply (Appendix B, Figures 1-7). 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 East Basin, Ashokan West Basin, and West Branch reservoirs. When operating as a source, water from these reservoirs would be regulated by the Surface Water Treatment Rule (SWTR).

3.2 Reservoir Turbidity Patterns in 2017

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 erosional processes (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 (i.e., Schoharie and Ashokan) due to the occurrence of easily erodible lacustrine clay deposits found in these watersheds.

In 2017, turbidity levels in all Catskill/Delaware System reservoirs were close to their median historic levels (Cannonsville, Rondout, Schoharie and West Branch) or below (Ashokan East and West, Neversink, and Pepacton) (Figure 3.1). (An explanation of the boxplots used in this and other figures in this chapter is provided in Appendix C).

The low turbidity levels coincide with low rainfall amounts observed throughout most of the NYC water supply watersheds in 2017 (Figure 3.1). The Pepacton watershed was the only exception with rainfall amounts exceeding historic levels by 18%. Annual rainfall totals were down 15-20% in the Rondout, Schoharie and Ashokan basins and 4-5% lower in the Neversink and Cannonsville basins.

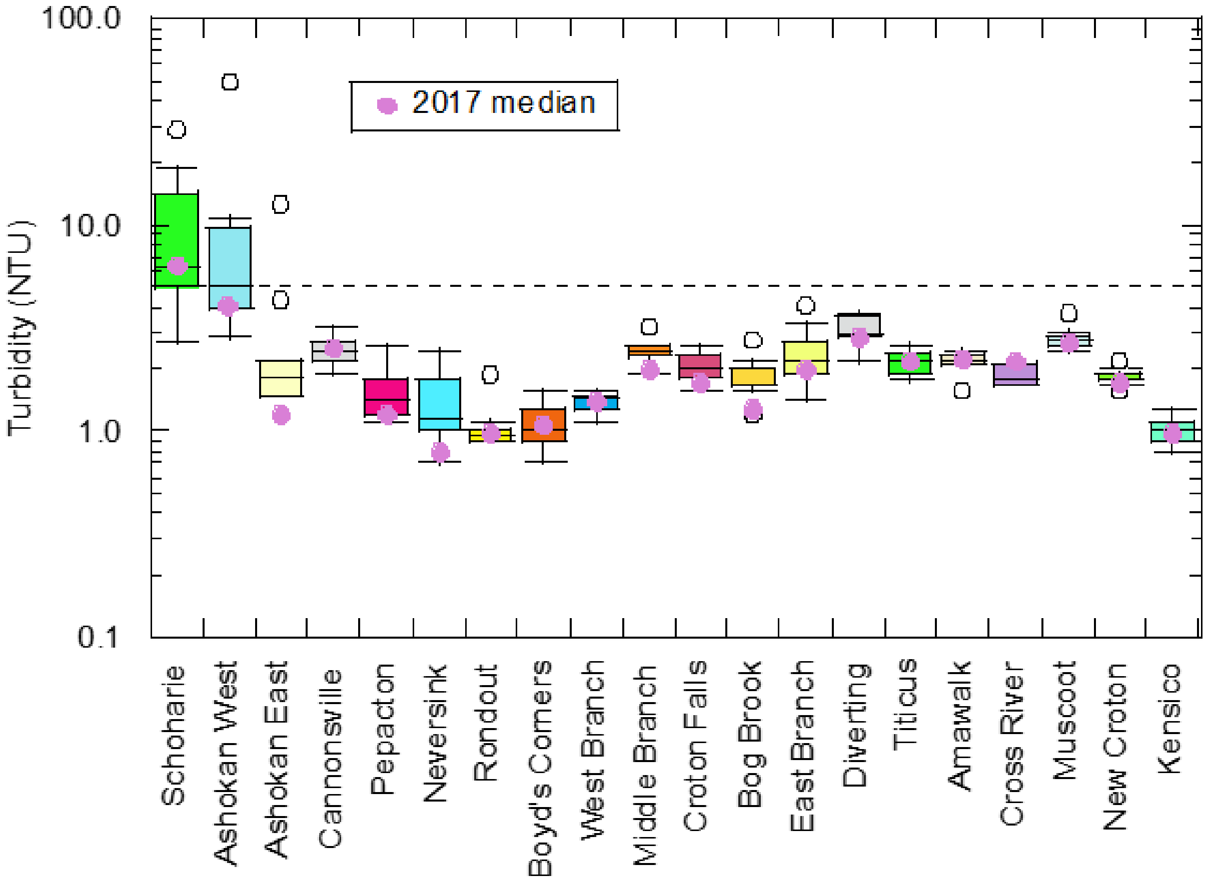

Figure 3.1 Annual median turbidity in NYC water supply reservoirs (2017 vs. 2007-2016) with the 2017 values displayed as a solid dot. The dashed line represents the standard for source waters as a reference.

Since 2012, approximately 2 kilometers of stream restoration sediment and turbidity reduction projects (STRPs) have been completed in the Stony Clove Creek watershed, which may account in part for the low turbidity observed in the Ashokan basins in 2017. Previous research found that the Stony Clove Creek watershed produced the largest suspended sediment loads of any Esopus Creek tributaries, accounting for 30 to 57 percent of the annual suspended sediment load for the period 2010-2012 (McHale and Siemion 2014). Subsequent research shows that the STRPs have been effective at reducing turbidity and suspended sediment for the range of flows between the period of STRP construction in 2012 to 2015 (Siemion et al. 2016). Based on turbidity and suspended sediment monitoring for most of the Esopus Creek tributary streams for 2017, Stony Clove Creek accounted for a smaller proportion of the total monitored sediment load and turbidity and was equal to or surpassed by Woodland Creek as the consistently highest proportional source of suspended sediment and turbidity. Basin-wide turbidity and suspended sediment monitoring will continue through 2026 as part of a sediment source characterization and STRP effectiveness study.

West Branch Reservoir, which receives inputs from both the Delaware and Croton Systems, also had low turbidity levels in 2017. Low turbidity water transfers from Rondout and low turbidity inputs (due to both low concentration and flow) from local Croton streams resulted in an annual median turbidity of 1.4 NTU for West Branch in 2017. The slightly higher historic turbidity of West Branch Reservoir compared to its main inputs, Rondout Reservoir and Boyd's 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 and Delaware Systems, turbidity was low corresponding to the high clarity of water received from both systems in 2017.

Similar to the Catskill/Delaware Systems, turbidity in the Croton System was generally normal to well below normal in 2017 (reservoirs shown in Figure 3.1, controlled lakes in Table 3.1). The low turbidity is probably related to the lack of runoff events in the Croton region in 2017. Annual rainfall in the region was 10.3 inches less (23% below average) than the average rainfall from the previous 25-year period with June, November, and December being particularly dry (Figure 2.8).

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

Lake	Median Turbidity (2007-16)	Median Turbidity (2017)
Gilead	1.5	1.1
Gleneida	1.5	1.0
Kirk	4.3	3.2

3.3 Coliform-Restricted Basin Assessments in 2017

Coliform bacteria serve as indicators of potential pathogen contamination. To protect the City's water supply, the City's WR&R restrict potential sources of coliform bacteria in the watershed area of threatened water bodies. 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).

There were two method changes made during 2017 that may affect the data. On April 1, 2017, DEP implemented the 2006 version of Standard Methods 9222 B and D for total and fecal coliform, respectively. The prior version of the method (1997) was removed by EPA in the 8/28/17 Clean Water Act Methods Update Rule, and from NYS DOH laboratory accreditation on 4/1/17. The effect of this change was to modify the coding structure of the data. For example, the newer version no longer uses the TNTC (too numerous to count) code. TNTC was replaced by other codes including “>= “when colonies on the plate exceed 200 coliforms $100mL^{-1}$, “E” when target organisms are not in the ideal range, and “ >” when the target organisms exceeded 200 coliforms $100mL^{-1}$, or a combination of those codes. A second change made in September 2017 required that the two DEP WOH laboratories analyze two total coliform plates rather than a single plate used in prior years. This was consistent with DEP’s EOH laboratory practice. Adding an additional plate, notably with a different dilution, increased the likelihood that DEP would obtain a valid coliform result and potentially reduce the number of data codes.

3.3.1 Terminal Basin Assessments

Table 3.2 provides coliform-restricted assessments for the five terminal basins based on 2017 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 associated basin is rated 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 2017.

Table 3.2 Coliform-restricted basin status as per Section18-48(c)(1) for terminal reservoirs in 2017.

Reservoir basin	Effluent keypoint	2017 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 2017 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 2017, there was an increase in exceedances of the Part 703 standard for total coliform as compared to the previous year. The highest number of exceedances occurred in Diverting Reservoir for six months in 2017, whereas exceedances occurred in four months in the previous year. Ten additional reservoirs had increased exceedances in 2017 as compared to 2016, and exceedances declined from two months to one month in East Branch Reservoir. The increase in the number of months where total coliform counts exceeded the standard in 2017 is likely due in part to changes in methods and reporting that occurred this year.

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 2017.

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	1/8
Boyd's Corners	AA	50/240	3/8
Croton Falls	A/AA	50/240	4/8
Cross River	A/AA	50/240	2/8
Diverting	AA	50/240	6/8
East Branch	AA	50/240	1/8
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	0/8
Middle Branch	A	2400/5000	1/8
Titicus	AA	50/240	3/8
Cannonsville	A/AA	50/240	3/8
Pepacton	A/AA	50/240	1/8
Neversink	AA	50/240	0/8
Schoharie	AA	50/240	1/7

3.4 Reservoir Total and Fecal Coliform Patterns in 2017

Total coliform and fecal coliform bacteria are regulated by the Surface Water Treatment Rule (SWTR) at raw water intakes with regulatory levels of 100 and 20 coliform 100mL^{-1}, respectively. Both 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 3.2 and reservoir total coliform results in Figure 3.3. Coliform results for the controlled lakes of the Croton System are summarized in Table 3.4. 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 75th percentile values rather than the 50th 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.

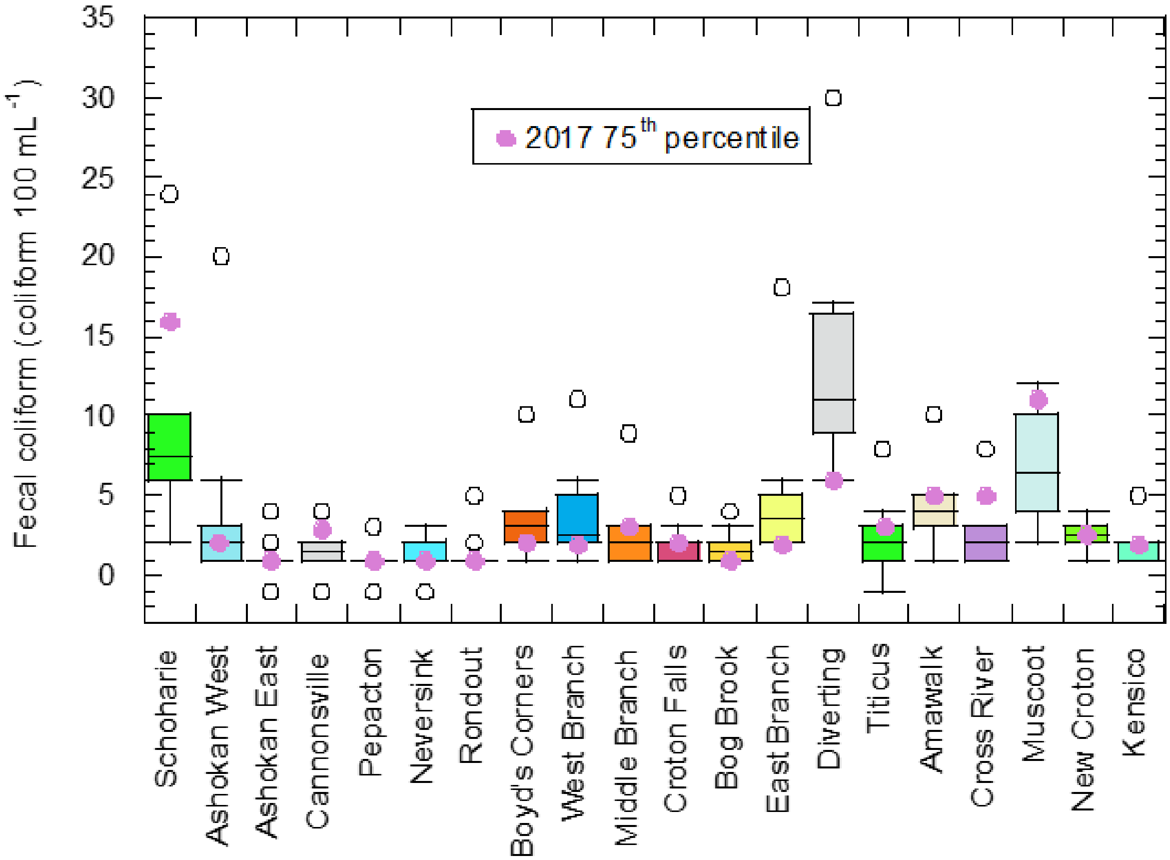

Figure 3.2 Annual 75th percentile of fecal coliforms in NYC water supply reservoirs (2017 vs. 2007-2016) with the 2017 values displayed as a solid dot. The dashed line represents the SWTR standard for source waters as a reference. Values below zero indicate that the annual 75th percentile was below the detection limit.

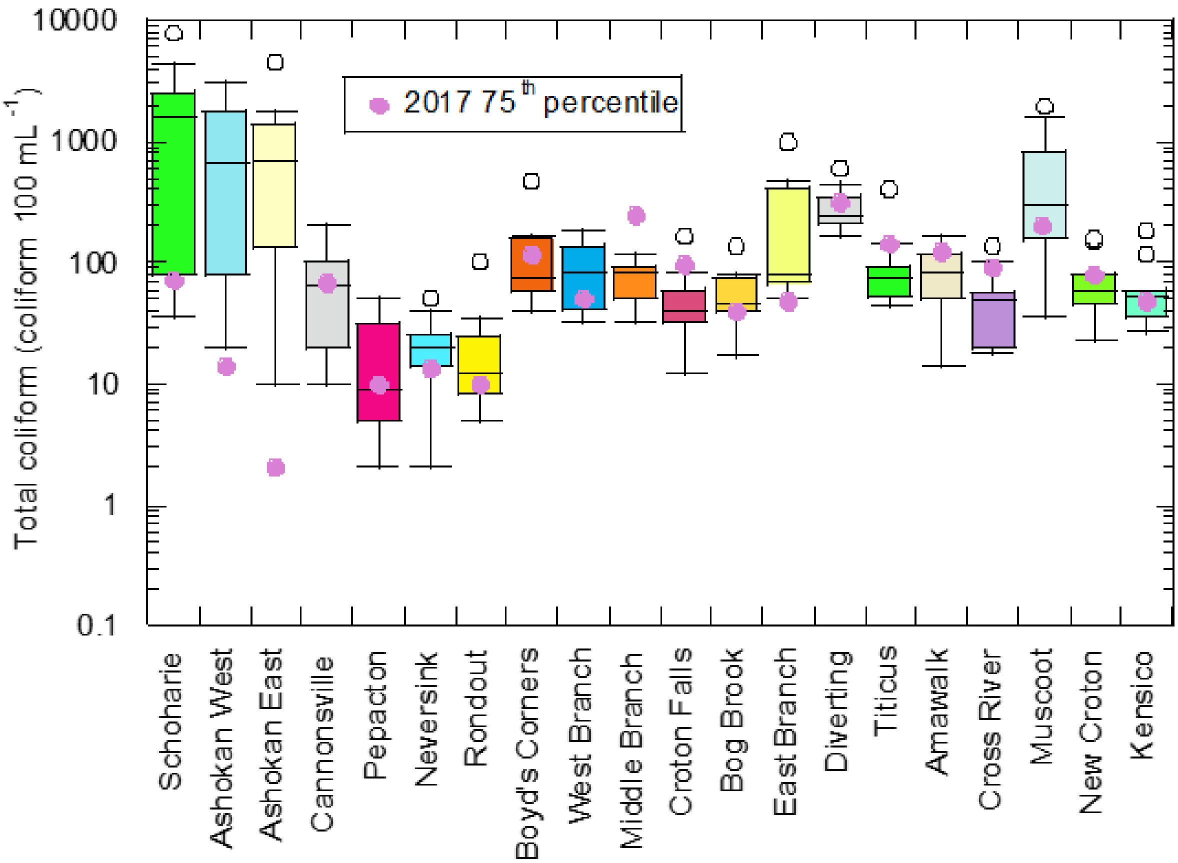

Figure 3.3 Annual 75th percentile of total coliforms in NYC water supply reservoirs (2017 vs. 2007-2016) with the 2017 75^{th} percentile values displayed as a solid dot.

Fecal coliform counts were generally low or within one coliform count of normal levels in most of the Catskill/Delaware and Croton System reservoirs in 2017 (Figure 3.2). However, higher than normal fecal counts were observed at Schoharie, Cannonsville, Cross River and Muscoot reservoirs. Despite the low annual rainfall, these reservoirs were sampled in close proximity to rainfall events to produce higher than normal fecal counts for the year. This was especially evident at Cross River where sampling within several days of a rain event occurred on five separate occasions in 2017.

Total coliform counts throughout the Catskill/Delaware System reservoirs were low (or low-to-normal) in 2017 coinciding with the generally low rainfall. Historically, the highest total coliform levels occur in the Catskill System reservoirs (Figure 3.3). Because coliforms commonly adhere to soil particles and soils are very susceptible to erosion in these watersheds, an equal volume of runoff tends to produce much higher coliform levels in the Catskill System reservoirs. However, in 2017, Catskill total coliform counts were 23 to 350 times lower than historical levels and consistent with, or in the case of Ashokan East, much lower than, levels typically observed for the rest of the water supply system.

In the Croton System, total coliform counts were higher than usual in nine of 14 reservoirs/controlled lakes in 2017 despite the low annual rainfall. Although annual rainfall was low, sampling soon after rain events occurred frequently at Cross River Reservoir and resulted in elevated counts for both fecal and total coliforms. For the other reservoirs, the majority of sample collections occurred when preceding weeks were relatively dry. It is not clear why total coliforms were elevated in these reservoirs, although stream temperatures were higher than usual when compared to median temperatures from the previous decade, and warmer conditions may have favored increases in environmental coliforms in streams and reservoirs.

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

Lake	Historical total coliforms (75th percentile 2007-16)	Current total coliforms (75th percentile 2017)	Historical fecal coliforms (75th percentile 2007-16)	Current fecal coliforms (75th percentile 2017)
Gilead	16	<5	1	<1
Gleneida	15	20	<1	<1
Kirk	100	100	3	<1

3.5 Phosphorus-Restricted Basin Assessments in 2017

The phosphorus-restricted basin status determination for 2017 is presented in Table 3.5. Basin status is determined from two consecutive assessments (2012-2016 and 2013-2017) 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.

Figure 3.4 graphically shows the phosphorus-restricted 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 2017, there were slight to moderate declines in annual geometric mean TP concentration in 14 reservoirs and lakes, with the largest declines from the previous year in Diverting, Middle Branch, and Ashokan West Basin (Appendix E). The 2017 geometric mean TP concentrations increased in nine reservoirs, with the largest increases in Muscoot, Croton Falls, and Cross River (Appendix E). As in the previous assessment, none of the Delaware or Catskill Systems were phosphorus-restricted (Table 3.5). All of the reservoirs in the Croton System were phosphorus-restricted, with the exception of Boyd's Corners Reservoir. Among the source water reservoirs and potential Catskill/Delaware 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.

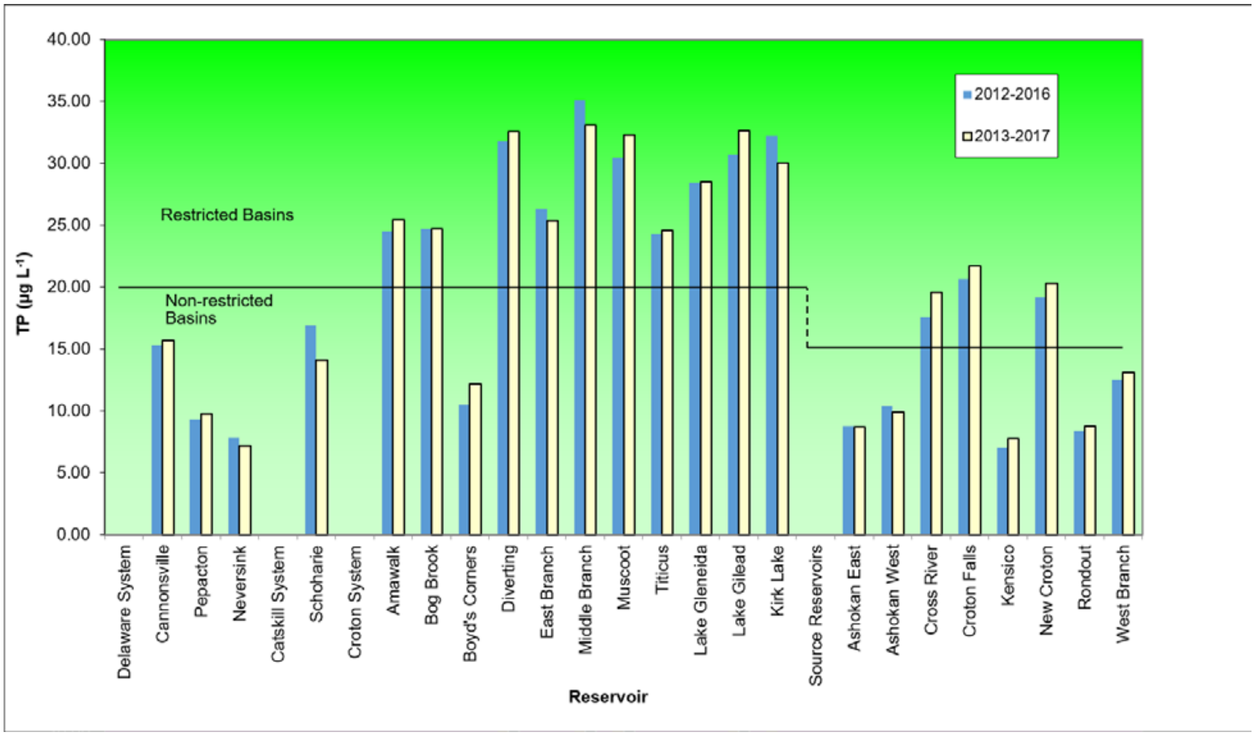

Figure 3.4 Phosphorus-restricted basin assessments.The horizontal solid lines at 20 µg L^{-1} and 15 µg L^{-1} represent the WR&R standard for non-source and source waters, respectively.

Table 3.5 Phosphorus-restricted reservoir basins for 2017.

Reservoir basin	2012-2016 Assessment[1] (µg L^{-1})	2013-2017 Assessment[1] (µg L^{-1})	Phosphorus restricted status[2]
Non-Source Waters (Delaware System)			
Cannonsville	15.3	15.7	Non-restricted
Pepacton	9.3	9.7	Non-restricted
Neversink	7.8	7.2	Non-restricted
Non-Source Waters (Catskill System)			
Schoharie	16.9	14.1	Non-restricted
Non-Source Waters (Croton System)			
Amawalk	24.5	25.5	Restricted
Bog Brook	24.7	24.7	Restricted
Boyd's Corners	10.5	12.1	Non-restricted
Diverting	31.8	32.6	Restricted
East Branch	26.3	25.3	Restricted
Middle Branch	35.1	33.1	Restricted
Muscoot	30.4	32.3	Restricted
Titicus	24.3	24.5	Restricted
Lake Gleneida	28.4	28.5	Restricted
Lake Gilead	30.7	32.6	Restricted
Kirk Lake	32.2	30.0	Restricted
Source Waters (all systems)			
Ashokan East	8.8	8.7	Non-restricted
Ashokan West	10.4	9.9	Non-restricted
Cross River	17.6	19.6	Restricted
Croton Falls	20.7	21.7	Restricted
Kensico	7.0	7.7	Non-restricted
New Croton	19.2	20.3	Restricted
Rondout	8.4	8.8	Non-restricted
West Branch	12.5	13.1	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 WR&R standard 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 2017

In 2017, total phosphorus (TP) levels in most of the Catskill/Delaware reservoirs (Figure 3.5, Table 3.6) located west of the Hudson River were within 1 µg L^{-1} of their historic median TP concentrations. TP concentrations were slightly higher at Pepacton Reservoir following multiple rain events from April to August and in November.

Median TP concentrations in West Branch Reservoir were 2 µg L^{-1} higher than historic levels. The median phosphorus concentration in West Branch's primary input, Rondout Reservoir, increased slightly in 2017 but was still relatively low compared to West Branch's median TP concentration. The median TP concentration at Boyd's Corners, which releases water to West Branch, was 16 µg L^{-1} in 2017, an increase of 7 µg L^{-1} compared to historic concentrations. Phosphorus concentrations in local streams entering West Branch were also elevated. In 2017, TP increased 8, 7, and 12 µg L^{-1} above historic concentrations at Long Pond outlet, Horse Pound Brook and Gypsy Trail Brook, respectively.

Median TP concentration in Kensico Reservoir, the terminal reservoir for the Catskill/Delaware system, was 2 µg L^{-1} higher than historic levels. The increase is likely due to the diversion of water from upstream reservoirs Rondout and West Branch with higher TP concentrations. High TP concentrations in several small streams located within the Kensico watershed may also be contributors.

Ten of 11 Croton System reservoirs and one of three controlled lakes showed increases in TP in 2017 (Figure 3.5, Table 3.6). The average increase was 4.7 µg L^{-1} and ranged from 1 to 7 µg L^{-1} compared to historic (2007-2016) concentrations. Similar to 2016, turbidity levels were generally low, as were stream flows and the number of storms exceeding 1 inch, indicating that transport of particulate phosphorus from the watersheds was probably minimal in 2017. Cross River was a notable exception. Storm events appeared to be a factor in this case as higher total and fecal coliforms, turbidity, and phosphorus were all associated with rain events that preceded several monthly sample collections within several days. However, the TP in most reservoirs (including Cross River) and East of Hudson streams appear to be trending upward.

Despite these noted increases in TP, there were no changes in phosphorus-restricted status from the previous assessment period (see sec. 3.5). DEP will continue to monitor TP concentrations and determine if this is a trend that persists or is an anomaly.

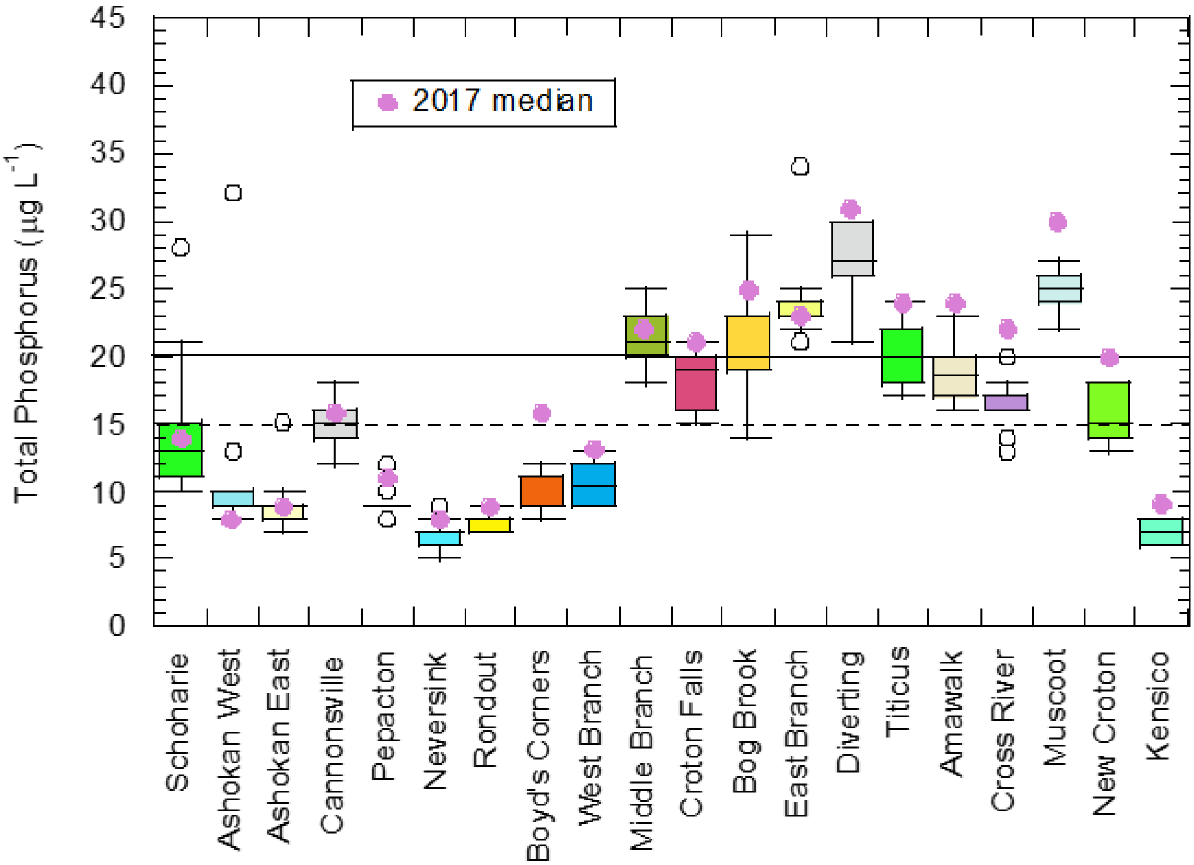

Figure 3.5 Annual median total phosphorus in NYC water supply reservoirs (2017 vs. 2007-2016) with the 2017 75th percentile values displayed as a solid dot. The horizontal dashed line at 15 µg L^{-1} refers to the NYC Total Maximum Daily Load (TMDL) guidance value for source waters. The horizontal solid 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 (2007-2016)	Median Total Phosphorus (2017)
Gilead	20	26
Gleneida	17	16
Kirk	30	23

3.7 Reservoir Comparisons to Benchmarks in 2017

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 2017 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 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.

Appendix F presents comparisons of 2017 reservoir sample results to benchmark values (Table 3.7). 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 2017 include the following:

pH

Reservoir samples were generally in the circumneutral pH range (6.5-8.5) in 2017. The majority of pH values outside the benchmark range for Kensico and West of Hudson reservoirs with lower alkalinities were below a pH of 6.5. McHale et al., 2017 documented recovery of Catskill streams from acid deposition but observed that pH is showing slower recovery and hypothesize that this is due to a decrease in mineral soil weathering rates. The greatest number of pH values below 6.5 were in Neversink Reservoir, with 70% of all samples below this benchmark. A few exceptions for WOH reservoirs where pH exceeded 8.5 occurred when phytoplankton counts were high. Occurrences of pH exceeding 8.5 are frequently associated with algal blooms. There were few exceedances for pH in Kensico, West Branch, and Rondout reservoirs in 2017 with 9%, 3%, and 14% of samples falling outside the benchmark range. In New Croton Reservoir, the number of pH exceedances was relatively low (9% of samples collected). Other Croton System reservoir pH values outside the benchmark limits ranged from 2% (Cross River) to 23% (Titicus). Two Croton System reservoirs (Boyd's Corners and East Branch) had no pH values outside the circumneutral range.

Phytoplankton

Phytoplankton counts exceeded the single sample maximum of 2000 ASU mL^{-1} for total phytoplankton for 9% of the samples collected in New Croton Reservoir in 2017. West Branch and Kensico reservoirs each had one sample exceeding this benchmark. There were no samples exceeding the total phytoplankton benchmark in Ashokan West, Ashokan East, and Rondout reservoirs, as well as four reservoirs and two controlled lakes in the Croton System. Other Croton System reservoirs, as well as Kirk Lake, had exceedances ranging from 1-7 samples representing 6-33% of samples collected. Croton Falls had the highest number of samples exceeding the benchmark in the entire system (7 samples representing 29% of routine monitoring samples). Phytoplankton samples are collected at a discrete depth of 3 m and algal blooms at the reservoir surface may be underrepresented as a consequence. Some additional surface samples were collected as part of screening for algal toxins in 2017 (see section 3.13.4). Three NYC reservoirs and one controlled lake were included on the NYSDEC Harmful Algal Blooms (HABs) Program notification page (NYSDEC 2017) (http://www.dec.ny.gov/docs/water_pdf/habsextentsummary.pdf). Kirk Lake was listed as having a confirmed bloom. NYSDEC categorizes confirmed blooms for water sampling results as those with confirmed presence of cyanobacteria that may produce toxins or other harmful compounds. Croton Falls, New Croton, 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 another measure of algal biomass. In 2017, none of the Catskill System reservoirs exceeded the single sample maximum or the mean standard. In the Delaware System, Cannonsville had seven samples (21%) that exceeded the single sample maximum and also exceeded the annual mean standard. Pepacton had two samples (5%) that exceeded the single sample maximum. Neversink and Rondout had no chlorophyll sample exceedances. Seven reservoirs in the Croton System exceeded the single sample maximum, and six exceeded the annual mean standard. Muscoot, Diverting, and Croton Falls had the highest number of chlorophyll *a* benchmark exceedances. There were no chlorophyll *a* exceedances in Kensico.

Color is an indicator of organic matter both from in reservoir and watershed sources. In 2017, all Croton System reservoirs and Kirk Lake had a high number of color exceedances, ranging from 76-100% of samples collected. Lake Gleneida had a single exceedance and Lake Gilead had four exceedances. Color in the Croton system is high due in part to the relatively high percentage of wetlands. The highest color values occurred in hypolimnetic (bottom) samples during summer when anoxic sediments release iron and manganese.

By contrast, Kensico Reservoir had few color exceedances (16 samples, representing 8% of samples collected), reflecting the characteristics of Catskill/Delaware water. West Branch receives water from the Delaware System and reflects the combined characteristics of Delaware System water and contributions from its local watershed. Color exceeded the single sample maximum for 63% of the samples collected. For WOH reservoirs, Cannonsville and Schoharie had the highest number of color exceedances (53% and 76%, respectively). There were no exceedances of the annual mean standards for dissolved organic carbon (DOC) in 2017 and four reservoirs (Rondout, West Branch, Cannonsville, and Muscoot) had one sample exceedance for the single sample maximum benchmark values for DOC.

Chloride

All samples collected in 2017 from Croton System reservoirs and controlled lakes exceeded the single sample maximum and annual mean standard for chloride. This is consistent with previous years and reflects the population and road density for the region. Four reservoirs in the system were not sampled for this analyte. The chloride exceedances in Kensico Reservoir were similar to 2015 levels (79% in 2017 as compared to 75% in 2015) and an increase from 2016 when there were no exceedances of the single sample maximum. The annual mean for Kensico in 2017 was 12.8 mg L^{-1} and was slightly above the mean value of 10.8 mg L^{-1} for the preceding year. Ashokan West, Ashokan East, Schoharie, Pepacton, and Rondout reservoirs had no exceedances of the single sample maximum and their annual means were slightly above the benchmark value of 8 mg L^{-1}. Neversink had no exceedances of the single sample maximum and was below the annual mean standard (mean of 4.7 mg L^{-1}). Cannonsville was the only WOH reservoir that had seven samples (41% of samples collected) that exceeded the single sample maximum and a small exceedance of the annual mean standard (11.6 mg L^{-1}). All chloride samples were well below the health secondary standard of 250 mg L^{-1}.

Turbidity

Turbidity levels in Kensico and Rondout reservoirs did not exceed the single sample maximum of 5 NTU in 2017. The highest number of values exceeding the benchmark of 5 NTU were for Schoharie Reservoir (65%), and Ashokan West (24%), while Ashokan East had only two samples that exceeded 5 NTU (3% of samples collected). There were some exceedances in the Croton System, a filtered supply, with the highest numbers occurring in Muscoot (19%), Diverting (18%), and Croton Falls (14%). New Croton Reservoir had few exceedances (7%) and West Branch had only one sample that exceeded 5 NTU.

Nutrients

The highest number of exceedances of the 15 µg L^{-1} benchmark TP concentration for terminal reservoirs occurred in the Croton System with exceedances ranging from 65% (Boyd's Corners) to 100% (Bog Brook, Diverting, Muscoot, and Kirk Lake). New Croton Reservoir, where 83% of the samples exceeded the single sample benchmark, compared closely to the previous year (84%). High values in the hypolimnion in the late summer to fall are indicative of phosphorus release from reservoir sediments. West Branch exceeded the TP benchmark for 38% of the samples, an increase from 25% in 2016. Ashokan West exceeded the TP benchmark for 14%, a decrease from 25% in 2016, and Ashokan East exceeded the benchmark for 2%, a decrease from 19% in 2016. In Rondout, 5% of the samples exceeded the TP benchmark in 2017. For nitrate/nitrite, Croton Falls, Muscoot, New Croton, and Cannonsville had a few exceedances of the single sample maximum of 0.5 mg L^{-1} (11%, 7%, 6%, and 4%, respectively), but none exceeded the annual mean standard of 0.3 mg L^{-1}. New Croton, Muscoot, and Croton Falls also exceeded the ammonia benchmark for both the single sample maximum (32%, 30%, and 27%, respectively) and the annual mean standard of 0.03 mg L^{-1}. Kensico, West Branch, and Schoharie exceeded the single sample maximum for 1%, 2%, and 7% of samples collected.

Fecal Coliform Bacteria

Fecal coliform counts exceeded the single sample maximum of 20 fecal coliforms 100mL^{-1} for two samples in Kensico and Rondout reservoirs, representing 1% and 3% of samples collected for the year. West Branch also had rare exceedances (three samples or 4%). One sample (2% of samples collected) in Ashokan West exceeded the single sample maximum, while Ashokan West had no exceedances. New Croton had seven of 155 samples collected (5%) that exceeded the fecal coliform benchmark value.

Table 3.7 Reservoir and controlled lake benchmarks as listed in the WR&R (DEP 2010).

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		≥40.00	
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.

3.8 Reservoir Trophic Status in 2017

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 (the DEP definition of “growing season” is May through October) when the relationship between the variables is most highly correlated. DEP water supply managers prefer reservoirs of a lower trophic state, because such reservoirs generally produce better water quality at the tap; eutrophic waters, by contrast, may be aesthetically unpleasant from a taste and odor perspective.

Historical (2007-2016) 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’s 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.

With the exception of Neversink in 2017, TSI was higher than historic median TSI levels in all Catskill/Delaware System reservoirs located west of the Hudson River. Elevated results at Pepacton coincided with high spring/summer phosphorus concentrations associated with runoff events in May, June and July. Productivity may have also been enhanced by higher than normal water temperatures from May to September. It is not clear why TSI was high at Cannonsville since nutrient levels and water temperatures were only slightly elevated compared to historic data. The high TSI in Rondout is likely due to greater diversion of higher phosphorus water from Pepacton and Cannonsville relative to lower phosphorus Neversink water in 2017. Local rain events could also be a factor. TSI in the Catskill System reservoirs was slightly elevated in 2017. Higher phosphorus and greater water clarity are probable factors.

In 2017, TSI was three units lower than historic levels at West Branch Reservoir. Although TSI in West Branch's primary input, Rondout Reservoir, was higher than normal, only deep, low-TSI, low-phosphorus water from Rondout is typically diverted to West Branch. Moreover, in 2017, the phosphorus load from West Branch's second most important input, Boyd's Corners, was diminished due to lower than normal flows from June to December.

Kensico Reservoir, the terminal reservoir for the Catskill/Delaware System, is primarily a blend of water transferred from the Ashokan and Rondout reservoirs with varying amounts from West Branch and small contributions from local Kensico watershed streams. Because the main diversions from Rondout and Ashokan are usually from low-productivity water, Kensico Reservoir is typically mesotrophic. In 2017, productivity was very low with TSI close to an oligotrophic rating.

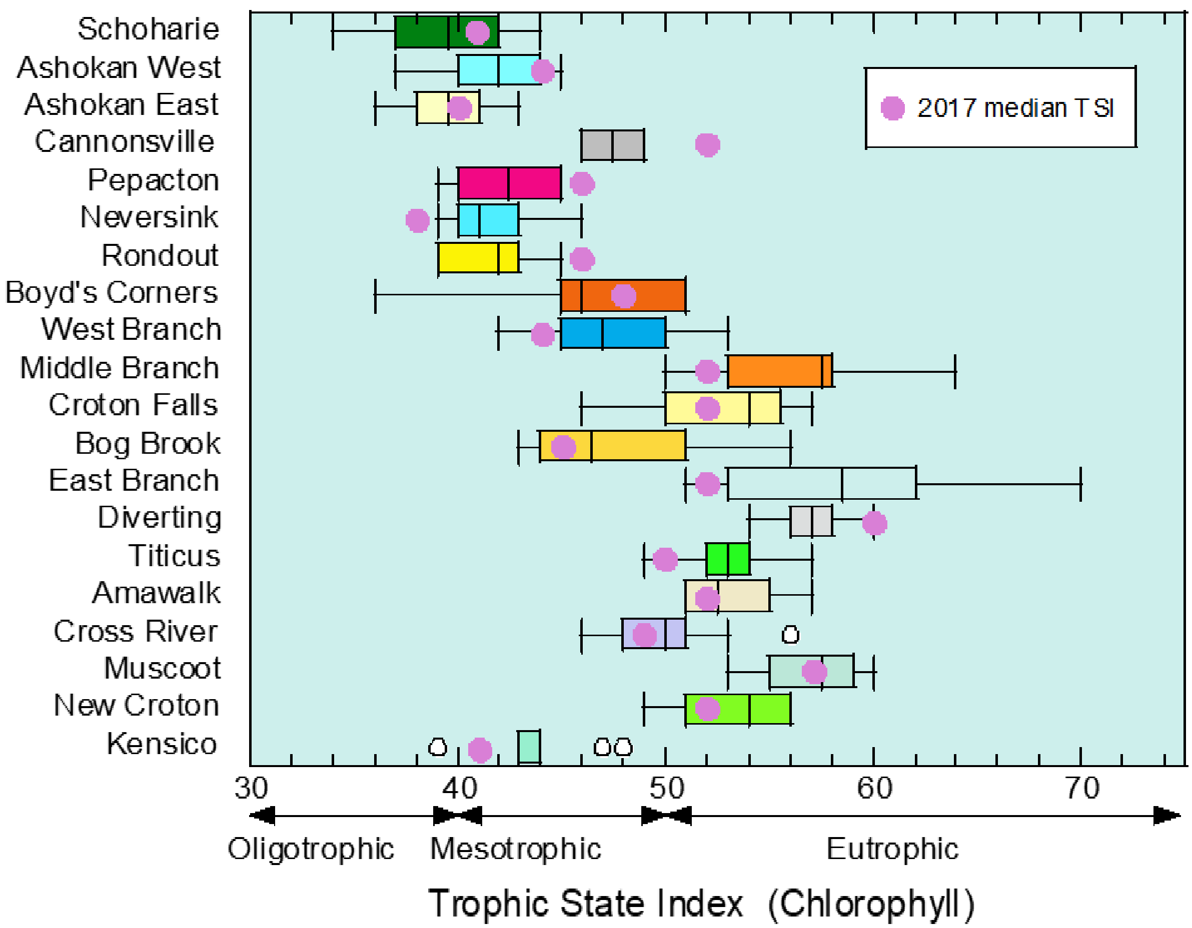

Figure 3.6 Annual median Trophic State Index (TSI) in NYC water supply reservoirs (2017 vs. 2007-2016). In general, data were obtained from epilimnetic depths at multiple sites, at routine sampling frequencies once per month from May through October. TSI is based on Chlorophyll *a* concentration.

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

Lake	Median TSI (2007-2016)	Median TSI (2017)
Gilead	47	44
Gleneida	43	39
Kirk	59	58

Similar to 2015 and 2016, TSI was lower than historic levels in most reservoirs and controlled lakes of the Croton System in 2017 (Figure 3.6, Table 3.8). Reasons for the low values are not clear since phosphorus levels were relatively high throughout the Croton System in 2017 (Figure 3.5) as was water clarity (Figure 3.1). The highest phosphorus concentrations were found to occur in the bottom waters, so perhaps these nutrients were less available for utilization by algae located higher up in the water column. Relative to historic levels, small TSI increases were observed in two Croton System reservoirs: Boyd's Corners and Diverting. Boyd's Corners increased 2 TSI and was associated with algal blooms in May and June. TSI in Diverting Reservoir increased 3 TSI units due to blooms in June, July and October. Blooms in both reservoirs were usually associated with very warm temperatures.

3.9 Water Quality in the Major Inflow Streams in 2017

The stream sites discussed in this section are listed in Table 3.9, with locations shown in Figure 3.7. Since June 2016, both routine monitoring and storm event monitoring have been performed at the CBS site and sampling was discontinued at WDBN (a site listed in previous reports). These stream sites were chosen because they are the farthest sites downstream on each of the six main channels leading into the six Catskill/Delaware reservoirs and six of the Croton reservoirs. Moreover, they are the main stream sites immediately upstream from the reservoirs and therefore represent the bulk of the water entering the reservoirs from their respective watersheds. The exception is New Croton Reservoir, whose major inflow is from the Muscoot Reservoir release. Kisco River and Hunter Brook are tributaries to New Croton Reservoir and represent water quality conditions in the New Croton watershed.

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

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's 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

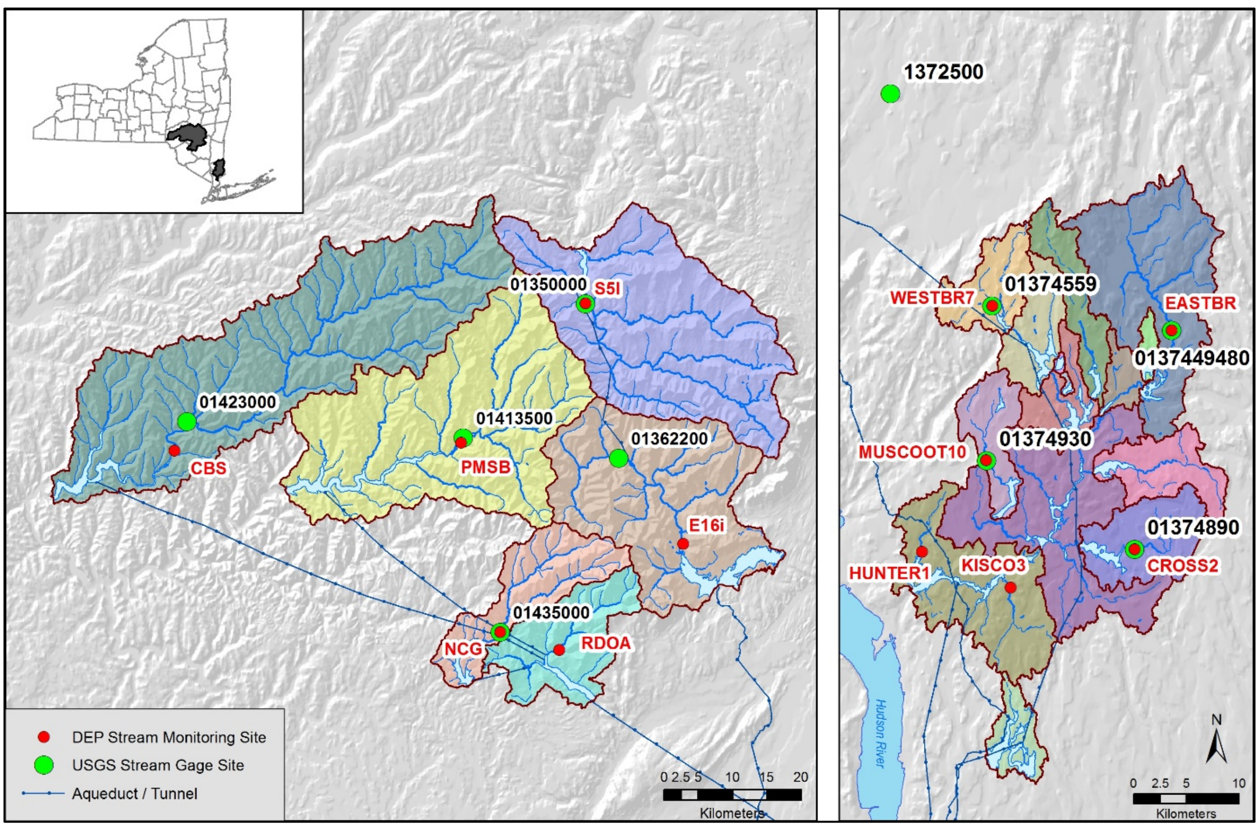

Figure 3.7 Locations of major inflow stream water quality sampling sites and USGS gage stations used to calculate runoff values (see Section 2.3).

The 2017 results presented in Figure 3.8 are based on routine grab samples generally collected once a month. Figure 3.8 compares the 2017 median values against historical median annual values for the previous 10 years (2007-2016).

Turbidity

The turbidity levels for 2017 were generally within the range of the annual medians observed over the previous 10 years (2007-2016) (Figure 3.8a). The 2017 annual median for Cross River (CROSS2) was the highest annual median for that site over this period, but was only 2.15 NTU. Likewise the Amawalk River (MUSCOOT10) had its lowest annual median turbidity compared to the last 10 years, but the range for annual medians over that period for this site was only 1.3-3.95 NTU. The WOH sites were similar in that the East Branch and West Branch Delaware River (PMSB and CBS, respectively), and the Neversink River all had their highest annual median for turbidity compared to the last ten years, but the annual medians for these sites were less than or equal to 2 NTU.

Total Phosphorus

The 2017 median TP concentrations (Figure 3.8b) exhibited mixed results among the major inflows. For example, four of the inflows (East Branch of the Croton River (EASTBR), West Branch of the Croton River (WESTBR7), East Branch of the Delaware River (PMSB), and Rondout Creek (RDOA)) had their highest median compared to the last 10 years. Another four inflows (Amawalk River (MUSCOOT10), Cross River (CROSS2), Schoharie Creek (S5I), and Neversink River (NCG) had the second or third highest median TP in 2017 compared to the last 10 years. Although 11 of the 12 inflows yielded a 2017 TP median above the median observed for the previous 10 years, the 2017 values were generally within the historical range observed over the last 10 years, expect for the median value at the West Branch of the Croton River (WESTBR7) site.

Fecal Coliform Bacteria

The fecal coliform bacteria levels for 2017 (Figure 3.8c) were generally near the annual medians observed over the past 10 years (2007-2016). None of the sites for 2017 had an annual median that was either the highest or lowest value compared to the last 10 years.

A fecal coliform benchmark of 200 coliforms $100mL^{-1}$ is shown as a solid line in Figure 3.8c. This benchmark relates to the NYSDEC water quality standard for fecal coliforms (expressed as a monthly geometric mean of five samples, the standard being <200 coliforms $100mL^{-1}$) (6NYCRR §703.4b). The 2017 median values for all streams shown here lie well below this value. There were only 12 individual samples with a result greater than or equal to 200 coliforms $100mL^{-1}$ and those were all at EOH sites. These elevated fecal coliform counts were mostly associated with rain events.

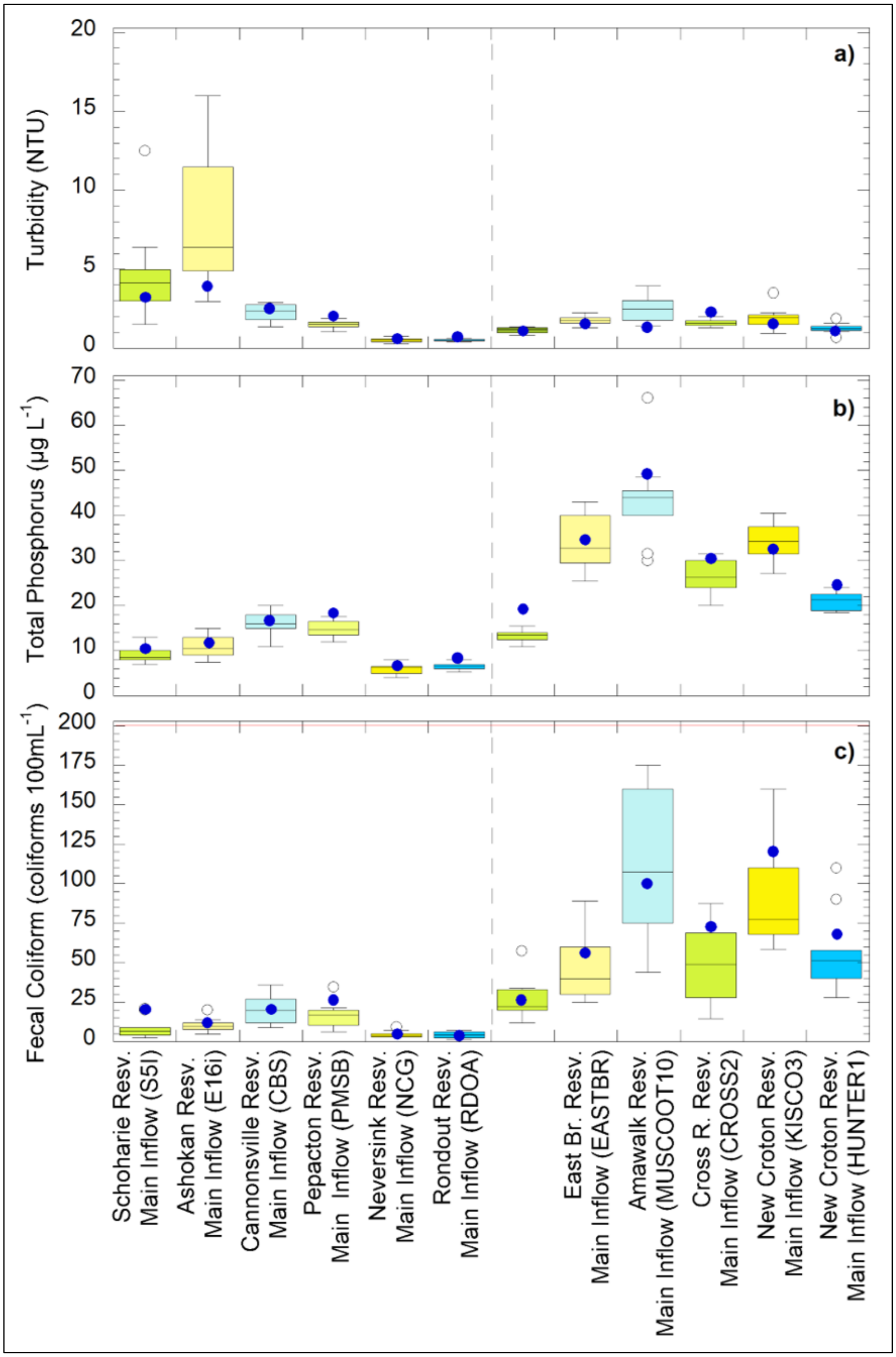

Figure 3.8 Boxplot of annual medians (2007-2016) for a) turbidity, b) total phosphorus, and c) fecal coliforms for selected stream (reservoir inflow) sites, with the 2017 values displayed as a solid dot. The dotted line separates WOH streams (left) from EOH streams (right). The solid red line indicates the fecal coliform benchmark of 200 coliforms $100mL^{-1}$.

3.10 Stream Comparisons to Benchmarks in 2017

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 2010). In this section, the application of these benchmarks has been extended to 40 streams and reservoir releases to evaluate stream status in 2017 (DEP 2016a). The benchmarks are provided in Table 3.10.

Table 3.10 Stream water quality benchmarks as listed in the WR&R (DEP 2010). 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 naturally acidic rain and melting snow moving over frozen or semi-frozen ground into the streams. Streams of the Schoharie basin did not go below 10 mg L^{-1} in 2017. A benchmark of 40 mg L^{-1} is used for the Croton System streams that reflects the much higher natural buffering capacity of this region. However, less buffering capacity does occur in the Boyd's Corners and West Branch watersheds with stream sites GYPSYTRL1, HORSEPD12, WESTBR7, and BOYDR often below 40 mg L^{-1}, with average alkalinities ranging from 34.5 to 46.8 mg L^{-1} in 2017.

Chloride

The Catskill/Delaware System annual mean benchmark of 10 mg L^{-1} was exceeded in 11 of the 24 streams monitored in the Catskill/Delaware System with the highest mean, 45.7 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 exceeded on four occasions at site NK6. 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 4.7 and 4.1 mg L^{-1}, respectively. The Kramer Brook watershed is very small (<1 sq. mile), is bordered by a state highway and contains pockets of development, all of which may contribute to the relatively high chloride levels.

Other Catskill/Delaware System streams with high annual means included Bear Kill at S6I (21.8 mg L^{-1}) located within the Schoharie watershed; Trout Creek at C-7 (15.5 mg L^{-1}), Loomis Brook at C-8 (12.7 mg L^{-1}), and the West Branch of the Delaware River at CBS (13.1 mg L^{-1}), all tributaries to Cannonsville Reservoir; and Chestnut Creek at RGB (18.9 mg L^{-1}), a tributary to Rondout Reservoir. Two Pepacton streams: Tremper Kill at P-13 (11.1 mg L^{-1}) and the East Branch of the Delaware River at PMSB (12.8 mg L^{-1}) exceeded the average benchmark in 2017. In general, higher chloride concentrations correlate with the percentage of impervious surfaces (e.g., roads, parking lots) in the watersheds. Average annual chloride was also high (31.8 mg L^{-1}) at the outflow from West Branch Reservoir release (WESTBRR). In 2017, less Rondout water – with its lower levels of chloride – was diverted to West Branch than in 2016. Coupled with high chloride streams in the West Branch basin, this caused chloride to increase from 20.7 mg L-1 in 2016 to 31.8 mg L-1 in 2017.

The Croton System annual mean benchmark of 35 mg L^{-1} was exceeded in all 16 monitored Croton streams. Annual means exceeding the benchmark ranged from 39.9 mg L^{-1} in the West Branch of the Croton River at WESTBR7 to 216.3 mg L^{-1} in Michael's Brook at MIKE2. The mean 2017 chloride concentration for all 16 Croton streams was 65.4 mg L^{-1}, substantially higher than the streams of the Catskill/Delaware System which together averaged 13.6 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 site 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 2017, 15 of 24 Catskill/Delaware streams had at least one exceedance of the TDS single sample maximum of 50 mg L^{-1}. With the exception of Esopus Creek at E5, 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 7.4 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 (approx. 7 mg L^{-1}) consistently met both TDS benchmarks.

TDS excursions in the Croton streams were also associated with elevated chloride concentrations (Figure 3.10). No streams in the Croton System met the annual benchmark of 150 mg L^{-1} or consistently met the single sample maximum criterion of 175 mg L^{-1}.

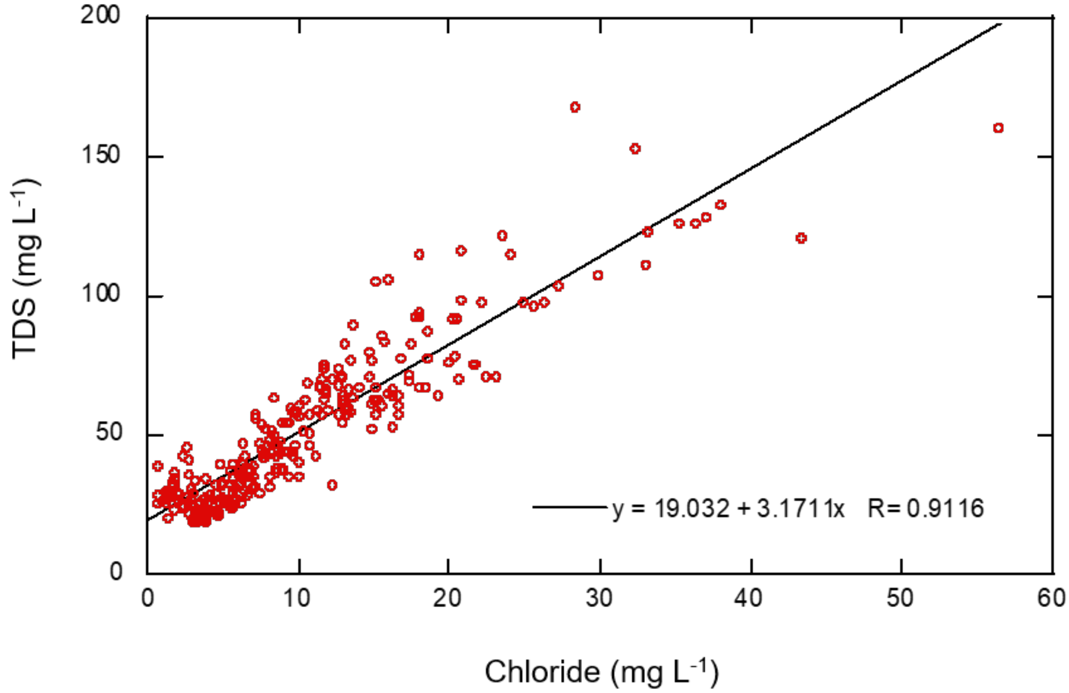

Figure 3.9 Total Dissolved Solids (TDS) versus chloride for Catskill/Delaware System streams in 2017.

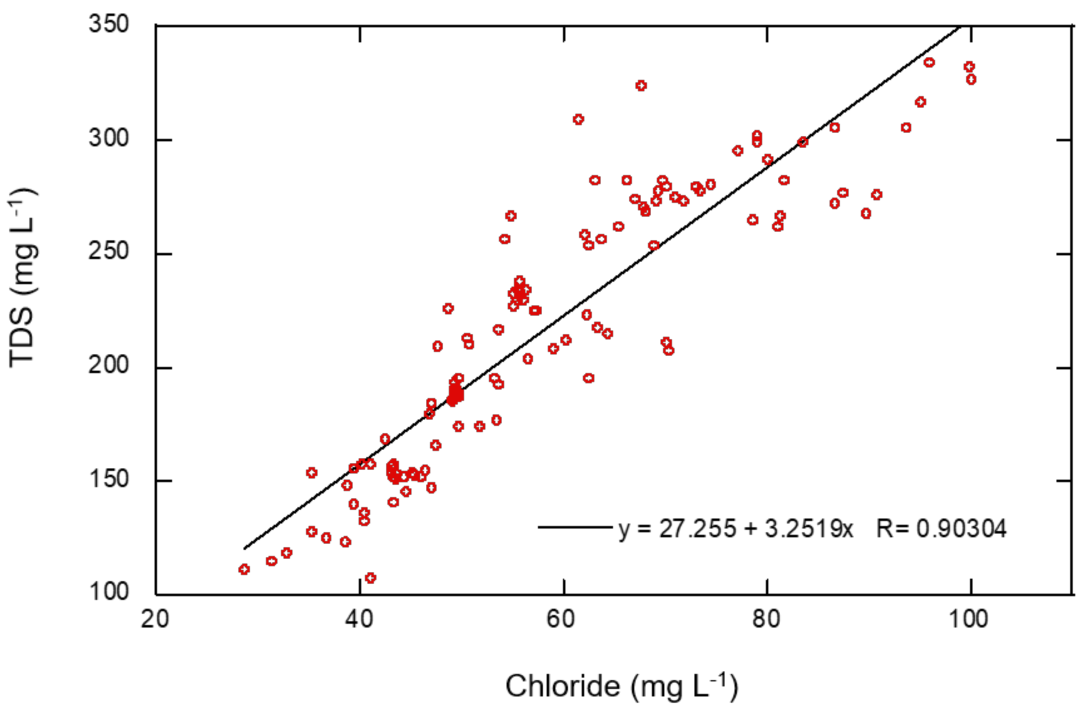

Figure 3.10 Total Dissolved Solids (TDS) versus chloride for Croton System streams in 2017.

Nitrogen

Nitrogen results were generally in compliance with benchmarks in the Catskill/Delaware System in 2017. No stream exceeded the single sample nitrate benchmark of 1.5 mg L^{-1}. The average annual benchmark of 0.40 mg L^{-1} was exceeded in the Bear Kill at S6I (0.43 mg L^{-1}), West Branch of the Delaware River at CBS (0.46 mg L^{-1}), and Kramer Brook at NK6 (0.57 mg L^{-1}). One likely source for nitrate in the Schoharie and Delaware watersheds is fertilizers associated with the relatively high agricultural activity in these basins. Wastewater treatment plants that discharge to these streams maybe another source. The source of excess nitrogen in the Kramer Brook watershed is unclear.

Two Croton streams exceeded the annual average benchmark of 0.35 mg L^{-1} for 2017: the Kisco River at KISCO3 (0.58 mg L^{-1}) and Michael Brook at MIKE2 (3.81 mg L^{-1}). The single sample nitrate benchmark of 1.5 mg L^{-1} was also exceeded at Michael Brook in 10 of 12 monthly samples and was especially high in June (6.5 mg L^{-1}) and September (11.7 mg L^{-1}).

Ammonia results were generally in compliance with benchmarks in the Catskill/Delaware System in 2017. No stream exceeded the single sample ammonia benchmark of 0.25 mg L^{-1} although the West Branch Reservoir Release (WESTBRR) did reach that level in one sample. The mean ammonia annual benchmark of 0.05 mg L^{-1} was exceeded at WESTBRR in 2017. Ammonia was detected in seven of 12 monthly samples producing an average concentration of 0.07 mg L^{-1}. Higher ammonia concentrations in the release were associated with the release of ammonia from anoxic reservoir sediments in late summer.

Three Croton System streams reached or exceeded the ammonia single sample maximum of 0.20 mg L^{-1} in 2017. The Titicus Reservoir Release (TITICUSR) exceeded it once, reaching 0.23 mg L^{-1} in November. The Cross River Release (CROSS2RVVC) exceeded the benchmark twice: 0.28 mg L^{-1} in October and 0.50 mg L^{-1} in November. The Croton Falls release (CROFALSSVC) reached the benchmark in August and exceeded it three times: 0.32 mg L^{-1} in September, 0.54 mg L^{-1} in October and 0.37 mg L^{-1} in November. All high ammonia results were associated with the release of ammonia from anoxic reservoir sediments in late summer/fall.

Sulfate

Neither the single sample maximum (15 mg L^{-1}) nor the annual mean (10.0 mg L^{-1}) benchmarks for sulfate were surpassed in the Catskill/Delaware streams in 2017. The collective average for the Catskill/Delaware streams was 4.1 mg L^{-1}. Most Croton stream results were below the Croton System single sample maximum of 25 mg L^{-1} and most were below the annual average of 15 mg L^{-1}. The lone exceedance of the single sample maximum occurred at Michael Brook (MIKE2) with one result of 25.5 mg L^{-1} in late November. Both Michael Brook and the Kisco River (KISCO3) exceeded the annual mean benchmark of 15 mg L^{-1} with averages of 22.0 mg L^{-1}, and 15.8 mg L^{-1}, respectively. Sulfate was consistently high throughout the year at these locations, ranging from 12.0-18.7 mg L^{-1} at KISCO3 and 18.0-25.5 mg L^{-1} at MIKE2 and suggesting an anthropogenic source. Both watersheds are relatively populous 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 and Croton Systems in 2017. In the Catskill/Delaware System, the highest single sample DOC result occurred at Tremper Kill at P-13 (6.1 mg L^{-1}) in the Pepacton watershed while the annual mean DOC in the Catskill/Delaware System ranged from 0.7 to 2.8 mg L^{-1}; well below the annual mean benchmark. DOC is generally higher in the Croton System than the Catskill/Delaware System (although still well below benchmarks) due to a higher occurrence of wetlands in the Croton watersheds. Mean DOC ranged from 2.9 to 5.6 mg L^{-1} in 2017, and the highest single sample DOC was 9.2 mg L^{-1}.

3.11 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 2017, DEP collected samples from 37 stations in 29 streams throughout New York City's watershed. Eleven sites were assessed on 11 streams in the Croton System, 13 sites were assessed on eight streams in the Catskill System, and 13 sites were assessed on 10 streams in the Delaware System (for site locations, see Appendix H). Some samples were analyzed twice as replicates. The mean values of those replicates are used when data are presented in figures in this section. Scores in Croton were again generally lower than in Catskill and Delaware, which is consistent with previous years' results (see e.g., DEP 2013a, 2013b, 2014, 2015, 2016b).

East of Hudson – Croton System

Of the 11 Croton System sites assessed in 2017 only two were considered moderately impaired (sites 102 and 112). However, both scored very close to the slightly impaired BAP threshold of 5.0. The remaining nine scored as slightly impaired (Figure 3.11). While 10 of the sites had BAP scores lower than their respective period of record means, one of the sites (141) scored higher than their period of record means. Additionally, eight of the sites scored higher than during the previous sampling year and only three sites showed modest declines (132, 140 and 146).

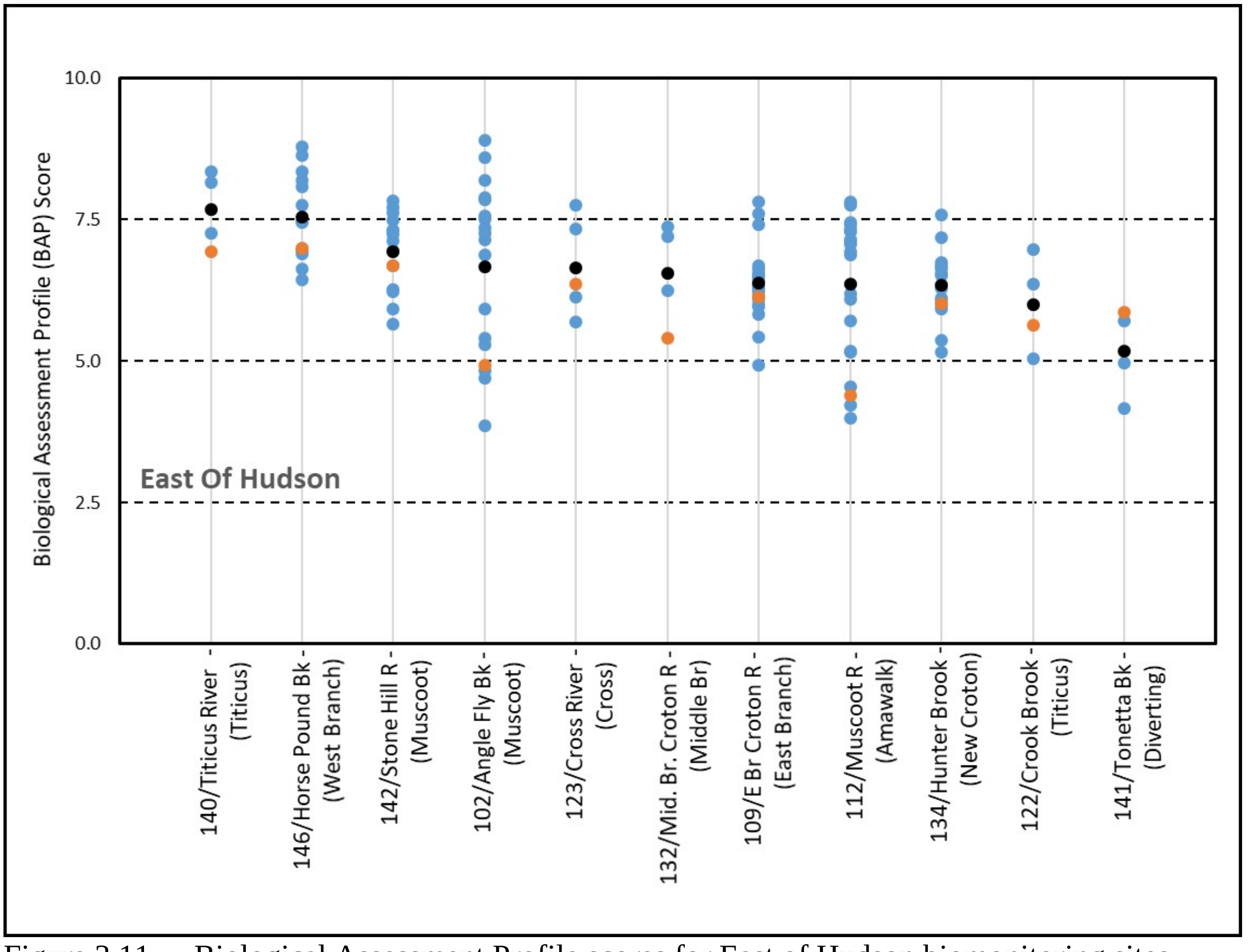

Figure 3.11 Biological Assessment Profile scores for East of Hudson biomonitoring sites sampled in 2017. Mean scores (black dots) are arranged from highest to lowest; 2017 score (orange dots), pre-2017 scores (blue dots). Watersheds are indicated in parentheses on x-axis.

The BAP score increased at Site 109 on the East Branch of the Croton River in 2017. After the drop in 2015 to within the moderately impaired range, it rebounded back into slightly impaired (Figure 3.12). While the increased BAP score is encouraging, the DEP will monitor this East Branch Reservoir watershed stream again in 2018.

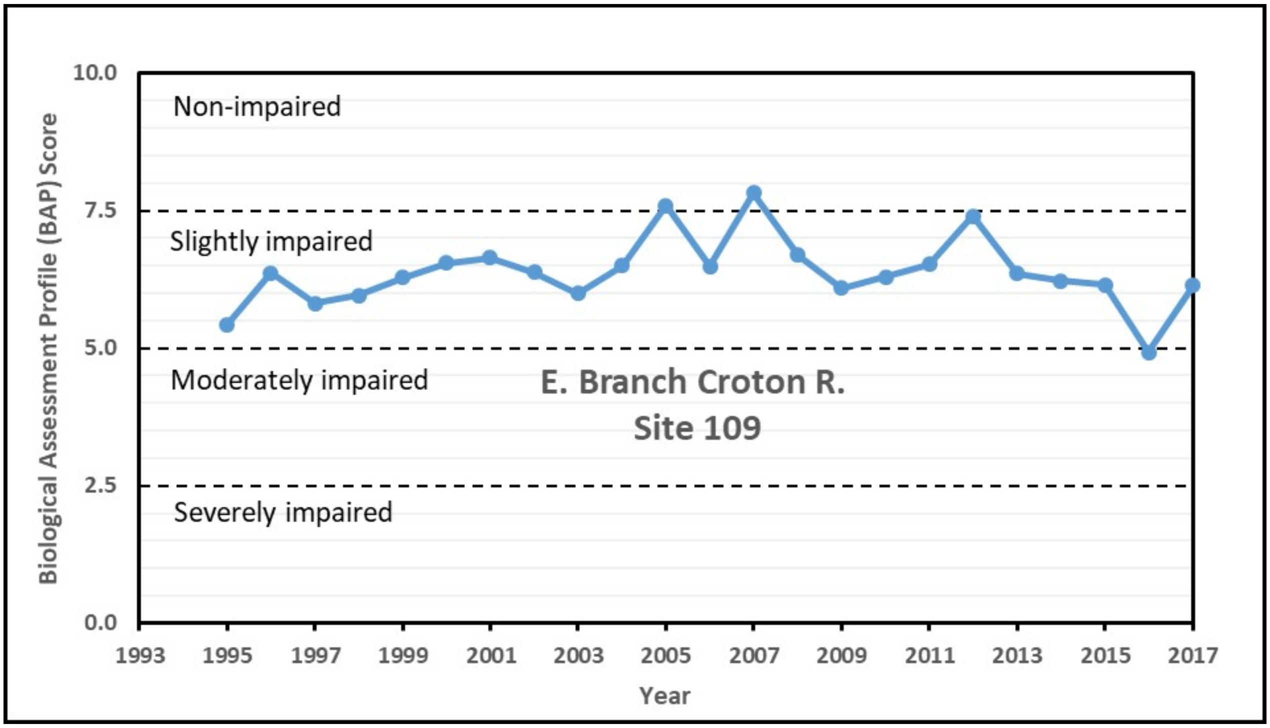

Figure 3.12 1995- 2017 BAP scores for the East Branch Croton River Site 109.

The assessment at Angle Fly Brook (Site 102) showed a second year of increased BAP score which, after the 2015 decline to 3.96, narrowly missed bringing the site back into the slightly impaired status (Figure 3.13). In fact, 2015 was the lowest score for this site for the period of record. With the exception of 2016 and 2017, the sites BAP scores have been on a general downward trend after years of being one of the highest rated sites in the East of Hudson System. As such, the DEP will continue to monitor this site in 2018.

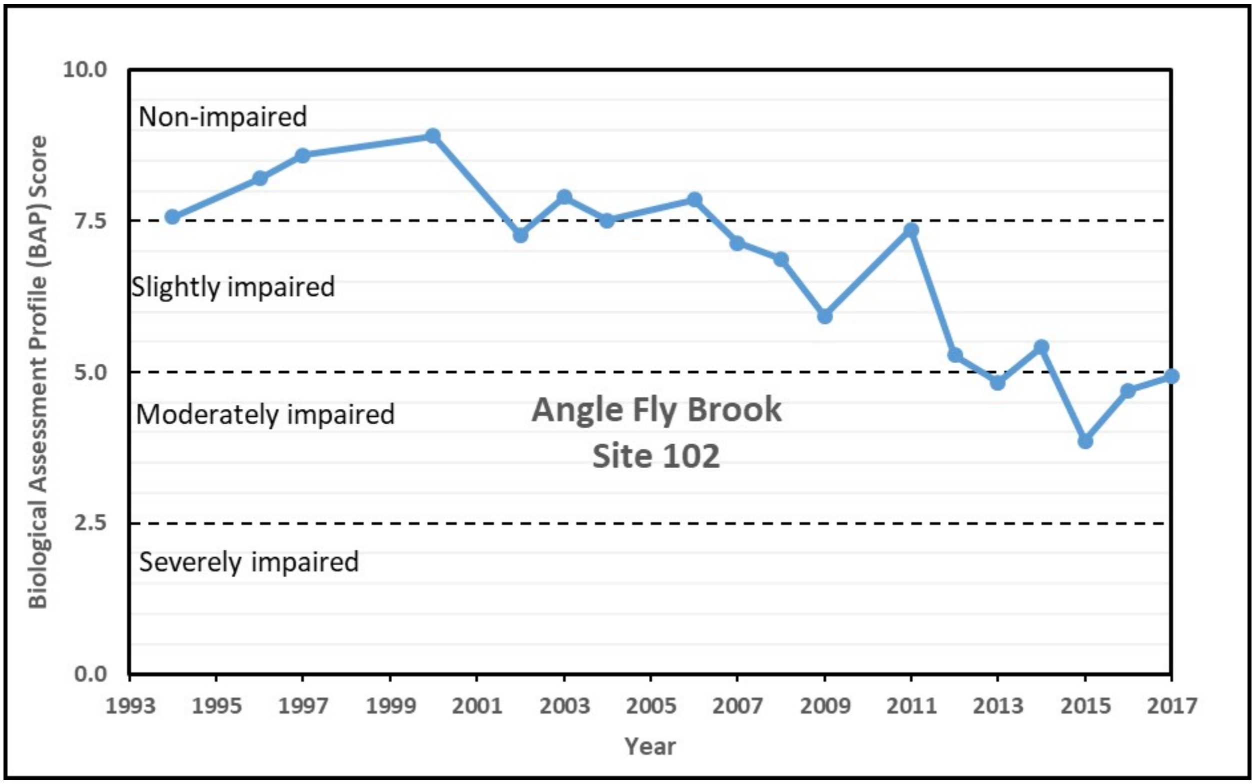

Figure 3.13 1994-2017 BAP scores for the Angle Fly Brook Site 102 showing a slightly improved rating in 2017.

West of Hudson - Catskill/Delaware System

Of the 13 Catskill System sites assessed in 2017, four were considered slightly impaired with the remaining nine considered non-impaired (Figure 3.14). While five of the 13 sites had BAP scores lower than their respective period of record means, the remaining seven sites scored higher than their period of record means while one site (216) matched its mean value. Additionally, seven of the sites scored higher than during the previous sampling year (sites 206, 215, 216, 252, 253, 256 and 260) with the remaining sites remained relatively unchanged.

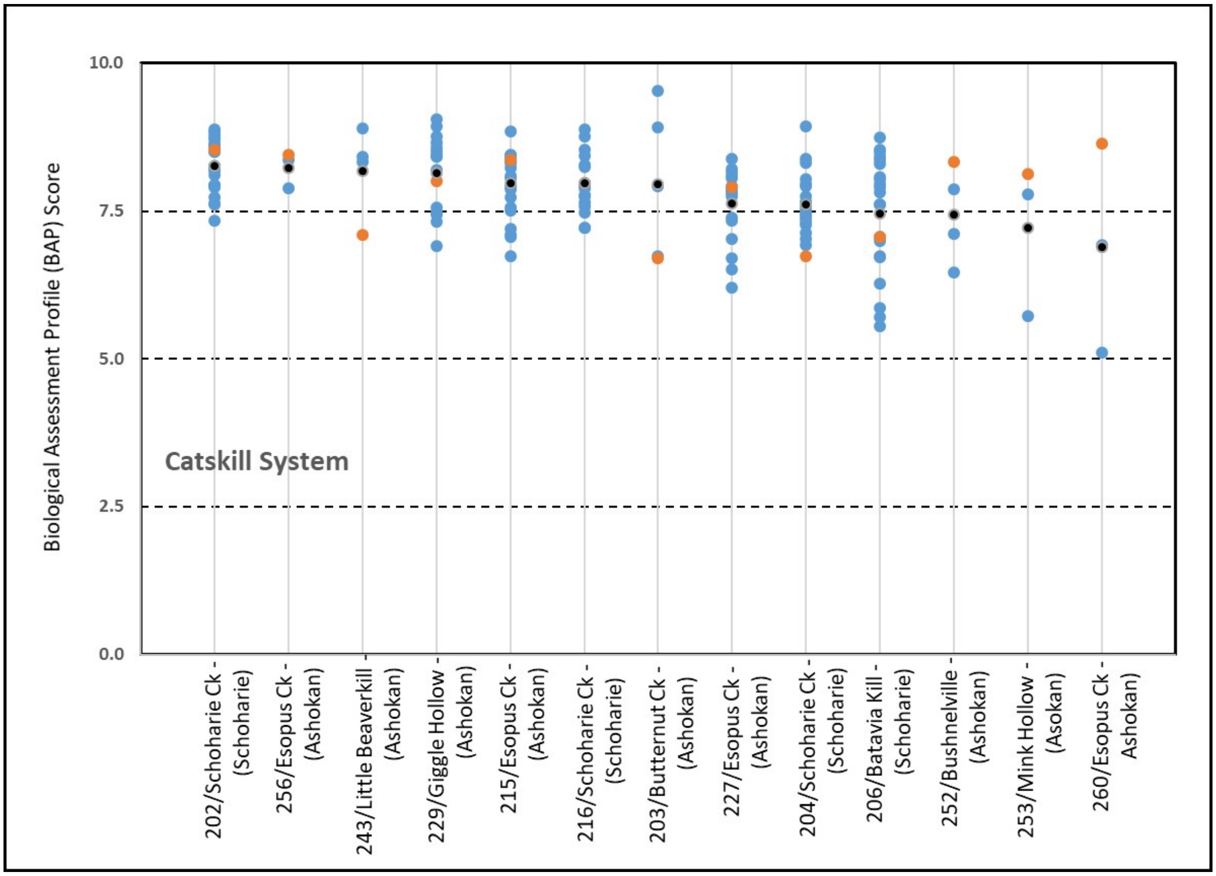

Figure 3.14 Biological Assessment Profile scores for Catskill System biomonitoring sites sampled in 2017. Mean scores (black dots) are arranged from highest to lowest; 2017 score (orange dots), pre-2017 scores (blue dots). Watersheds are indicated in parentheses on x-axis.

Of the 13 Delaware System sites assessed in 2017, four were considered slightly impaired (sites 301, 310 and 314 were relatively unchanged from their previous surveys and scored very close to the non-impaired BAP threshold of 7.5) and the remaining nine were considered non-impaired (Figure 3.15). While eight of the 13 sites had BAP scores lower than their respective period of record means, four of the sites scored higher than their period of record means and one site (321) remained unchanged. Additionally, five of the sites scored higher than during the previous sampling year (sites 301, 304, 312, 316, and 321) and six sites stayed relatively unchanged with a BAP score decreases of less than 0.5 (307, 310, 311, 314, 330 and 331).

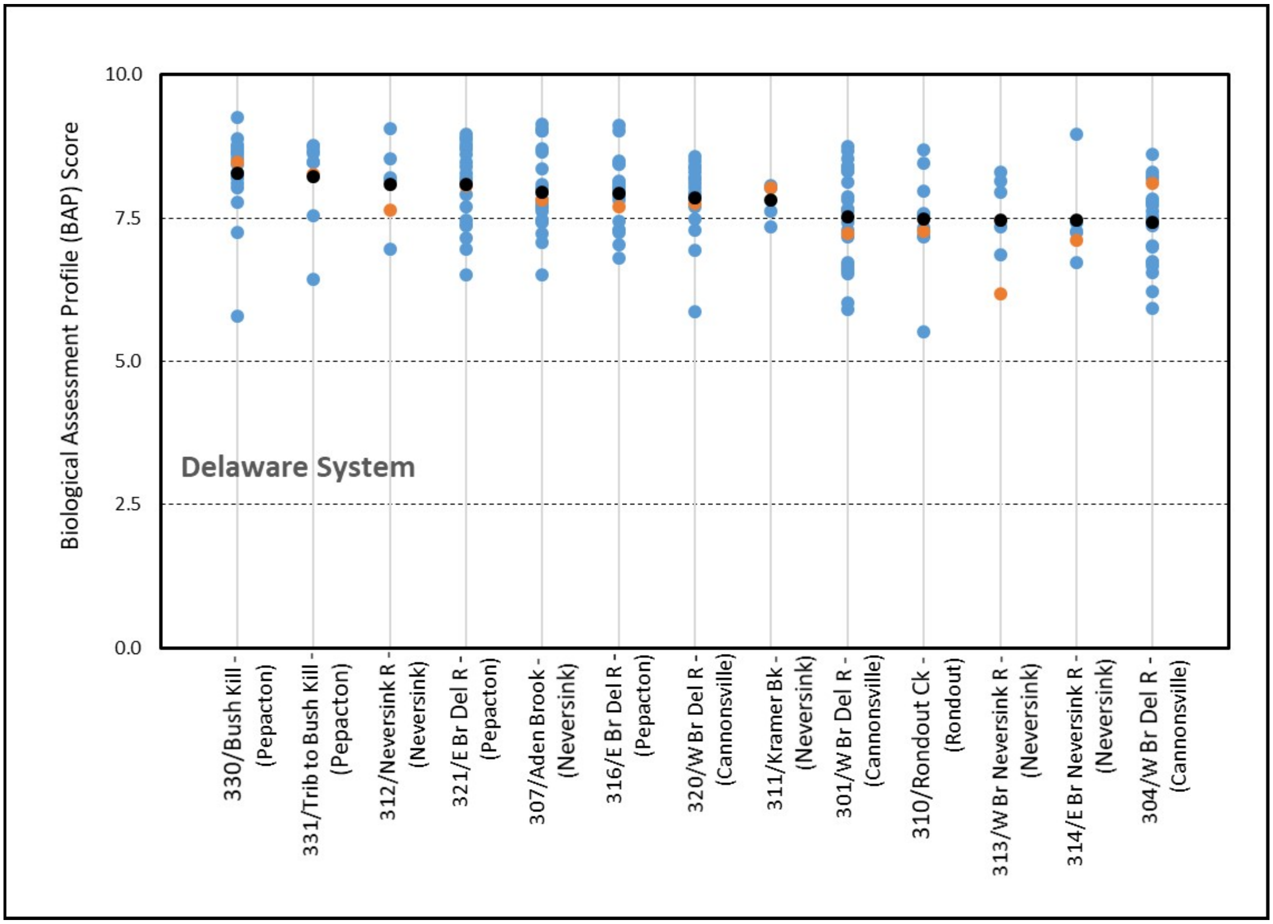

Figure 3.15 Biological Assessment Profile scores for Delaware System biomonitoring sites sampled in 2017. Mean scores (black dots) are arranged from highest to lowest; 2017 score (orange dots), pre-2017 scores (blue dots). Watersheds are indicated in parentheses on x-axis.

While all sites in both the Catskill and Delaware systems are well within the slightly to non-impaired range, it is worth noting that Site 301 on the West Branch of the Delaware River rebounded after having its lowest recorded BAP score last year (Figure 3.16). The parameters used to calculate the BAP score remained relatively unchanged except for SPP (species richness), PMA (model affinity) and NBI (nutrient biotic – phosphorus) (Table 3.11). The proximate cause of the drop in these parameters is unclear. Given that 2016 was a drought year, it is possible that Site 301 was impacted to a greater degree than the other sites. Nevertheless, the site improved this year and the DEP will continue to monitor its progress.

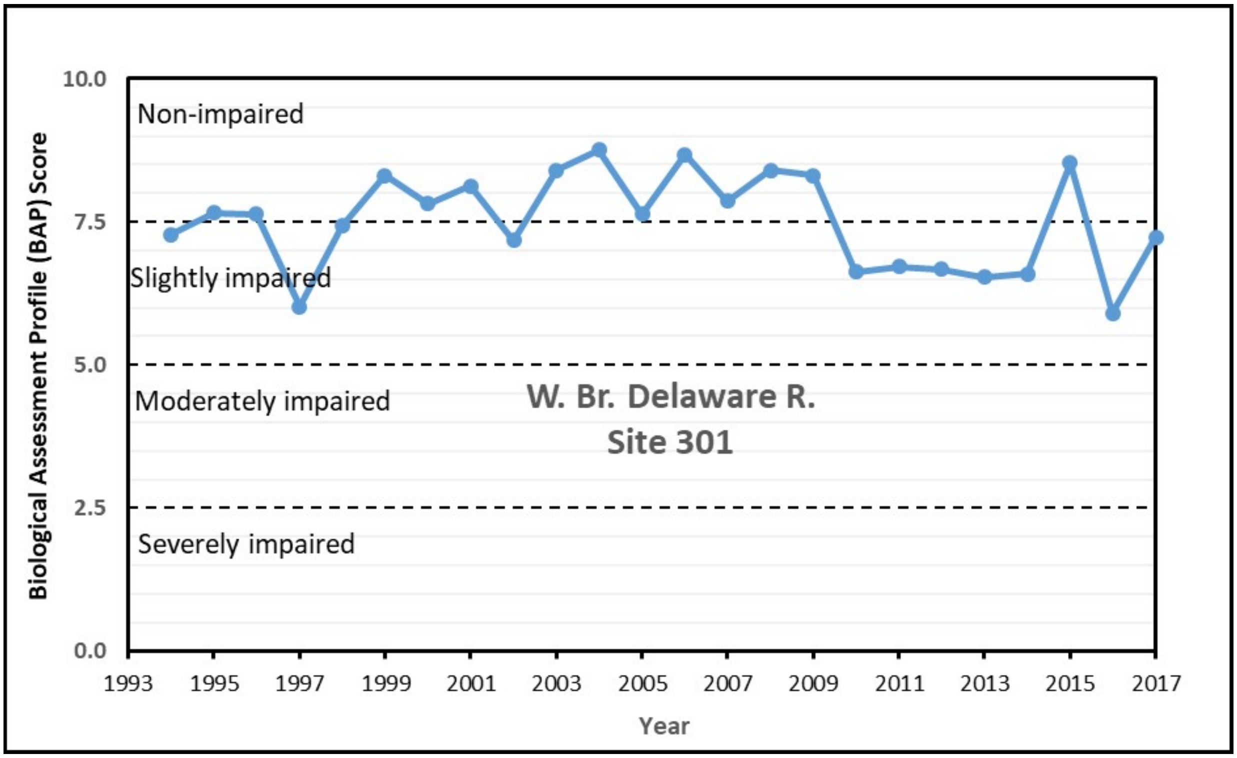

Figure 3.16 1994-2017 BAP scores for West Branch Delaware River Site 301.

Table 3.11 Parameter values used to calculate the BAP scores for Site 301 on the West Branch Delaware River.

Year	SPP	EPT	HBI	PMA	NBI-P	BAP
2015	10	10	7.3	8.5	6.9	8.53
2016	7.4	9	7.6	3.2	2.5	5.91
2017	8.6	8.0	7.7	6.9	4.9	7.23

3.12 Supplemental Contaminant Monitoring

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

DEP annually monitors a large number of volatile and semivolatile organic compounds and the herbicide glyphosate in the upstate watersheds to supplement the required distribution system monitoring for these compounds. The list of compounds is provided in Appendix I and the sites sampled are provided below in Table 3.12. In 2017, Delaware System samples were collected at sites NR2, PRR2CM, WDTOCM, and RDRRCM on October 30. Because Neversink Reservoir was off-line at the time of sampling, elevation tap NR2 was sampled instead of the Neversink intake, NRR2CM. Catskill System samples, EARCM and SRR2CM, were collected on November 29. East of Hudson samples were collected on October 17 at CRO1B, DEL10, and DEL18DT. Since New Croton Reservoir was off-line, a substitute sample was collected at the elevation tap, CRO1B, instead of at the Croton Gate House, CROGH. All samples were shipped to a contract lab for analysis. In 2017, no detections were observed in West of Hudson or East of Hudson samples for any of the compounds monitored.

Table 3.12 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.

3.12.2 Metals Monitoring

If metals are detected at unusual concentrations, supplemental (non-required) sampling of the Catskill, Delaware, and East of Hudson Systems is conducted to better determine more specific contaminant source(s). The following trace 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 3.13.

Table 3.13 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 the New York State Department of Environmental Conservation, Water Quality Regulations, Title 6, Chapter X, Part 703.5 and USEPA National Primary and Secondary Drinking Water Standards. Selected metals standards are presented in and Table 3.15.

Table 3.14 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 3.15 Water quality standards for metals from Part 703.5.

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 2017, most metal sample results were well below state and federal benchmarks. Selenium, lead, antimony, beryllium, cadmium, silver, and thallium were not detected above the detection limit of 1.0 µg L^{-1} for any sample. Likewise, chromium and zinc were not detected above their respective detection limits of 5 and 10 µg L^{-1}. Mercury was also not detected. The detection limit for mercury was determined to be 0.06 µg L^{-1} for February and May samples, which increased to 0.10 µg L^{-1} for August and November samples based on an EPA change to the method detection limit determination (EPA 2016). A single arsenic detection of 1.3 µg L^{-1} occurred on November 13 at SRR2CM, the diversion from Schoharie Reservoir, but was below the USEPA primary standard of 10 µg L^{-1}. Nickel was detected at CROGH, the untreated effluent from Croton Reservoir selective withdrawal blend, on February 14 (1.8 µg L^{-1}). Nickel was also detected in May, August and November at CRO1B, an elevation tap used when New Croton is off-line. Here detections ranged from 1.1 to 1.5 µg L^{-1}, well below the NYSDEC regulation (Title 6, Chapter X, Part 703.5) of 100 µg L^{-1}. Barium was detected in all samples, ranging from 6.5 µg L^{-1} at EARCM to 41.6 µg L^{-1} at CROGH. Copper detections ranged from 1.0 to 22.0 µg L^{-1} with no detections in 24 of 54 samples. Note that these detected barium and copper results were all well below their respective benchmarks. Also, samples from WDTOCM and PRR2CM were collected in May, August and November only, as the West Delaware Tunnel and East Delaware Tunnel, respectively, were not in use during the February sampling period.

Benchmarks for iron, aluminum, and manganese were occasionally exceeded in 2017. The iron benchmark of 300 µg L^{-1} was exceeded at SRR2CM in May (343 µg L^{-1}) and August (324 µg L^{-1}). The manganese benchmark of 50 µg L^{-1} was exceeded on seven occasions (down from eleven in 2016), while the aluminum benchmark of 50 µg L^{-1} was exceeded in six samples. Manganese exceedances occurred in one sample each at CWB1.5 (55 µg L^{-1}), CATALUM (61 µg L^{-1}), CRO1B (62 µg L^{-1}), and SRR2CM (98 µg L^{-1}) and on two occasions at NRR2CM (52 µg L^{-1}, 80 µg L^{-1}). Aluminum exceedances occurred in one sample each at WDTOCM (52.6 µg L^{-1}), EARCM (57.4 µg L^{-1}), and NRR2CM (61.2 µg L^{-1}) and in three samples at SRR2CM, ranging from 128 to 410 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 well below the benchmarks, ranging from <10.0 to 16.2 µg L^{-1} for aluminum, <3.0 to 31.0 µg L^{-1} for iron, and 11.0 to 19.0 µg L^{-1} for manganese. Note that "<" designates the analytical detection limit. The Croton keypoint closest to the distribution system, CROGH (or CRO1B), was also below benchmarks, ranging from <10.0 to 11.9 µg L^{-1} for aluminum and from 34.0 to 84.0 µg L^{-1} for iron. However, the benchmark for manganese was exceeded in one sample at 62.0 g L^{-1} and equivalent to the benchmark in another.

3.13 Special Investigations

There were a total of six special investigations conducted throughout the watershed during 2017, three of which are described here, and three others were in the Kensico basin (see Chapter 4). All of these special investigations had the potential to compromise drinking water quality in different respects.

3.13.1 Cannonsville Reservoir Drainage Basin – Kerr's Creek Manure Pile

DEP Police were investigating the apparent dumping of farm manure at a site located alongside Kerr's Creek just north of the town of Walton in the Cannonsville watershed. It was suspected that a local farmer was dumping manure at this location. As part of his investigation, DEP Police requested that the Grahamsville Laboratory collect water quality samples from Kerr's Creek above and below the location of the manure pile and analyze the samples for routine water quality parameters. On October 10, 2017, water samples were collected and analyzed for total and fecal coliforms, dissolved oxygen, pH and temperature. The results of these analyses were reported to the DEP Police. The results did not indicate any significant difference in water quality between the samples collected above and below manure pile and also did not indicate an exceedance of NYS ambient water quality standards.

3.13.2 Cannonsville Reservoir Drainage Basin - Dryden Brook Milk Discharge

DEP Police were investigating reports that a farm was dumping unwanted raw milk into Dryden Brook, a tributary of Cannonsville Reservoir. As part of this investigation, DEP Police requested that the Grahamsville Laboratory collect water quality samples from Dryden Brook at two locations downstream from the location of the suspected milk dumping and analyze the samples for routine water quality parameters. On October 2, 2017, Grahamsville Water Quality staff collected and analyzed water samples for the two sites along Dryden Brook. The results of these analyses were reported to the DEP Police. The results did indicate an improvement in water quality parameters at the sampling located further downstream, however no results from either site indicated an exceedance of NYS ambient water quality standards.

3.13.3 Catskill Aqueduct Leak – Yonkers, New York

In November 2017, Water Treatment Operations North requested sample collection and analysis to determine whether a groundwater seep identified at 2035 Central Park Avenue originated from the Catskill Aqueduct, or from the Yonkers distribution system. Samples were collected from three separate locations, and analyzed for total plankton, fluoride residual, specific conductance, total chlorine residual, and soluble reactive phosphorus. The soluble reactive phosphorus analysis was used to determine whether orthophosphate had been added to the system. If present at levels higher than background concentrations, then the data would suggest that the source was from the Yonkers Distribution system and not the Catskill Aqueduct. Soluble reactive phosphorus concentrations at the leak site were higher than background levels, pointing towards Yonkers as the source of the leak, and not our aqueduct. Follow up sampling was requested in 2018.

3.13.4 Algal Toxins

In 2017, algal toxins were found in 4 upstate watershed reservoirs. Using LC/MS analysis through a contract laboratory, three reservoirs (New Croton, Croton Falls, and Diverting) had anatoxin-a present, but at low levels (0.029 µg L^{-1}, 0.082 µg L^{-1}, and 0.058 µg L^{-1}, respectively). Anatoxin-a was detected in Cannonsville Reservoir at a level of 3.3 µg L^{-1}. Microcystin-LA was detected in the Croton Falls Reservoir at a level just above the detection limit (0.16 µg L^{-1}). Two outlying reservoirs (Croton Falls and Cannonsville) had detectable levels of microcystin in surface blooms in remote areas of each reservoir. At Croton Falls Reservoir, microcystins were detected in a surface bloom on October 3 at 0.57 µg L^{-1} and at Cannonsville Reservoir microcystins were detected in surface blooms on August 15 and October 25, at 1.9 µg L^{-1} and 459.2 µg L^{-1}, respectively.

To put these cyanotoxin results in perspective, the EPA health advisory limit for microcystin is 0.3 µg L^{-1} for children and 1.6 µg L^{-1} for adults. NYSDEC criteria for a harmful algal bloom (“confirmed with high toxin bloom”) is 10 µg L^{-1} microcystin in open water.

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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 and is the last impoundment of unfiltered Catskill/Delaware water prior to treatment and delivery to the City's distribution system. Protection of this reservoir is critically important to prevent water quality degradation and to maintain Filtration Avoidance. 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 2016a). These sampling site locations are shown in Figure 4.1. The plan 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 2017. The "Other Chemistry" column from the 2016 report has been replaced with "Other Analyses" to create a more complete count of the analyses performed. "Other Analyses" includes the "Other Chemistry" sample counts plus field measurements and non-nutrient/physical analytes. 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 coliform 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 2017. 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.

Table 4.1 Summary of Kensico Watershed water quality samples collected in 2017.

Kensico sampling programs	Turbidity	Bacteria	Giardia/ Crypto-sporidium	Virus	Phyto-plankton	Other Analyses
SWTR Turbidity compliance	2190					
Keypoint effluent	366	365	56	12	174	2467
Keypoint influent	521	521	104	24	104	3326
Reservoir	609	392			115	3215
Streams	154	147	107			1321

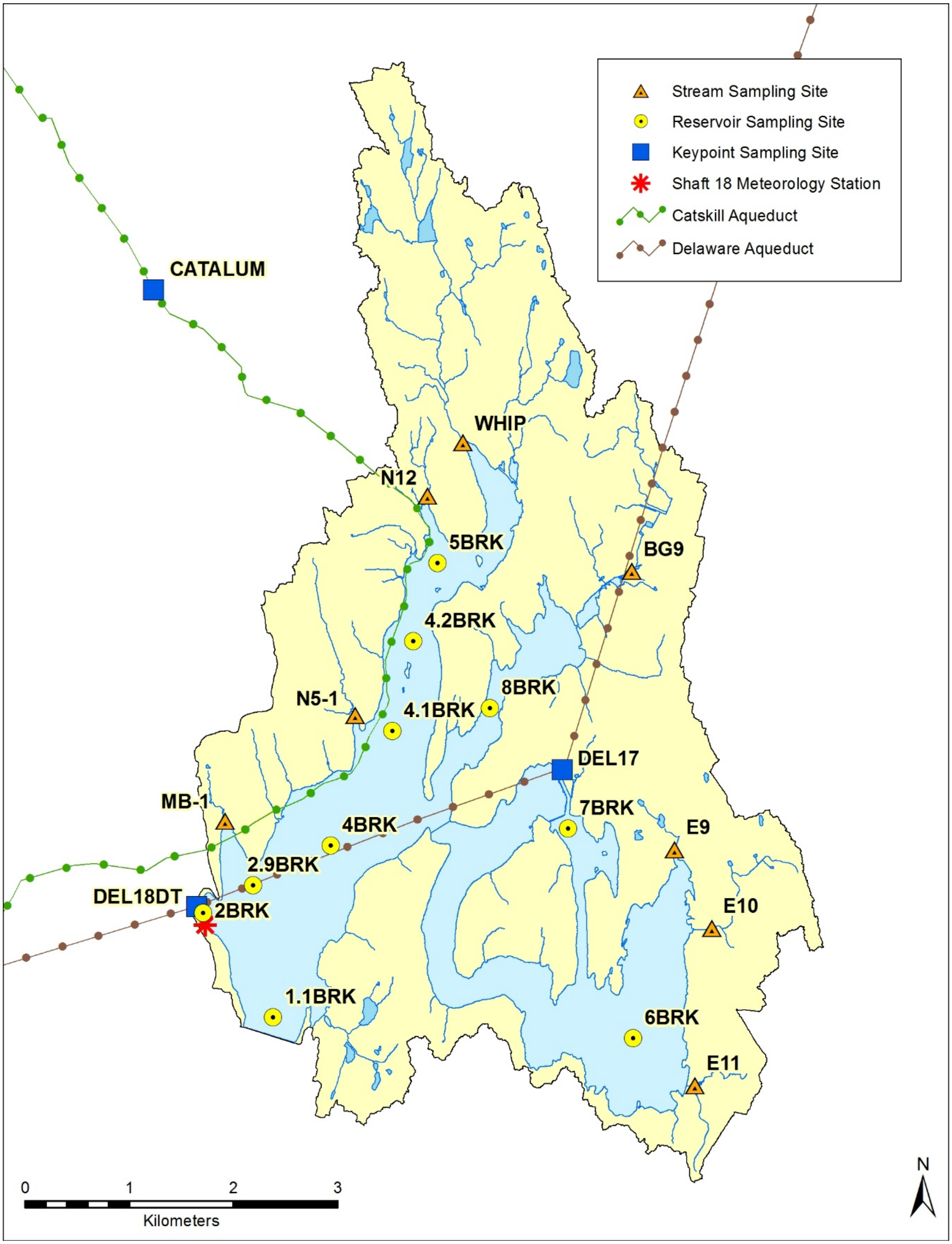


Figure 4.1 Kensico Reservoir showing limnological, hydrological, and keypoint sampling sites, meteorology stations, and aqueducts.

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 requirements for CATALUM and DEL17 were 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 2017. 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 2017.

Site	Fecal and Total Coliform, Turbidity, Specific Conductivity, Scent, and Apparent Color	Field pH and Temperature	Turbidity (SWTR)	Phytoplankton	UV254	TP	DOC	Alkalinity, Ammonia, Chlorophyll *a*, NOx, TDN, Orthophosphate, TDP, TN, Total Suspended Solids	Anions (SO4, Cl), Major Metals (Ca, K, Na, Mg), Trace Metals, Fe, Mn, Hg
CATALUM	5D	5D		W		W	M	M	Q
DEL17	5D	5D		W	W	W	W	M	Q
DEL18DT	7D	7D	4H	3D	W	M	W	M	Q

4H – Sampled every four hours
3D – Sampled three times per week
M – Sampled Monthly
7D – Sampled seven days per week
W – Sampled Weekly
Q – Sampled Quarterly
5D – Sampled five days per week.
SDPES permit monitoring requirements are in bold.

Table 4.3 shows the Kensico Reservoir influent and effluent turbidity and fecal coliform samples collected during 2017. All of the sites continued to have median values at or less than 1 fecal coliforms 100mL^{-1} and the single sample maximum values were slightly higher than in 2016. On April 1, 2017, DEP initiated a change to the reporting procedure for fecal and total coliforms to comply with the Federal Register Vol. 82, No. 165 Method Update Rule which could account for any differences between 2016 and 2017. For turbidity, all of the sites had similar or slightly lower median and single sample maximum values in 2017 as compared to the previous year.

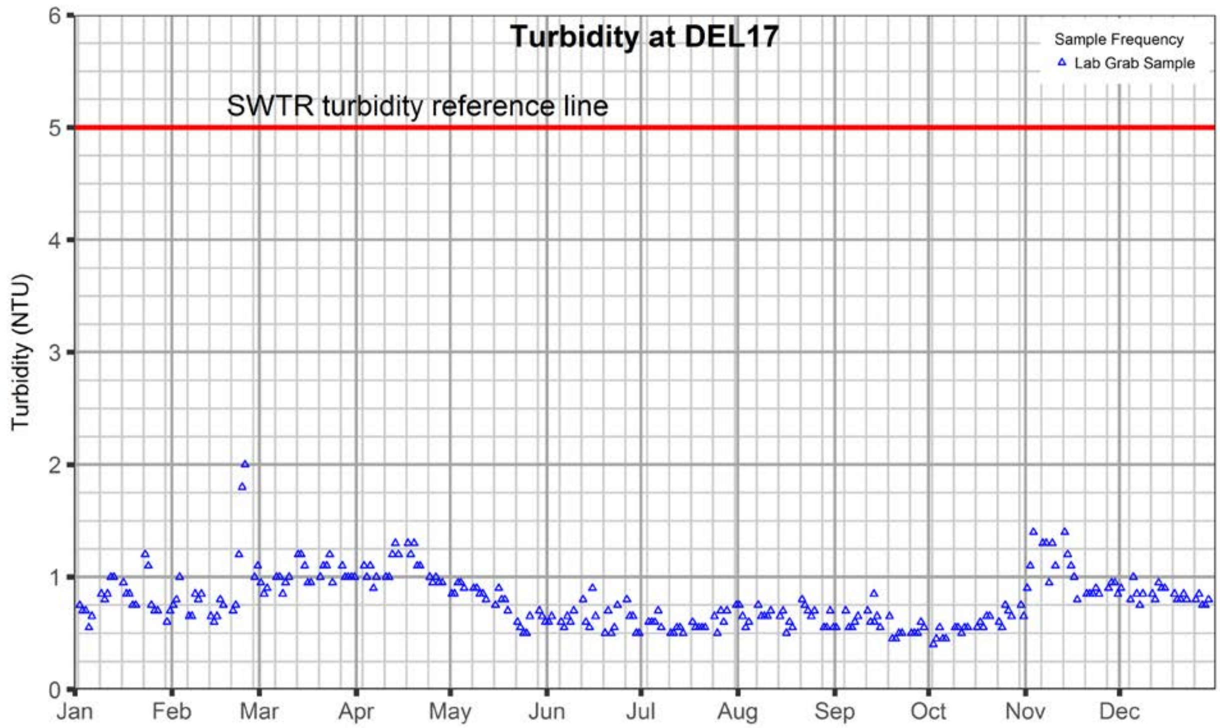
Table 4.3 Kensico keypoint fecal coliform and turbidity results from January 1, 2017, to December 31, 2017.

Analyte	Kensico Sampling Location	Median	Single Sample Maximum
Fecal Coliform (coliform $100mL^{-1}$)	CATALUM	<1	E11
	DEL17	<1	24
	DEL18DT	1	E12
Turbidity (NTU)	CATALUM	1.8	4.8
	DEL17	0.8	2
	DEL18DT	0.8	1.8

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

The routine grab sample analytical results at CATALUM, DEL17, and DEL18DT for the 2017 turbidity and fecal coliform results can be seen 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. Additionally, the fecal coliform plots contain "drop lines" connecting to the x-axis to indicate that the result is censored (below detection) values. The length of the "drop lines" goes up to the top of the censored range. A "drop line" that goes to 1 indicates that the result was less than 1. A "drop line" that extends the full range of the y-axis indicates that the non-detect value was greater than the range expressed on the plot.

For most of 2017, short term increases in turbidity or fecal coliforms could be attributed to changes in reservoir operations and/or rainfall/runoff events. At CATALUM, turbidity shows a longer-term, general upward trend from May through the end of the year, which never exceeded the SWTR turbidity reference line, and shows a trend similar to EARCM that can be related to the selective withdrawals from Ashokan Reservoir. There were two large storm events, about 2.3 inches of rainfall in the Kensico watershed on May 5-6 and between 2 and 4 inches of rainfall over the entire NYC watershed on October 29-30. The responses to these storm events at the keypoints were slight increases, remaining below the SWTR limits, for turbidity and fecal coliforms. Water quality in 2017 was excellent overall, with the source water at Kensico meeting the SWTR limits for both fecal coliforms and turbidity.



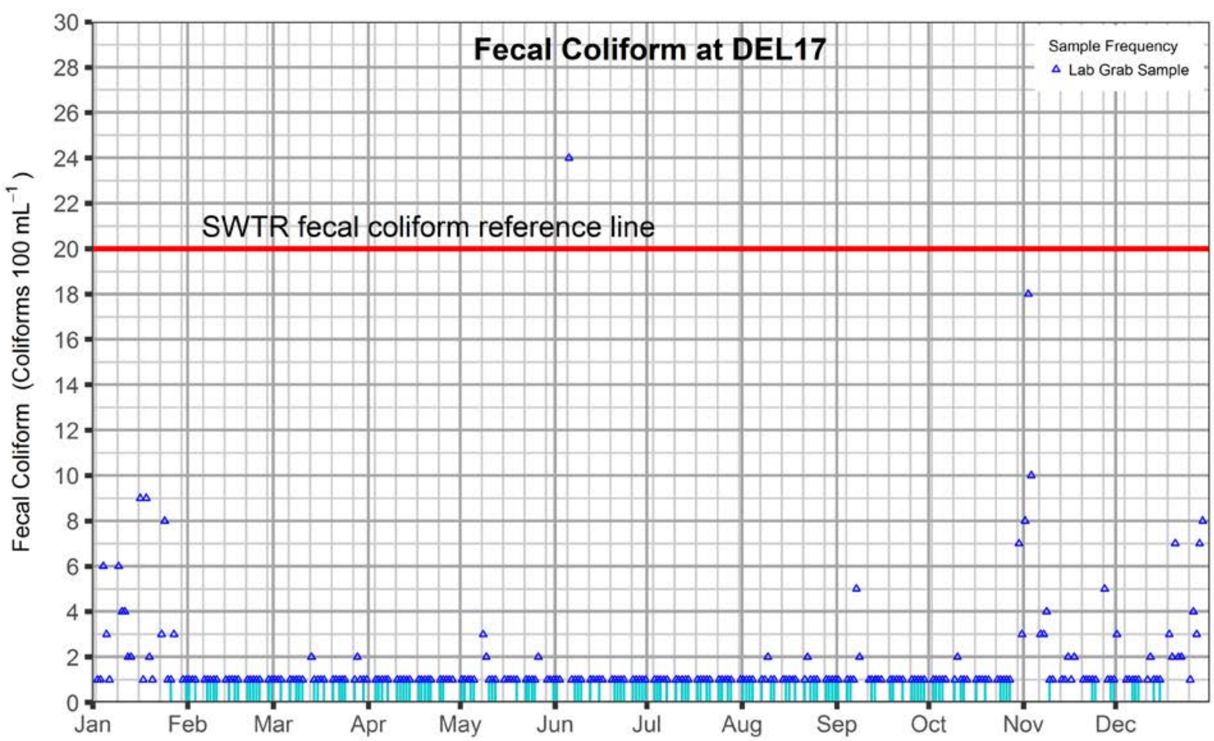
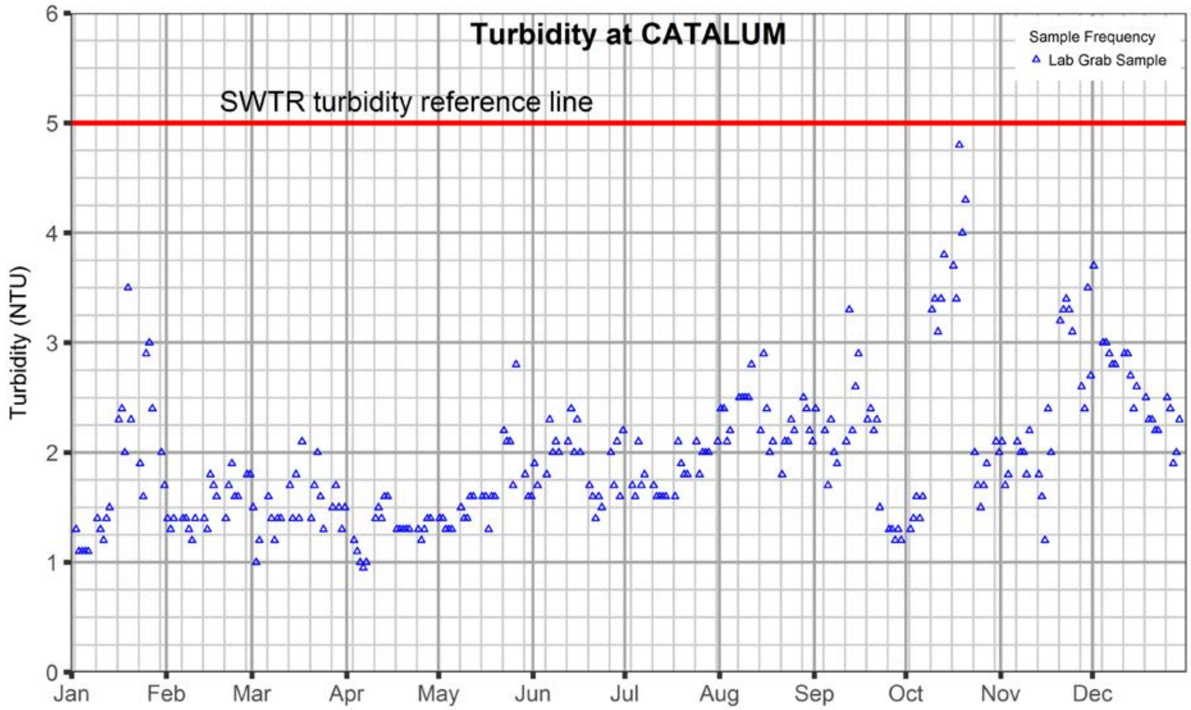


Figure 4.2 Five-day-per-week turbidity and fecal coliform grab samples at DEL17.



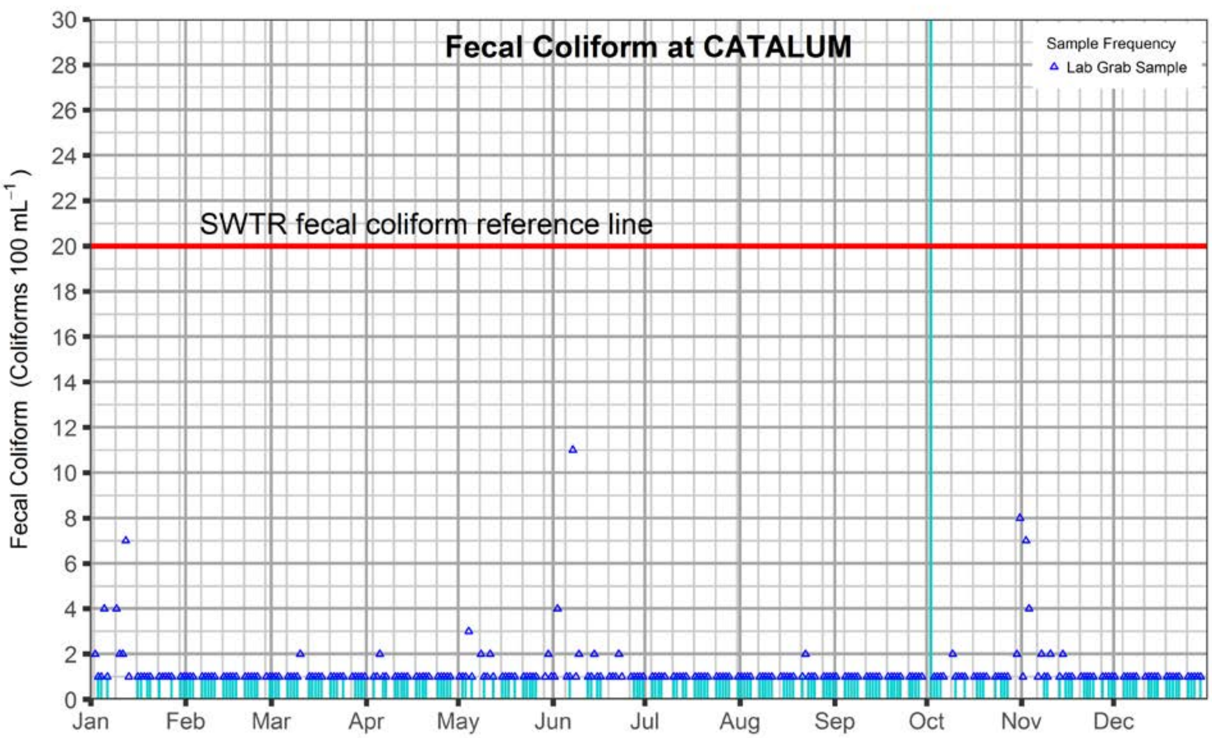
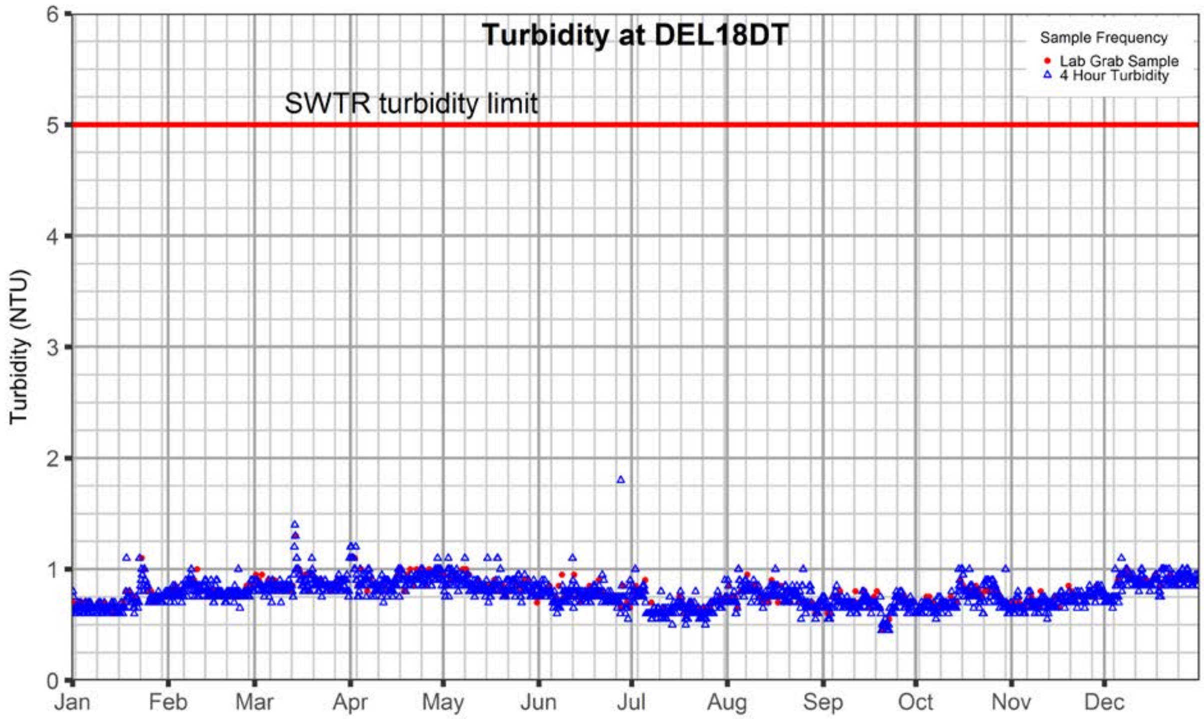


Figure 4.3 Five-day-per-week turbidity and fecal coliform grab samples at CATALUM.



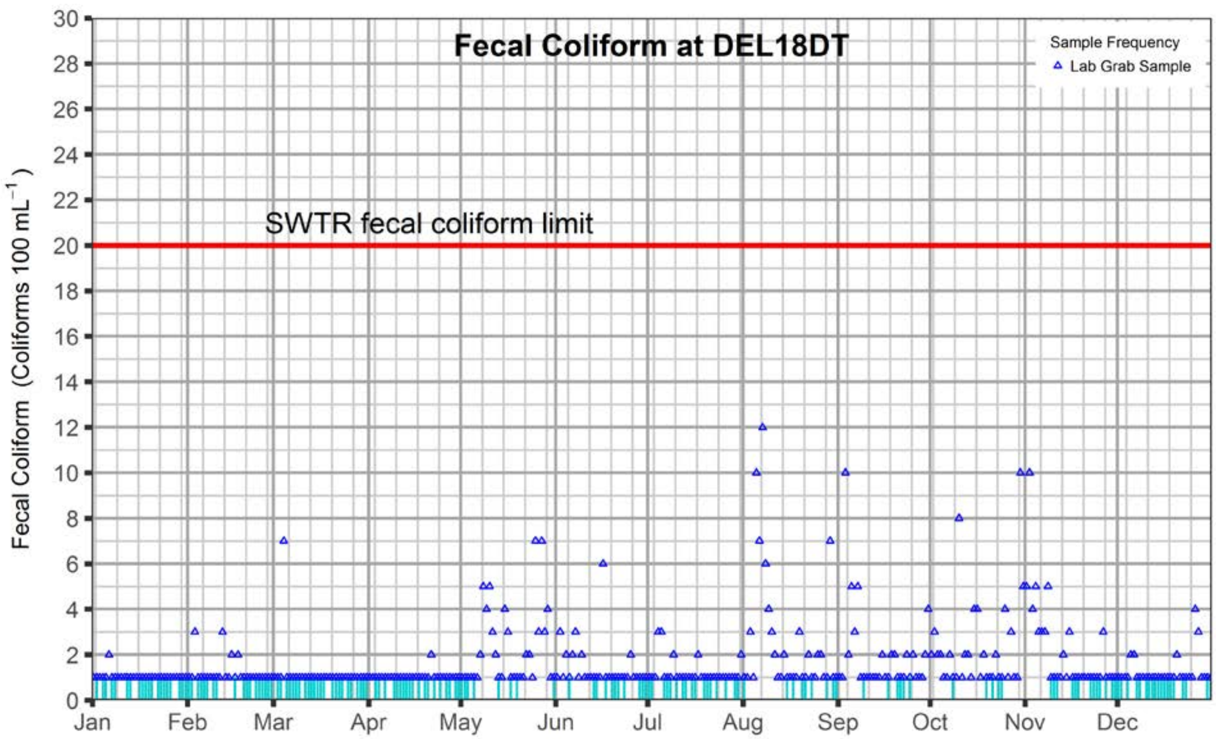


Figure 4.4 Seven-day-per-week turbidity and fecal coliform grab samples at DEL18DT.

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. Summary statistics for these streams are presented in Table 4.4.

Table 4.4 Summary statistics for Kensico watershed streams for 2017.

Analyte	Site	Obs	ND	Minimum	25th Percent-ile	Median	75th Percent-ile	Maximum	Note
Ammonia (as N) (mg L^{-1})	BG9	12	0	0.02	0.02	0.03	0.05	0.11	
	E11	12	9	<0.02	<0.02	<0.02	<0.02	0.04	ROS
	MB-1	12	1	<0.02	0.02	0.04	0.06	0.10	KM
	N12	12	8	<0.02	<0.02	<0.02	0.02	0.04	ROS
	N5-1	12	2	<0.02	0.02	0.06	0.12	0.32	KM
	WHIP	12	10	<0.02	<0.02	<0.02	<0.02	0.03	>80%
NO3+NO2 (as N) (mg L^{-1})	BG9	12	0	0.10	0.15	0.23	0.29	0.47	
	E11	12	5	<0.02	<0.02	0.03	0.09	0.26	KM
	MB-1	12	0	0.24	0.27	0.30	0.36	0.65	
	N12	12	0	0.71	0.79	0.93	1.11	1.62	
	N5-1	12	0	0.37	0.61	0.87	1.17	1.65	
	WHIP	12	0	0.57	0.64	0.80	0.92	1.39	
Total Nitrogen (as N) (mg L^{-1})	BG9	12	0	0.34	0.42	0.48	0.55	0.60	
	E11	12	0	0.22	0.29	0.33	0.39	0.49	
	MB-1	12	0	0.44	0.51	0.57	0.66	0.90	
	N12	12	0	0.80	0.93	1.00	1.21	1.58	
	N5-1	12	0	0.62	1.01	1.17	1.39	1.66	
	WHIP	12	0	0.71	0.77	0.92	1.06	1.42	
Total Phosphorus (as P) (µg L^{-1})	BG9	12	0	18	23	40	44	147	
	E11	12	0	15	25	47	55	85	
	MB-1	12	0	17	33	49	66	160	
	N12	12	0	15	20	26	41	62	

Table 4.4 Summary statistics for Kensico watershed streams for 2017.

Analyte	Site	Obs	ND	Minimum	25th Percent-ile	Median	75th Percent-ile	Maximum	Note
	N5-1	12	0	48	62	80	122	199	
	WHIP	12	0	13	24	30	38	45	
Alkalinity (mg L^{-1})	BG9	12	0	42.3	55.3	71.9	105.5	134.0	
	E11	12	0	55.0	107.8	124.5	139.3	161.0	
	MB-1	12	0	43.2	63.3	83.4	92.1	101.0	
	N12	12	0	49.4	58.5	67.7	78.8	113.0	
	N5-1	12	0	36.0	65.3	78.5	90.0	104.0	
	WHIP	12	0	37.4	45.4	59.8	78.2	98.0	
Chloride (mg L^{-1})	BG9	12	0	104.0	154.3	190.0	271.0	345.0	
	E10	1	0	324.0				324.0	<5
	E11	12	0	31.6	56.1	62.7	78.9	106.0	
	E9	1	0	171.0				171.0	<5
	MB-1	12	0	116.0	160.0	171.0	184.0	273.0	
	N12	12	0	58.2	71.6	80.3	97.4	120.0	
	N5-1	12	0	38.1	83.7	95.1	105.5	122.0	
	WHIP	12	0	60.3	82.9	95.1	98.6	116.0	
Dissolved Organic Carbon (mg L^{-1})	BG9	12	0	2.4	3.1	3.4	4.0	7.2	
	E11	12	0	3.7	4.1	4.5	4.9	7.3	
	MB-1	12	0	1.7	2.5	3.1	4.0	5.2	
	N12	12	0	1.7	2.1	2.5	3.3	3.9	
	N5-1	12	0	1.7	2.2	2.6	4.1	5.1	
	WHIP	12	0	1.6	2.3	2.9	3.3	4.3	
TSS (mg L^{-1})	BG9	12	0	1.1	1.5	3.2	7.6	57.4	
	E11	12	2	<1.0	1.2	3.1	7.7	10.4	KM
	MB-1	12	0	1.3	2.6	3.1	4.3	61.6	
	N12	12	6	<1.0	<1.0	<1.0	2.7	45.3	ROS
	N5-1	12	3	<1.0	<1.0	2.7	3.3	61.2	KM
	WHIP	12	3	<1.0	<1.0	2.1	4.9	9.9	KM
Specific Conductivity (µmhos cm^{-1})	BG9	12	0	447	651	735	1140	1440	
	E10	12	0	605	1193	1325	1555	1720	
	E11	12	0	250	404	479	585	688	
	E9	12	0	515	600	724	787	1130	

Table 4.4 Summary statistics for Kensico watershed streams for 2017.

Analyte	Site	Obs	ND	Minimum	25th Percent-ile	Median	75th Percent-ile	Maximum	Note
	MB-1	12	0	386	675	763	846	1110	
	N12	12	0	333	452	499	544	556	
	N5-1	12	0	214	422	539	565	598	
	WHIP	12	0	361	430	463	530	566	
Turbidity (NTU)	BG9	12	0	0.9	2.0	3.3	3.6	4.7	
	E10	12	0	0.1	1.0	1.5	3.8	19.0	
	E11	12	0	0.9	2.2	3.1	5.9	12.0	
	E9	12	0	0.6	1.0	2.0	4.4	9.4	
	MB-1	12	0	1.6	2.9	4.3	6.3	50.0	
	N12	13	0	0.3	0.5	0.6	1.0	6.2	
	N5-1	12	0	0.7	1.8	2.2	3.1	65.0	
	WHIP	12	0	0.5	0.7	1.1	2.3	4.9	
Fecal Coliform (coliforms $100mL^{-1}$)	BG9	12	0	2	24	45	160	600	
	E10	11	0	5	19	70	115	970	
	E11	11	0	3	8	160	270	1200	
	E9	12	1	<2	10	90	220	E850	KM
	MB-1	12	0	3	85	110	775	E1000	
	N12	12	0	5	56	88	143	E450	
	N5-1	12	0	2	10	55	273	E1300	
	WHIP	12	0	2	20	34	97	250	
Total Coliform (coliforms $100mL^{-1}$)	BG9	12	0	100	143	250	2550	13000	
	E10	12	0	150	643	1500	2625	>=9800	
	E11	12	0	77	218	620	4575	17000	
	E9	12	0	41	190	2700	7000	>=21000	
	MB-1	12	0	190	250	830	3400	8800	
	N12	12	0	100	168	1100	3850	5600	
	N5-1	12	0	73	245	785	2950	9000	
	WHIP	12	0	86	310	1100	2400	4800	
Dissolved Oxygen (mg L^{-1})	BG9	12	0	2.2	5.3	7.2	10.1	12.1	
	E10	12	0	7.9	9.2	10.2	11.2	13.3	
	E11	12	0	0.3	4.4	6.7	9.3	11.1	
	E9	12	0	3.6	4.6	5.9	7.4	9.8	

Table 4.4 Summary statistics for Kensico watershed streams for 2017.

Analyte	Site	Obs	ND	Minimum	25th Percent-ile	Median	75th Percent-ile	Maximum	Note
	MB-1	12	0	7.2	8.8	10.0	11.2	13.8	
	N12	12	0	8.9	9.8	10.9	11.7	14.4	
	N5-1	12	0	5.8	7.4	9.2	11.4	13.5	
	WHIP	12	0	8.4	9.6	11.0	11.7	14.1	
pH (SU)	BG9	12	0	6.76	6.96	7.17	7.24	7.50	
	E10	12	0	7.45	7.69	7.78	7.85	7.92	
	E11	12	0	6.93	7.21	7.36	7.46	7.77	
	E9	12	0	6.67	6.84	6.95	7.11	7.22	
	MB-1	12	0	6.74	7.00	7.16	7.31	7.44	
	N12	12	0	7.39	7.67	7.76	8.01	8.34	
	N5-1	12	0	7.24	7.31	7.46	7.50	7.69	
	WHIP	12	0	7.42	7.66	7.76	7.89	8.24	
Temperature (ºC)	BG9	12	0	3.6	8.0	12.8	18.0	23.0	
	E10	12	0	3.8	8.1	11.6	15.6	19.9	
	E11	12	0	5.1	7.7	13.0	16.6	23.7	
	E9	12	0	0.5	6.5	11.9	17.1	20.6	
	MB-1	12	0	3.2	8.0	12.3	15.4	20.4	
	N12	12	0	4.6	8.1	10.9	16.4	19.6	
	N5-1	12	0	3.5	7.5	12.3	16.0	21.7	
	WHIP	12	0	4.0	8.1	11.6	17.5	22.6	

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 5 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 maintained around the Catskill Upper Effluent Chamber cove in Kensico Reservoir protect water entering into distribution system from the impacts of storm events by local streams. DEP conducts at least a monthly visual inspection of the turbidity curtains from fixed shore locations around the cove. Additional observations were made in 2017 in response to boat ramp construction in the DEL18 cove. The construction work in the DEL18 cove took place between May 31, 2017, and August 4, 2017. Additional measures were taken to ensure excellent water quality, including the installation of an additional turbidity curtain and automated monitoring buoys. Figure 4.5 lists the dates and results of the turbidity curtain inspections carried out in 2017. 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
01/11/17	Curtains appear intact and afloat as seen from shore.
01/25/17	Curtains appear intact and afloat as seen from shore.
02/08/17	DEL18 attachment points may be problematic. Turbidity Curtain committee notified. MB-1 and UEC appear intact and afloat as seen from shore.
02/22/17	DEL18 attachment points may be problematic. Turbidity curtain committee notified. MB-1 and UEC appear intact and afloat as seen from shore.
03/08/17	DEL18 North attachment point may be problematic. Turbidity curtain committee notified. MB-1 and UEC appear intact and afloat as seen from shore.
03/22/17	Curtains appear intact and afloat as seen from shore.
04/06/17	Curtains appear intact and afloat as seen from shore.
04/18/17	Curtains appear intact and afloat as seen from shore.
05/04/17	Curtains appear intact and afloat as seen from shore.
05/31/17	Curtains appear intact and afloat as seen from shore.
06/14/17	Curtain at DEL18 appeared to be hung up on the shore/log/rock. Turbidity curtain committee notified. MB-1, UEC, and boat launch curtains appear intact and afloat from shore.
06/29/17	Curtain at DEL18 appeared like it was hung up near the shore. While most of the turbid water was contained within the first turbidity curtain, it appears that some turbid water travelled past the first curtain and is contained by the second curtain. Management was notified, and the contractor deployed a diver to secure the interior curtain and correct the issue. The other curtains appear intact and afloat as seen from shore.
07/12/17	All curtains appear intact and afloat as seen from shore. At DEL18 dock, after fixing the inside curtain last month, the

Table 4.5 Visual inspections of the Kensico Reservoir turbidity curtains.

Date	Observations
	water between inside and outside curtains is still slightly more cloudy than reservoir water. However, it is much clear than water inside curtain, and no leak is seen from outside curtain.
07/20/17	DEL18 boat launch construction curtains appear intact and afloat as seen from shore.
07/26/17	Curtains appear intact and afloat as seen from shore.
08/09/17	Curtains appear intact and afloat as seen from shore.
08/24/17	Curtains appear intact and afloat as seen from shore.
09/06/17	Curtains appear intact and afloat as seen from shore.
09/20/17	Curtains appear intact and afloat as seen from shore.
10/04/17	Curtains appear intact and afloat as seen from shore.
10/18/17	Curtains appears intact and floating as seen from shore, except one section located near DEL18 where the fabric is hung-up on shore.
11/02/17	Curtains appear intact and afloat as seen from shore.
11/16/17	The curtain appears intact and floating as seen from shore, except one section located near DEL18 that is washed ashore.
11/28/17	The curtain at DEL18 appeared like it was hung up near the shore. Management was notified. The other curtains appear intact and afloat as seen from shore.
12/13/17	Curtains appear intact and afloat as seen from shore.
12/27/17	Curtains appear intact and afloat as seen from shore.

4.4 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. Upon implementation of the avian dispersal measures, both waterbird counts and fecal coliform levels declined, 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. In addition, in advance of storm events that are expected to yield excessive precipitation levels, pre-storm wildlife sanitary surveys are conducted adjacent to the Delaware Shaft 18 Effluent Facility 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.

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.

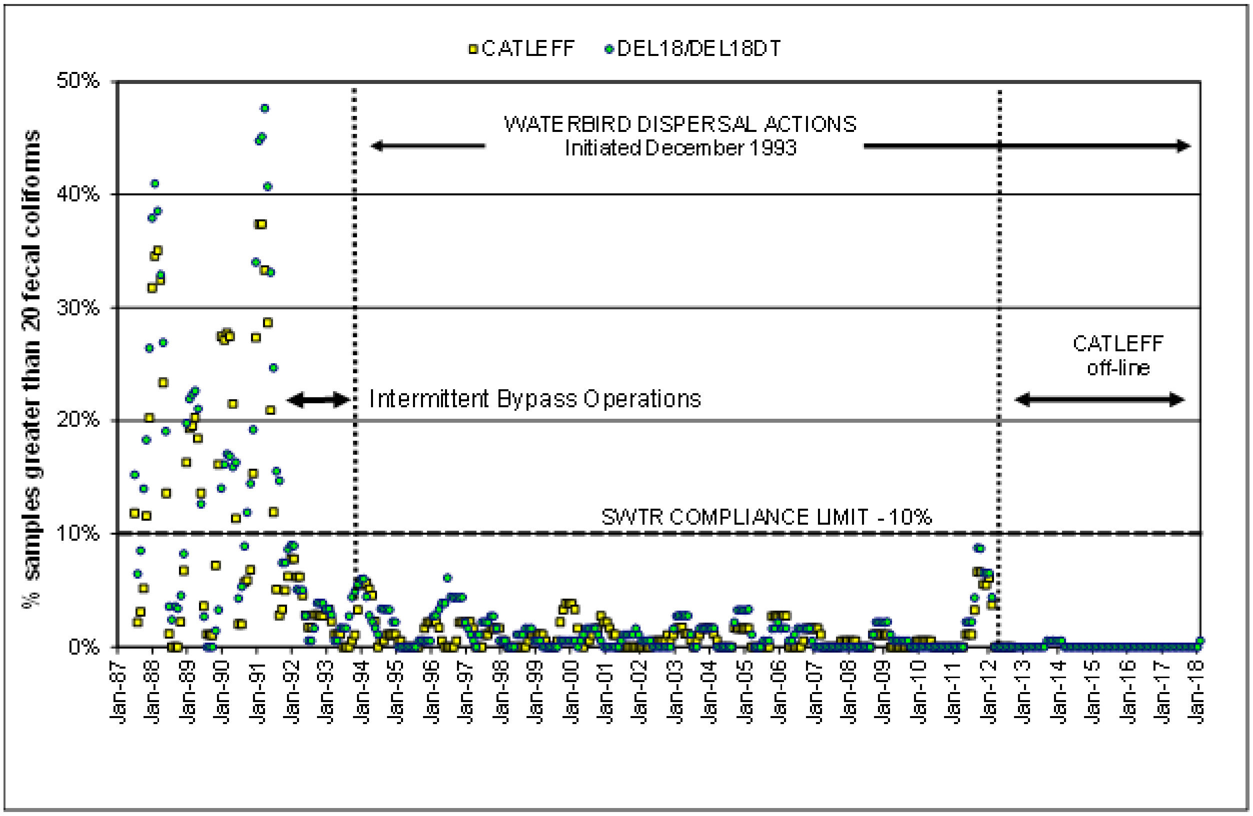


Figure 4.5 Percent of keypoint fecal coliform samples at Kensico Reservoir greater than 20 fecal coliforms $100mL^{-1}$ for the previous six-month period, 1987-2017.
The vertical dashed line indicates the year in which the WMP was implemented.

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. The most obvious bryozoan, due to its large, gelatinous, spherical shape, was identified as far back as the late 1980s as *Pectinatella magnifica. 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 Delaware outflow of the reservoir at DEL18. Moreover, it has been observed in numerous other reservoirs throughout the watershed. The presence of these organisms was inconsequential until the fall of 2012, shortly after the UV Disinfection Facility came on line. Bryozoan colonies were found downstream of DEL18 at the UV facility and caused clogging issues at the 1-inch perforated 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 for a drinking water supply.

Monitoring

DEP staff began monitoring bryozoan colonies in the sluiceways at DEL18 using an underwater video camera in 2014. The process of monitoring includes the lowering of an underwater video camera 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 gates. Notes on water quality parameters (temperature, turbidity, etc.) and operational conditions (flow rate) are also taken at the time of the visits. Video monitoring is predominantly focused on the access ladder and adjacent wall area in each sluiceway.

As in previous years, the 2017 monitoring began in late June to document conditions prior to colony growth. The first survey was on June 29 and continued approximately monthly until the last survey on September 19. A total of four surveys with video observations were completed in 2017, though not all sluiceways could be monitored on each visit due to maintenance activities. On August 24, maintenance and repair activities on the traveling screens for sluiceways 1, 2, and 5 prevented surveys from being conducted.

Results

Numerous still-frame shots documenting the temporal growth of colonies were collected from the videos, usually on specific ladder rungs. As has occurred in the previous three years, *Cristatella mucedo* appeared earlier in the season than *Pectinatella magnifica,* and it resided at lower depths since it tolerates cooler water than *P. magnifica*. *C. mucedo* colonies were numerous at the time of the June 29 survey, while *P. magnifica* did not appear until the July 14 survey. *C. mucedo* began to die and peel off the walls in mid-August; whereas *P. magnifica* survived until late September.

Sluice gate 5 was closed in the late summer of 2017. Prior to that, Kensico Reservoir was operated in float mode for almost a month. Similar to 2015, a severe reduction in the number of colonies found in sluiceway 5 was observed. It is apparent that these colonies cannot thrive without a minimum level of flow to deliver nutrients to maintain growth. This observation may help DEP manage this organism if the flow through the various gates can be altered during the course of the growing season to possibly limit growth.

The photo progression shown in Figure 4.6 illustrates how quickly the *P. magnifica* colonies normally develop during the later summer months and compares four years of photos on the nearby ladder rungs in sluiceway 3 for 2014 through 2017. The colonial growth rate appears to be very similar in 2014, 2015, and 2016 when compared at approximately the same three dates. In 2017, however, *P. magnifica* appears to have taken longer to colonize and grew at a slower rate in this sluiceway. This was likely due to the reduced flow in the sluiceway while in float mode for part of July and August with a short term gate closure in early August. Many large colonies (more than 60 colonies larger than 12 inches in diameter on the ladder and walls) were present by late September when divers were contracted to remove them and, as in the past, sluice gate 3 was the most populated. The largest of the *P. magnifica* colonies had grown to several feet wide. A report (DEP 2018) summarizing bryozoan monitoring results from 2014 - 2017 was finalized in 2017 and is available for review.

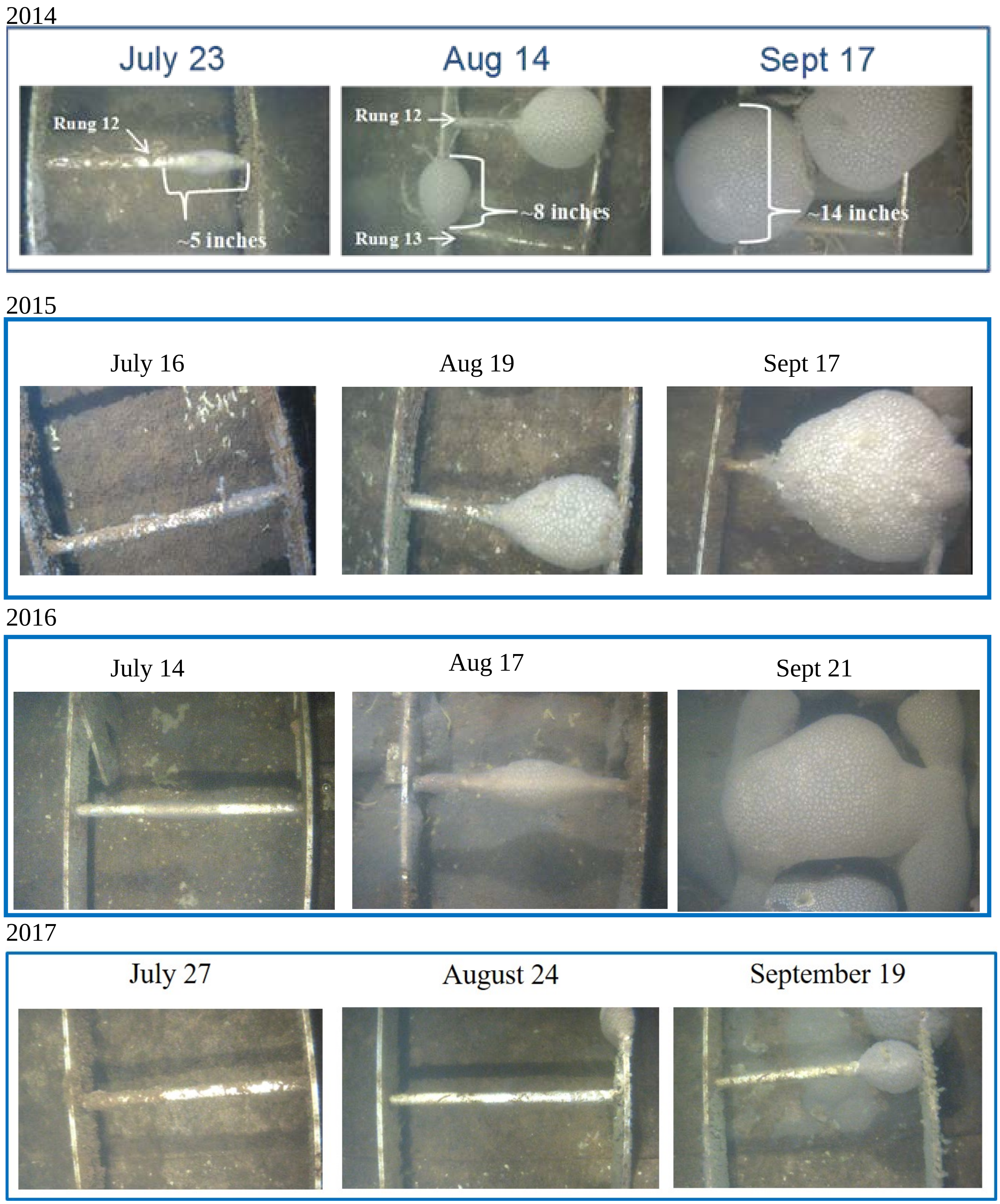


Figure 4.6 Photographs showing progression of *P. magnifica* colony growth for 2014 to 2017 on ladder rungs 12, 13, 15 and 11 (respectively) at DEL18 in Sluice Gate 3. For scale, each of the ladder rungs is about 12 inches across.

4.5.2 Special Investigations within the Watershed

There were three special investigations conducted during 2017 in the Kensico watershed. These special investigations involved stream storm sampling at Malcolm Brook and/or N5 tributaries and the boat launch construction monitoring. A brief summary of each investigation and the events follow in chronological order.

Storm Event Kensico Reservoir: May 5–May 6, 2017

During May 5 - May 6, 2017, a storm event occurred that resulted in approximately 2.3 inches of rain, triggering storm event monitoring at Kensico Reservoir. Analytes investigated were turbidity, fecal coliform, and conductivity, as well as Microbial Source Tracking (MST**).** Flow data from N5-1 and MB-1 show there was a sharp increase in flow on May 5 up to about 35 cfs at N5-1, remaining relatively high during the day of May 6 and then decreasing over the next few days. With MB-1, fecal coliform and turbidity results peaked along with flow with very elevated levels at the onset of the storm event (42,000 coliforms $100mL^{-1}$ and 75 NTU respectively). N5-1 turbidity and fecal coliform peaks were different than MB-1 in this respect, with turbidity at its peak near the beginning of the storm event (140 NTU), and peak fecal coliform coming later in the storm (32,000 coliforms $100mL^{-1}$). The reservoir effluent at DEL18DT had no turbidity issues as a result of these storms (maximum of 1.1 NTU), and fecal coliform results did not exceed 5 coliforms $100mL^{-1}$ during the 10 days after the storm**.**

Three of the N5-1 samples and two of the MB-1 samples were analyzed for *Bacteroides* to help identify the fecal source. The three N5-1 storm water samples were positive for the human marker at trace levels (below the level of quantification). The two MB-1 samples were negative for the human marker. Since trace levels were detected, testing for *Bacteriodes* will be performed for the next significant storm event.

Kensico Boat Ramp Construction Monitoring: Summer 2017

Under DEP contract CRO544G, the boat launch at DEL18 on Kensico Reservoir was replaced during the summer of 2017. The previous launch of approximately 600 square feet of paver stones was replaced with 12’ by 36’ pre-cast concrete interlocking pavers. The construction area was surrounded by three separate turbidity curtains that isolated the work zone from the reservoir. Prior to construction activities, the contractor installed a continuous monitoring buoy (KENBR1) with two turbidity sensors, between the inner and second curtains, where the water depth ranged from 9 to 11 feet. The two sensors were placed at depths of approximately 2 and 6 feet below the surface and took measurements every 15 minutes. The monitoring plan sent alarms when the turbidity at KENBR1 exceeded 1.5, 2.0 or 2.5 NTU. Data from the contractor’s buoy were found to be unreliable, so DEP deployed the following equipment in support of the project:

1. Buoy 2.1BRK with two turbidity sensors was moved to a location between the work zone and DEL18.

2. Buoy KENBR2 with two turbidity sensors was installed between the second and third turbidity curtains.
3. Buoy KENBR3 with two turbidity sensors was installed between the third turbidity curtain and DEL18.

In addition to the three turbidity curtains, the contractor developed a pumping plan that removed turbid water from the work zone, discharging it to an upland area outside of the Kensico watershed. DEP Water Quality staff programmed the turbidimeters and dataloggers, set up telemetry, and responded to maintenance requests throughout the construction project. In addition, DEP Water Quality staff was included on data logger notifications when turbidity readings exceeded alarm conditions, and coordinated with DEP Water Treatment Operations North staff to discuss operational changes that might be necessary as a result of the high turbidity results monitored by the equipment. Water quality criteria were not contravened at the DEL18 monitoring locations during the installation of the new boat launch.

Storm Event Kensico Reservoir: October 29–October 30, 2017

During October 29–October 30, 2017, a storm event occurred that resulted in approximately 4.1 inches of rain, triggering storm event monitoring at Kensico Reservoir. Analytes investigated were turbidity, fecal coliform, and conductivity as well as Microbial Source Tracking (MST**)**. Flow data from N5-1 and MB-1 show there was a very sharp increase in flow on October 29 up to about 28.2 cfs at N5-1, remaining relatively high during the day of October 29, descending quickly over the day, and then gradual tapering over the next few days. With MB-1, both fecal coliform and turbidity results peaked along with flow with very elevated levels during the beginning of the second day of the storm event (13,000 coliforms $100mL^{-1}$ and 27 NTU respectively). N5-1 turbidity and fecal coliform peaks were different than MB-1 in this respect, with turbidity at its peak near the beginning of the sampling event (31 NTU), and peak fecal coliform coming later (28,000 coliforms $100mL^{-1}$). The reservoir effluent at DEL18DT had no turbidity issues as a result of these storms (≤0.85NTU), and fecal coliform results did not exceed an estimated 10 coliforms $100mL^{-1}$ for 10 days after the storm.

Samples collected during the early rising limb and the early descending limb of the hydrograph were analyzed for MST using *Bacteroides* at both N5-1 and MB-1. Results from this storm event indicated the detection of low levels of the human marker at both sites. Samples collected upstream, including the storm drain, were also positive for the human marker at trace levels. Previous test results for samples collected during dry conditions were negative for the human marker; therefore, testing during storm events will need to be continued in order to narrow down the source. As a note, the sample collected at the reservoir outflow (DEL18DT) on October 30 was negative for the human marker.

5. Pathogen Monitoring and Research

5.1 Introduction

Cryptosporidium, *Giardia*, and human enteric viruses (HEV) are monitored throughout the 1,972-square-mile NYC watershed each year by DEP as part of compliance and surveillance monitoring. Samples collected for protozoan analysis were analyzed by Method 1623.1 with EasyStain. DEP collected and analyzed 567 protozoan samples in 2017, of which 502 samples will be discussed further in this chapter. The remaining 65 samples were collected as part of ongoing research for method studies. Samples collected from streams in the watershed made up the largest portion of the sampling effort (35.7%), with samples from Kensico, New Croton and Jerome Park Reservoirs composing the second largest component (34.1%). Samples collected at the Hillview downtake, upstate reservoir releases, and the wastewater treatment plants combined to make up the remaining 30.4% (Figure 5.1). In addition to protozoan sampling, DEP collected and analyzed 40 HEV samples in 2017. All virus samples were analyzed by DEP using a modified version of the Information Collection Rule (ICR) Manual Method (USEPA 1996).

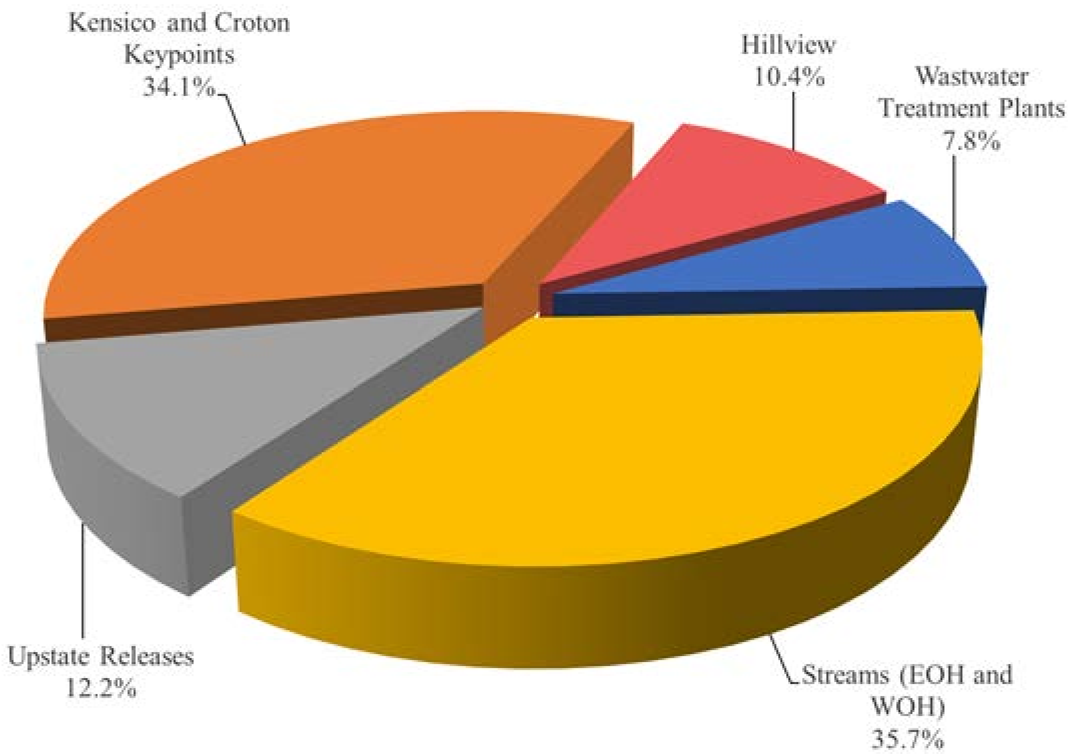


Figure 5.1 DEP protozoan sample collection type distribution for 2017.

As with most years, there are often notable changes or operational facts worth mentioning. Protozoan samples were collected weekly at the Jerome Park Reservoir outflow (1CR21) representing Croton source water until the Croton Aqueduct was shut down on February 27, 2017, and it remained offline through December 2017. In August 2017, DEP modified its laboratory processing of protozoan samples, replacing an acid dissociation step with a heat dissociation step. Heat dissociation had been in use for Hillview protozoan samples since March 2016 as a means to improve recovery. DEP began monitoring for protozoans at the Catskill Connection Chamber (CCC) along the Catskill Aqueduct just downstream of the CDUV in December 2017. Additionally, sample collection frequency for the outflow of New Croton Reservoir (CROGH) was changed from monthly to quarterly after October 2016. As a reminder, the Catskill Aqueduct south of Kensico Reservoir remained shut down throughout 2017. Kensico outflow results are posted weekly on DEP's website (www.nyc.gov/html/dep/pdf/pathogen/path.pdf), and reported annually in this report.

5.2 Source Water Results

Catskill Aqueduct Inflow

There were less detections of *Cryptosporidium* in 2017 compared to 2016 at the Catskill inflow to Kensico Reservoir (CATALUM), and oocysts were found at lower concentrations. One positive sample was detected out of 52 (1.9%) (Table 5.1), which was fewer than the 7 detections found in 2016. The mean annual *Cryptosporidium* concentration was 0.02 oocysts $50L^{-1}$ in 2017, compared to 0.17 oocysts $50L^{-1}$ in 2016.

The detection and concentration of *Giardia* at CATALUM in 2017 was slightly more than 2016. There were 21 samples positive for *Giardia* out of 52 (40.4%), compared to 17 positives (32.7%) in 2016. The mean *Giardia* concentration for 2017 was 1.02 cysts $50L^{-1}$, compared to 0.83 cysts in 2016.

Both the occurrence and concentration of HEVs were lower at CATALUM in 2017 compared to 2016. One HEV sample was positive out of the 12 samples taken (8.4%), which was fewer than 2016 when there were 3 positives (25.0%, n=12). Mean HEV concentration was about 0.29 MPN $100L^{-}1$ in 2017, slightly lower than the 2016 mean of 0.38 MPN $100L^{-1}$.

Table 5.1 Summary of *Cryptosporidium*, *Giardia*, and HEV compliance monitoring data at the five DEP keypoints for 2017.

	Keypoint Location	Number of Positive Samples	Mean[2]	Maximum
Cryptosporidium oocysts $50L^{-1}$	CATALUM (n=52)	1	0.02	1
	DEL17 (n= 52)	2	0.04	1
	DEL18DT (n=52)	3	0.06	1
	CROGH[1] (n= 4)	0	0.00	0
	1CR21 (n= 9)	2	0.33	2
Giardia cysts $50L^{-1}$	CATALUM (n=52)	21	1.02	6
	DEL17 (n=52)	25	1.00	8
	DEL18DT (n=52)	26	0.92	4
	CROGH[1] (n=4)	0	0.00	0
	1CR21 (n=9)	3	0.44	2
Human Enteric Virus $100L^{-1}$ (HEV)	CATALUM (n=12)	1	0.29	3.45
	DEL17 (n= 12)	3	0.61	4.90
	DEL18DT (n=12)	1	0.09	1.11
	CROGH[1] (n= 4)	0	0.00	0.00
	1CR21 (n= 0)	NS[3]	NS[3]	NS[3]

[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 re-calculated to 50L for determination of means. Zero values are substituted for non-detect values when calculating means.
[3]NS = not sampled.

Delaware Aqueduct Inflow and Outflow

There were fewer *Cryptosporidium* detections at Kensico Reservoir’s Delaware inflow (DEL17) in 2017 (two in 52 samples, 3.8%) than in 2016 (six in 52 samples, 11.5%). The mean annual concentration of 0.04 oocysts $50L^{-1}$ was also lower than 2016 (0.17 oocysts $50L^{-1}$) (Figure 5.2). *Cryptosporidium* detections at the Delaware outflow from Kensico Reservoir (DEL18DT) were similar in 2017 (three in 52 samples, 5.8%) compared to 2016 (four in 52 samples, 8.2%). The mean annual concentration for DEL18DT in 2017 (0.06 oocysts $50L^{-1}$) was similar to 2016 (0.10 oocysts $50L^{-1}$).

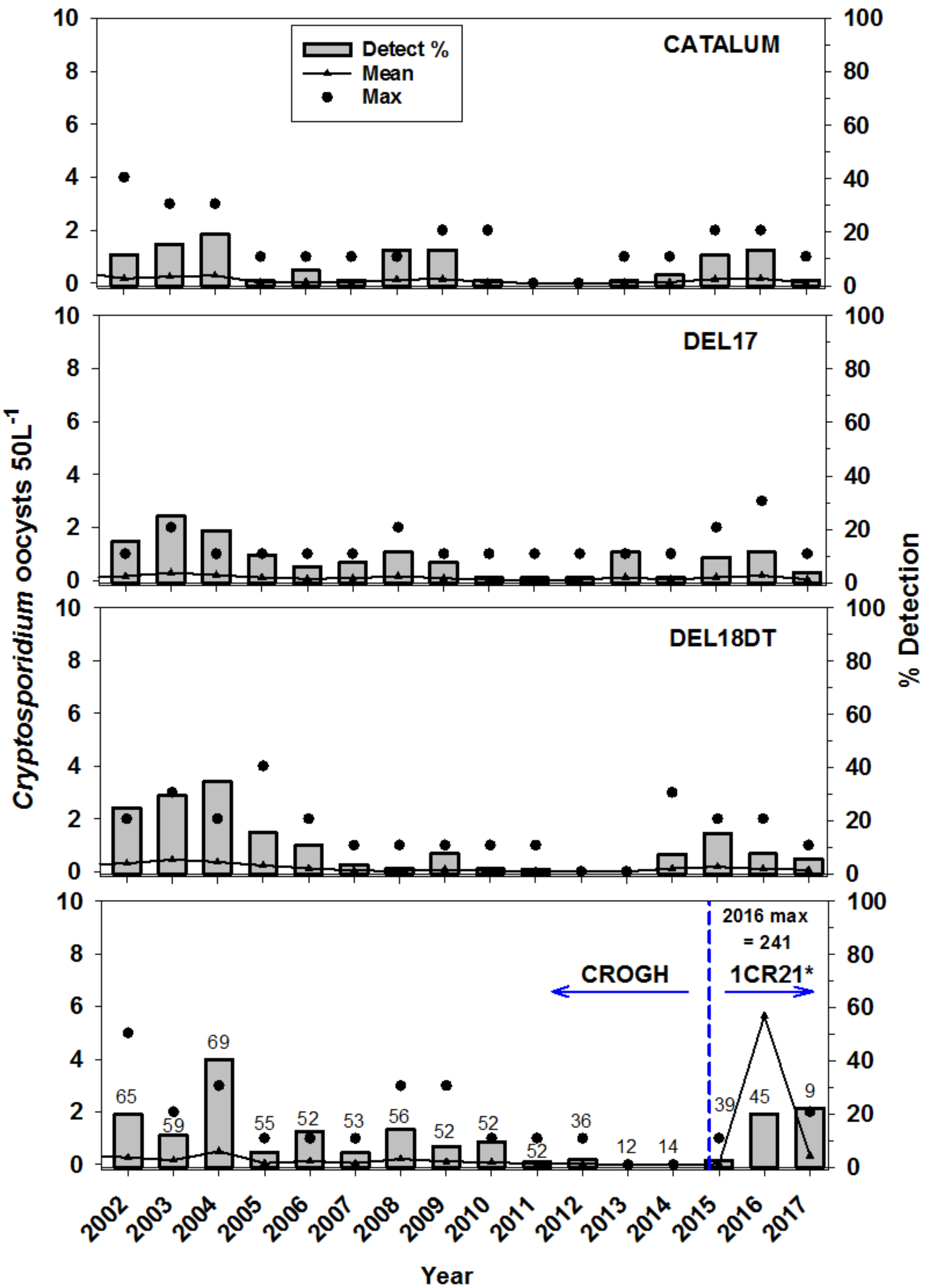


Figure 5.2 *Cryptosporidium* annual percent detection, and mean and maximum concentrations for the keypoint sites during each year from 2002 through 2017. Numbers above each bar on the Croton System plot indicate sample size. *1CR21 (the outflow of Jerome Park Reservoir) became the Croton System source water site in May 2015.

The number of *Giardia* detections at DEL17 in 2017 was slightly higher than in 2016, (25 versus 20 out of 52 samples). Mean *Giardia* concentrations were similar in 2016 and 2017 (1.08 and 1.00 cysts $50L^{-1}$, respectively). Consistent with the Delaware inflow to the reservoir, there were more detections at the outflow (DEL18DT) this year when compared to 2016 (26 versus 20 out of 52 samples). In addition, this site had a slightly higher mean *Giardia* concentration in 2017 (0.92 cysts $50L^{-1}$) compared to 2016 (0.73 cysts $50L^{-1}$) (Figure 5.3).

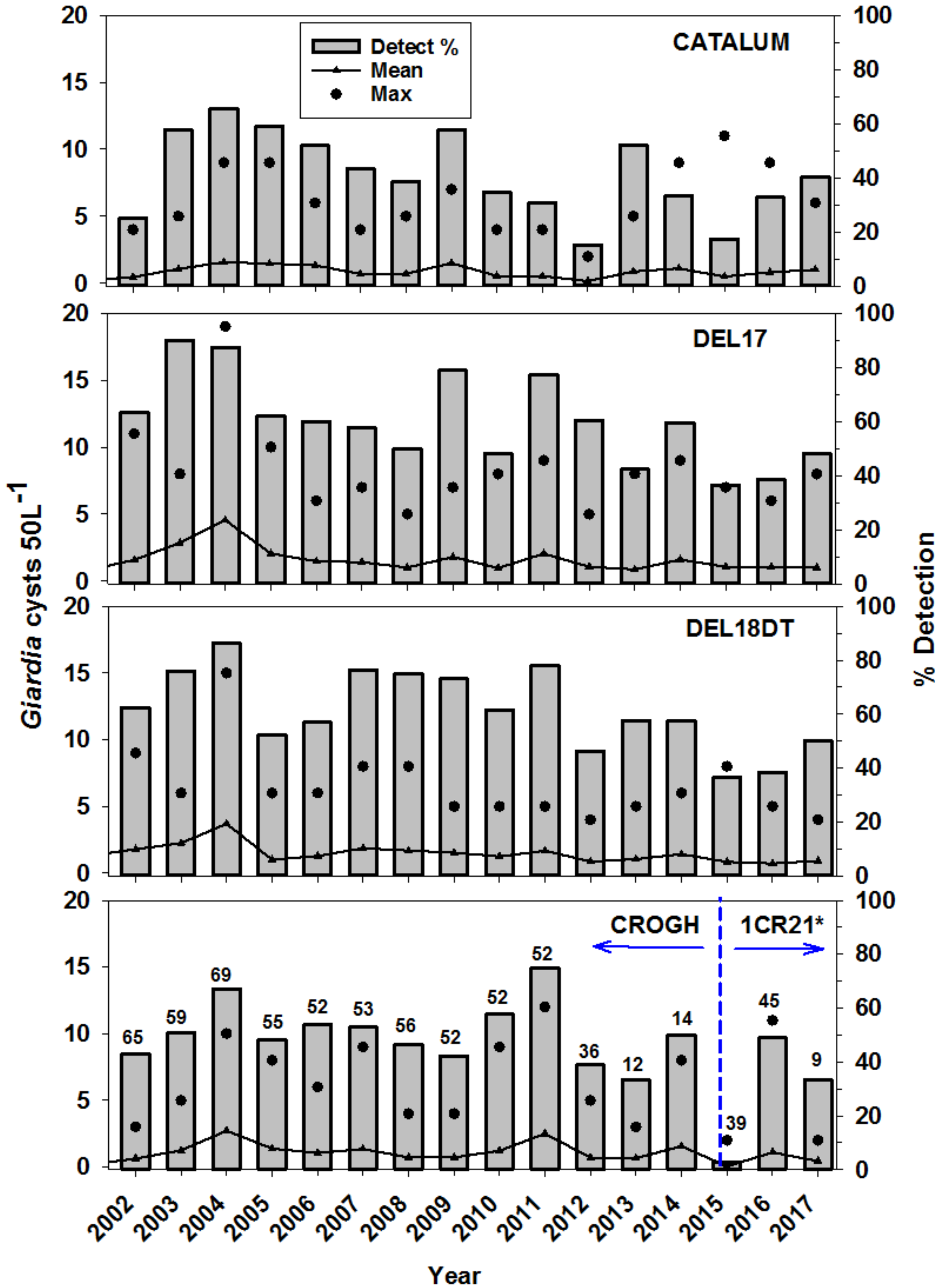


Figure 5.3 *Giardia* annual percent detection, mean concentration, and maximum result for the keypoint sites during each year from 2002 to 2017. Numbers above each bar on the Croton System plot indicate sample size. *1CR21 (the outflow of Jerome Park Reservoir) became the Croton System source water site in May 2015.

Viruses were detected in three out of 12 samples (25.0%) at DEL17, one more than in 2016 when two out of 12 samples (16.7%) were positive for HEV. The mean HEV concentration for DEL17 in 2017 was 0.61 MPN $100L^{-1}$, very similar to 2016 (0.60 MPN $100L^{-1}$). DEL18DT resulted in the same HEV detection rate in 2017 compared to 2016 (one out of 12 samples, 8.3%). The annual mean concentration for HEV at DEL18DT was quite low in 2017 (0.09 MPN $100L^{-1}$) as it was in the previous year (0.18 MPN $100L^{-1}$).

Croton System

In 2017, the Croton system was shut down on February 27 and was not put back into operation for the remainder of the year. Protozoan samples were collected weekly at the outflow of Jerome Park Reservoir (1CR21) during January and February for a total of nine samples. This site is the source water for the Croton System since filtration began in May 2015. One sample was collected at 1CR21 on March 6, shortly after the Croton system was shutdown. While this sample was analyzed, it was not representative of Croton source water and is not included in the analysis below. Protozoan and HEV samples were collected quarterly throughout the year at the outflow site of New Croton Reservoir. As a note, HEV sampling is not required at the 1CR21 location.

Jerome Park Reservoir

Of the nine samples collected at 1CR21 in 2017, two were positive (22.2%) for *Cryptosporidium*, similar to the 20.0% *Cryptosporidium* detection rate (nine out of 45 samples) found in 2016. Mean annual concentration was 0.33 oocysts $50L^{-1}$ for 2017, lower than the mean for 2016 (5.64 oocysts $50L^{-1}$).

Giardia was detected in three out of the 9 (33.3%) samples collected at 1CR21 in 2017, a lower detection rate than in 2016 (48.9%, 22 out of 45 samples). Although a much smaller sample size, the mean concentration for *Giardia* in 2017 was 0.44 cysts $50L^{-1}$, lower than the mean from 2016 (1.11 cyst $50L^{-1}$). When comparing multiple years of *Giardia* and *Cryptosporidium* results for this site, one must consider that the sampling effort has not been equivalent between years, and there has not yet been a full year of weekly samples. This is especially true for 2017, with only two months of winter samples.

New Croton Reservoir

Results for the four quarterly protozoan samples at the New Croton Reservoir outflow (CROGH or the alternate site CRO1B) were all negative for *Cryptosporidium* and *Giardia*.

HEV were not detected in any of the four quarterly samples in 2017 at CROGH (or the alternate site CRO1B). Results in 2016 were higher with three detections out of ten samples (30.0%) and a mean annual concentration of 0.33 MPN $100L^{-1}$.

In general, *Giardia* continues to be detected more frequently and at higher concentrations during winter and spring months compared to summer and fall (Figure 5.4), as has been noted in previous reports. It is important to note that the increase in *Cryptosporidium* and decrease in *Giardia* which began in 2015, and continued in 2016 at some sites, may be a result of the analytical change to Method 1623.1 with EasyStain, and not an actual increase or decrease of these organisms in the environment. Additional years of data collection will help to assess the possibility of an overall shift in the data.

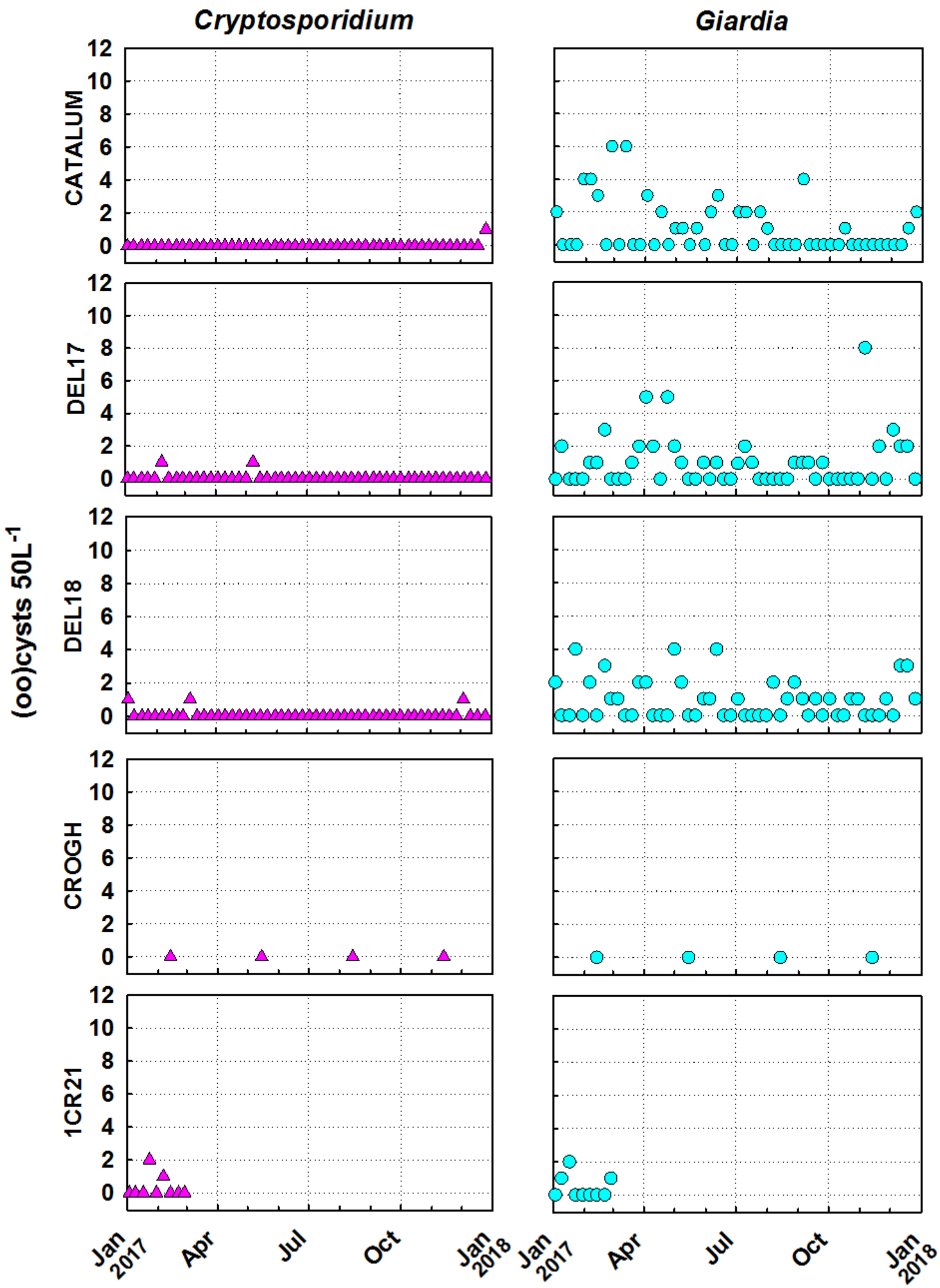


Figure 5.4 Weekly routine source water keypoint protozoan monitoring results for 2017.

5.2.1 2017 Source Water Compared to Historical Data

Water quality at the different source water sites can vary due to the many influences in the 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. A few changes have occurred since 2001, such as the change in frequency of monitoring at the New Croton Reservoir outflow from weekly 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) and lastly, the laboratory's switch to heat dissociation in August 2017. Each modification has added a layer of complexity when comparing the current year's data to the historical dataset.

Cryptosporidium

Kensico Reservoir

In 2017, there were three samples positive out of 104 pooled samples (2.9%) for *Cryptosporidium* at the two Kensico Reservoir inflows (CATALUM and DEL17) (Table 5.2) compared to three positives at the outflow (n=52, 5.8%) (Table 5.3). There were fewer detects of oocysts at the Kensico inflows in 2017 than in 2016 (13 out of 104, 12.5%) but well within the historical range from 0.0% to 20.5%. One positive sample was detected out of 52 (1.9%) at CATALUM, which was fewer than the seven detections found in 2016, and six detections found in 2015. There were fewer *Cryptosporidium* detections at Kensico Reservoir's Delaware inflow (DEL17) in 2017 (two in 52 samples, 3.8%) than in 2016 (six in 52 samples, 11.5%) and 2015 (five in 52 samples, 9.6%). *Cryptosporidium* detections at the Delaware outflow from Kensico Reservoir (DEL18DT) were similar in 2017 (three in 52 samples, 5.8%) compared to 2016 (four in 52 samples, 8.2%), but lower than the number of detects found in 2015 (eight in 52 samples, 15.4%).

The mean *Cryptosporidium* concentrations for both the Kensico inflow and outflow sites were at or below 0.06 oocysts $50L^{-1}$ in 2017. The mean concentration at CATALUM was 0.02 oocysts $50L^{-1}$ in 2017, compared to 0.17 oocysts $50L^{-1}$ in 2016 and 0.15 oocysts $50L^{-1}$ in 2015. The mean annual concentration at DEL17 was 0.04 oocysts $50L^{-1}$, also lower than 2016 and 2015 (0.17 and 0.12 oocysts $50L^{-1}$, respectively) (Table 5.2). *Cryptosporidium* concentration at DEL18DT were similar in 2017 (0.06 oocysts $50L^{-1}$) to the mean in 2016 (0.10 oocysts $50L^{-1}$) and the mean for the previous 10 years (2007 – 2016 mean = 0.05 oocysts $50L^{-1}$, n=534). The decrease in 2017 was somewhat unexpected as it was anticipated that we might continue to see elevated oocyst detection/concentration at some sites after the method change implemented in 2015.

Table 5.2 Annual sample detection and mean oocyst concentration of *Cryptosporidium* at inflow keypoints to Kensico Reservoir 2002-2017.

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

Table 5.3 Annual sample detection and mean concentration of *Cryptosporidium* at Kensico and New Croton Reservoir source water outflows 2002-2017.

Site	DEL18DT			CROGH / 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

[1]Monitoring at CROGH was modified from weekly to monthly in August 2012.

[2]The source water sampling site for the Croton System changed from CROGH to 1CR21 on May 4, 2015.

Croton System Reservoirs

There were two samples positive for *Cryptosporidium* at the 1CR21 source water site in 2017 (out of 9 samples), with a maximum concentration of 2 oocysts $50L^{-1}$. With only nine samples taken only during the months of January and February, the two positives raised the mean concentration for 2017 to 0.33 oocysts $50L^{-1}$ (Table 5.3). Interestingly, there were no *Cryptosporidium* detections at the New Croton Reservoir outflow (CROGH) in 2017. *Cryptosporidium* detections have been rare at this site in the last few years with only one *Cryptosporidium* oocyst found (February 2015) at CROGH in the past five years (2013-2017, n=54). This is the fourth year out of the last five with no *Cryptosporidium* detections at this site, and only three detections in the last seven years (n=142) with a maximum result of 1 oocyst $50L^{-1}$.

Giardia

Kensico Reservoir

Giardia detection rates at the Kensico Reservoir keypoint sites were higher in 2017 compared to 2015 and 2016. CATALUM had a higher detection rate in 2017 (40.4%) than in 2015 or 2016 (17.3% and 32.7%, respectively), but quite close to the historical detection rate of 40.1% (2001-2016, n=798). DEL17 had a higher *Giardia* detection rate in 2017 (48.1%) than in either 2015 or 2016 (36.5% and 38.5%, respectively), but well below the historical detection rate of 61.0% (2001-2016, n=810). At the outflow of Kensico Reservoir, there was one more *Giardia* detection at DEL18DT in 2017 than at DEL17, similar to the three prior years (2014-2016) when the two sites had the same number of detections. The Kensico Reservoir outflow (DEL18DT) had a lower detection rate (50.0%) and lower annual mean concentration (0.92 cysts $50L^{-1}$), when compared to historical statistics from 2001 through 2016 (1.57 cysts $50L^{-1}$ and 62.6%, respectively, n=924).

Mean *Giardia* concentrations for 2017 at the two inflows to Kensico Reservoir (CATALUM – 1.02 cysts $50L^{-1}$ and DEL17 – 1.00 cysts $50L^{-1}$) were also close to or below the historical means for these sites (2001-2015; 0.89 and 1.72 cysts $50L^{-1}$, respectively). DEL18DT had a slightly higher mean *Giardia* concentration in 2017 (0.92 cysts $50L^{-1}$) compared to 2016 (0.73 cysts $50L^{-1}$), however, that was the lowest observed since 2001 and historical results up to 2016 were higher on average (2001-2015; mean = 1.62 cysts $50L^{-1}$; n=872). DEP switched in April 2015 from Method 1623HV to Method 1623.1 with EasyStain with the goal of improving *Cryptosporidium* recovery. The new stain is, however, known to be more specific for human-infective species of *Giardia*, therefore some decrease in *Giardia* results was anticipated going forward. Mean *Giardia* concentrations in 2017 could also have been affected by the change in the method from acid to heat dissociation, as the purpose of the change was to improve *Giardia* recovery. Additional years of sampling will be necessary to help determine the overall effect of the method changes versus any change in the abundance of *Giardia* in the environment.

Croton System Reservoirs

Giardia detections and concentrations at the New Croton Reservoir outflow (CROGH) have been low in the last three years, with four detections in 28 samples (14.3%) and mean annual concentrations at or under 0.25 cysts $50L^{-1}$. CROGH and the Croton source water site at Jerome Park (1CR21) both had annual means (0.00 and 0.44 cysts $50L^{-1}$, respectively) lower than the historical means for data from 2001 through 2016 (1.57 and 0.62 cysts $50L^{-1}$, respectively).

Seasonality

Seasonal variation in 2017 *Giardia* results can be observed in the locally weighted regression (LOWESS) smoothed line for CATALUM (Figure 5.5), however, this seasonality is more difficult to see for the Delaware keypoints in 2017. A LOWESS line cannot be estimated for 2017 Croton source water as the site was offline after February. Additionally, LOWESS has not performed well for the Croton source water sites in the last few years as sample frequency changed from weekly to monthly in 2012 and back to weekly in 2015. The LOWESS uses uniformly specified proportions of the dataset to determine regressions with no mechanism to adapt the proportions to changes in sample frequency.

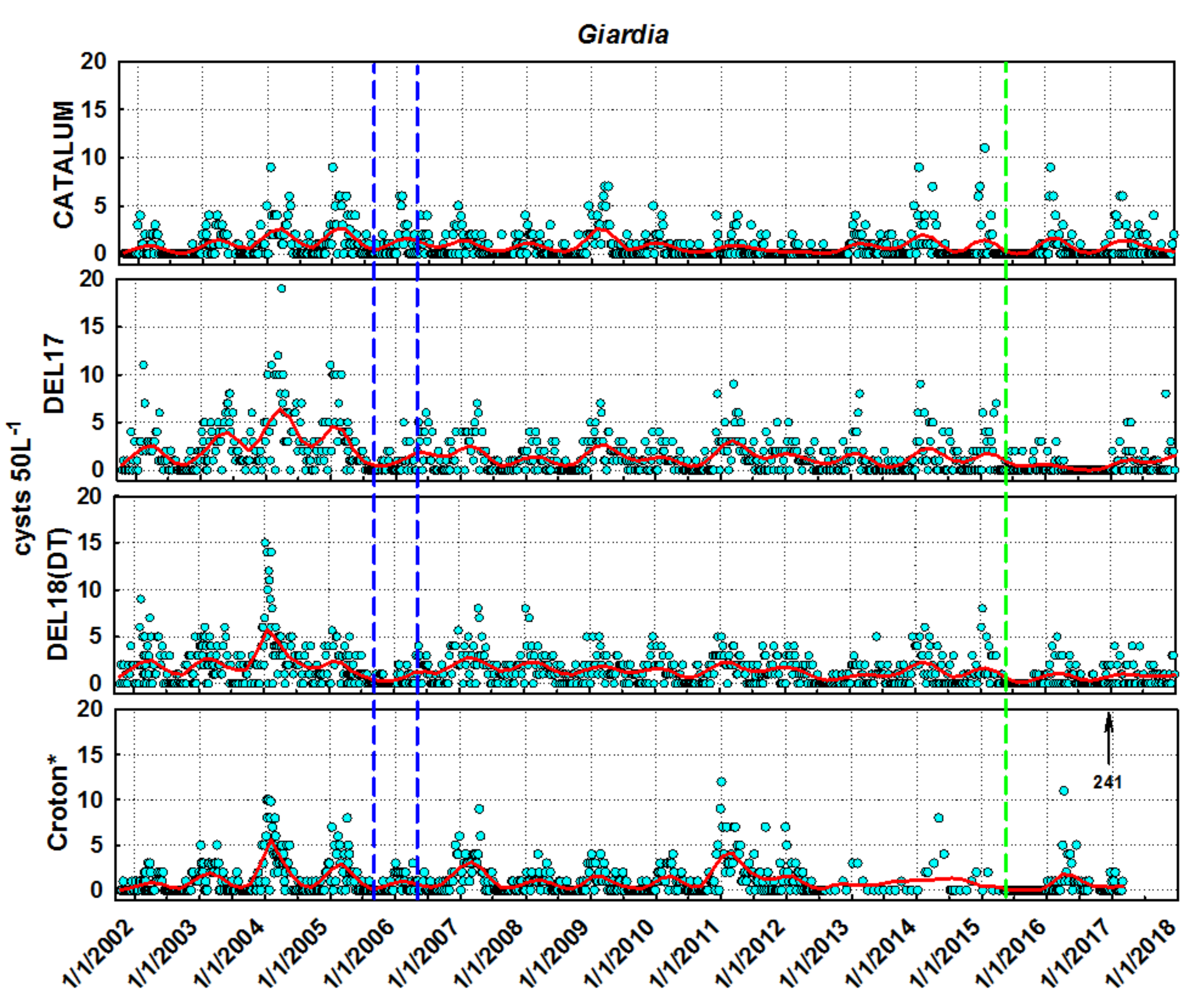


Figure 5.5 Weekly routine source water keypoint results for *Giardia* (circles), and LOWESS 5% smoothed regression (red curved line) from October 15, 2001 to December 31, 2017. The area between the blue dashed lines indicates the period during which DEP temporarily switched to EasyStain. The green dashed line indicates the change from Method 1623HV to Method 1623.1 with EasyStain. *The Croton System's source water sampling location changed from CROGH to 1CR21 on May 4, 2015.

5.2.2 2017 Source Water Compared to Regulatory Levels

The Long Term 2 Enhanced Surface Water Treatment Rule (LT2) (USEPA 2006) requires utilities to conduct monthly source water monitoring for *Cryptosporidium* and report data from two 2-year periods, though a more frequent sampling schedule is permitted. The LT2 requires all unfiltered public water supplies to "provide at least 2-log (i.e., 99%) inactivation of *Cryptosporidium*." If the average source water concentration exceeds 0.01 oocysts L^{-1} based on the LT2 monitoring, "the unfiltered system must provide at least 3-log (i.e., 99.9%) inactivation of *Cryptosporidium*.” For filtered supplies, the average needs to be below 0.075 oocysts L^{-1} to remain in Bin 1, which is the category that defines needing no additional treatment. The average source water *Cryptosporidium* concentration is calculated by taking a mean of the monthly *Cryptosporidium* mean concentrations at the source water outflows over the course of two, 2-year periods. A portion of the year 2017 falls within the reporting period of the second round of the LT2 (April 2015 – March 2017). However, since this report covers through 2017, results have been calculated here using data from the two most recent complete calendar years (January 1, 2016-December 31, 2017) using all analyzed routine and non-routine samples (Table 5.4).

Table 5.4 Number and type of samples used to calculate the LT2 values from January 1, 2016 to December 31, 2017.

Site	Number of routine samples 2016-2017	Number of non-routine samples 2016-2017	Total n
New Croton (CRO1T,1B)	5	0	5
New Croton (1CR21)	53	1	54
Delaware (DEL18DT)	104	0	104

Unfiltered Supply

The Catskill/ Delaware System is NYC’s unfiltered water supply. The 2016 to 2017 mean of monthly means for *Cryptosporidium* is 0.0016 oocysts L^{-1} for the Delaware outflow, well below the LT2 threshold level of 0.01 oocysts L^{-1} for unfiltered systems (Figure 5.6). These results are consistent with NYC source water historical LT2 calculations which have always remained below the threshold levels. With the exception of the two prior years’ calculated values for the Delaware outflow, the monthly means have generally been declining since 2009. As DEP has switched to a new method for protozoan analysis, which was predicted to possibly recover more *Cryptosporidium* from samples, at least some of the increase in those years may be attributed to the new method.

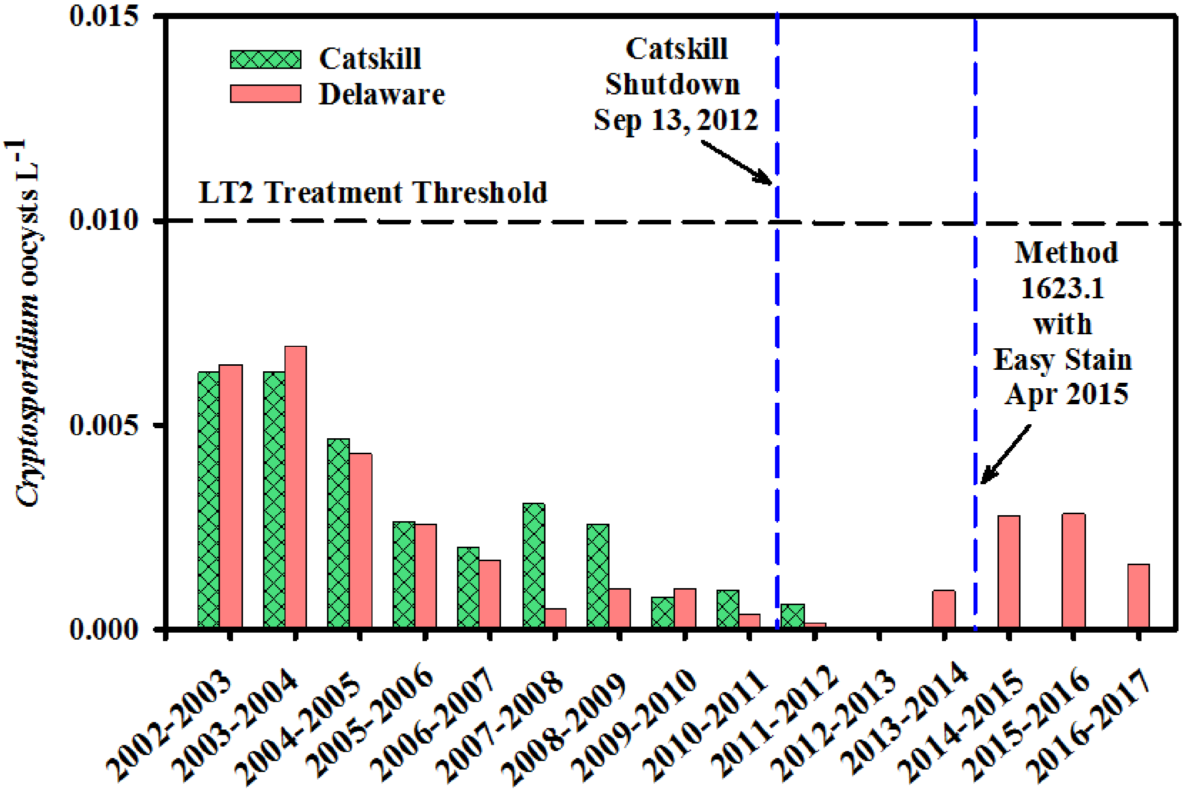


Figure 5.6 *Cryptosporidium* means using LT2 calculation method since initiation of Method 1623HV (1623.1 with EasyStain since April 2015) at the Delaware Aqueduct 2002-2017 and the Catskill Aqueduct 2002-2012.

Filtered Supply

The Croton System is the source of NYC's filtered water supply. The source water site since filtration began in May 2015 is 1CR21, prior to which the sampled source water site was the outflow of New Croton Reservoir (CROGH). As the Croton Aqueduct was offline for several weeks in 2016, and ten months in 2017, DEP received approval from the Department of Health to incorporate samples (n=5) from the New Croton Reservoir outflow as supplemental for periods when routine monitoring was not being conducted at the 1CR21 site. For the two year period from January 1, 2016 to December 31, 2017, there were 54 representative samples taken at the Jerome Park source water site over 13 months of sampling. The samples incorporated from the New Croton Reservoir outflow include two monthly samples from CRO1T taken in September and October 2016 when the Croton System was offline, and three quarterly samples (May, August and November) taken at CRO1B from 2017 taken while the system was offline. With the addition of the five samples from the New Croton Reservoir outflow, there were 59 sample results from 17 months of sampling. The mean of these 17 monthly means was 0.0612 oocysts L^{-1}, which is below the filtered system bin threshold value of 0.075 oocysts L^{-1} (Figure

5.7). There were no positive *Cryptosporidium* samples at the New Croton Reservoir outflow in 2016 or 2017.

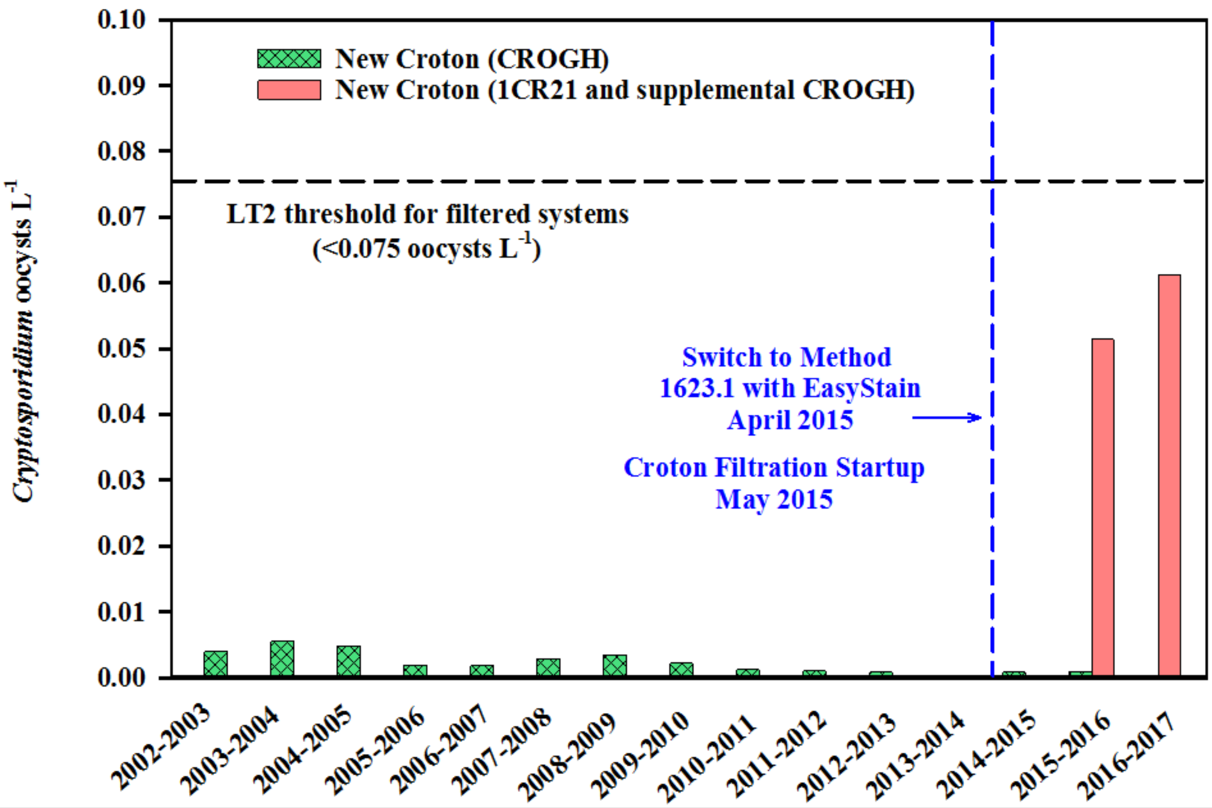


Figure 5.7 *Cryptosporidium* means using LT2 calculation method since initiation of Method 1623HV (1623.1 with EasyStain since April 2015) at the Croton System source water sites 2002-2017.

5.3 Upstate Reservoir Outflows

The Catskill and Delaware Aqueducts bring 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. The outflow of each reservoir is sampled monthly for protozoans to ensure high quality water prior to entering downstream reservoirs. In addition, the water leaving Ashokan Reservoir is monitored weekly for protozoans just upstream of Kensico Reservoir at the Pleasantville Alum Plant (CATALUM). Monthly reservoir sampling is not required when water from that basin is not being delivered to a downstream reservoir for eventual consumption. For this reason, two of the WOH reservoirs (Neversink and Cannonsville) do not have samples for all 12 months of 2017.

In 2017 there were 109 samples collected at WOH reservoir outflows, seven samples (6.4%) were positive for *Cryptosporidium* (Table 5.5). This is lower than 2015 or 2016 (13.5% and 9.3%, respectively). Pepacton had the highest oocyst detection rate (25.0%, 3 out of 12 samples) of the WOH reservoir outflow sites in 2017 and this was the highest detection rate on record for this site. Accordingly, Pepacton also had the highest mean annual concentration of the WOH reservoir outflows and the highest annual mean recorded for this site, 0.25 oocysts $50L^{-1}$, but with no more than one oocyst found in each sample. Detections at this site have been consistently low (previously, no more than two detections per year) and the historic mean (2002-2016) for Pepacton's outflow is 0.06 oocyst $50L^{-1}$. Neversink and Rondout outflows had no *Cryptosporidium* detections in 2017, and in the last 10 years these two sites have had only 10 detections combined (seven and three detections, respectively), each with only one oocyst in a sample. Schoharie and Cannonsville Reservoir outflows had one and two *Cryptosporidium* detections (respectively) in 2017, with annual mean concentrations remaining at the lower end of the historical range of annual means for these site (0.00 to 0.61 oocysts $50L^{-1}$, respectively).

Table 5.5 Summary of 2017 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	12	0.08	8.3%	1 (50.2L)	0.02	12.53	66.7%	31 (50.0L)	0.62
Ashokan (CATALUM)	52	0.02	1.9%	1 (50.0L)	0.02	1.02	40.4%	6 (50.0L)	0.12
Cannonsville	11	0.17	18.2%	1 (50.1L)	0.02	4.67	45.5%	40 (50.1L)	0.80
Pepacton	12	0.25	25.0%	1 (50.3L)	0.02	0.74	33.3%	4 (50.9L)	0.08
Neversink	10	0.00	0.00%	0	0.00	0.20	20.0%	1 (50.0L)	0.02
Rondout	12	0.00	0.00%	0	0.00	0.89	58.3%	2 (50.1L)	0.04

[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.

In 2017, there were 47 *Giardia* detections (43.1%) out of the 109 samples collected at the WOH reservoir outflow sites. This is higher than 2015 (28 positive out of 104 samples, 27.0%) and 2016 (33 positive out of 108 samples, 30.6%). Schoharie and Rondout Reservoir had the highest detection rate for *Giardia* (66.7% and 58.3% respectively). Schoharie also had the highest mean annual *Giardia* concentration in 2017 (12.53 cysts $50L^{-1}$) as well as in 2016 (3.17 cysts $50L^{-1}$). The 2017 annual mean is slightly higher than the historical mean of 10.14 cysts $50L^{-1}$ (2002-2016) for Schoharie. Cannonsville had a mean annual concentration of 4.67 cysts

50L^{-1} in 2017, higher than the 2016 annual mean (1.50 cysts 50L^{-1}) but quite similar to the historical mean of 4.33 cysts 50L^{-1} (2002-2016). *Giardia* concentrations were low in samples from Ashokan, Pepacton, Neversink, and Rondout, with no samples greater than 6 cysts 50L^{-1}, and annual means at or below 1.02 cysts 50L^{-1}.

In East of Hudson (EOH), as part of a two-week pre-activation startup sampling program (which outlines sampling required before pumping Croton Falls Reservoir water into the Delaware Aqueduct), four weekly protozoan samples were collected at the Croton Falls Pump Station (CROFALLSVC) from March 20 to April 10. While all four samples were negative for *Cryptosporidium*, three of the samples were positive for *Giardia* with a maximum count of 4 cysts 50L^{-1} and a mean concentration of 2.00 cysts 50L^{-1}. The Croton Falls Pump Station was not operated for the water supply in 2017.

5.4 Watershed Streams and WWTPs

Routine monitoring of protozoans was conducted at 16 stream sites in the WOH and EOH watersheds in 2017. A total of 179 stream samples were collected and analyzed, 72 from the WOH watershed and 107 from the Kensico Reservoir (EOH) watershed. Eight stream sites in the WOH watershed were selected as part of an objective aimed at determining upstream sources of protozoans – four were sampled monthly and four were sampled bi-monthly. Monthly sampling EOH continued at the eight perennial tributaries to Kensico Reservoir. Additionally, 11 samples were taken at the Kensico streams as part of special investigations after elevated *Cryptosporidium* concentrations were detected in the routine samples.

In 2017, 39 samples were collected at WWTPs, with three samples positive for protozoans. A discussion of WOH and EOH WWTPs results will follow the stream results discussion for each watershed.

West of Hudson Streams

As in 2016, four of the eight WOH stream sites (PROXG, PROXG-1, PROXG-2, and S7i) were sampled monthly and the remaining four (CDG1, S4, S5i, and CBS (formerly WDBN)) were sampled bimonthly in 2017 (Figure 5.8). Two of these sites (upstream of PROXG) were added in May 2016 (Figure 5.9). The DEP target volume when sampling for protozoans is 50 liters; however, the method allows for a minimum of 10 liters for an acceptable sample. Of the 72 samples filtered at WOH streams, 59 were between 47 and 55 liters. The remaining 13 samples had volumes less than 47L due to the occasional clogging of filters during sampling. Of these 13 samples, 11 were from either PROXG or PROXG-2, with the lowest sample volume at 25.5 liters. In order to normalize the data, 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 5.6).

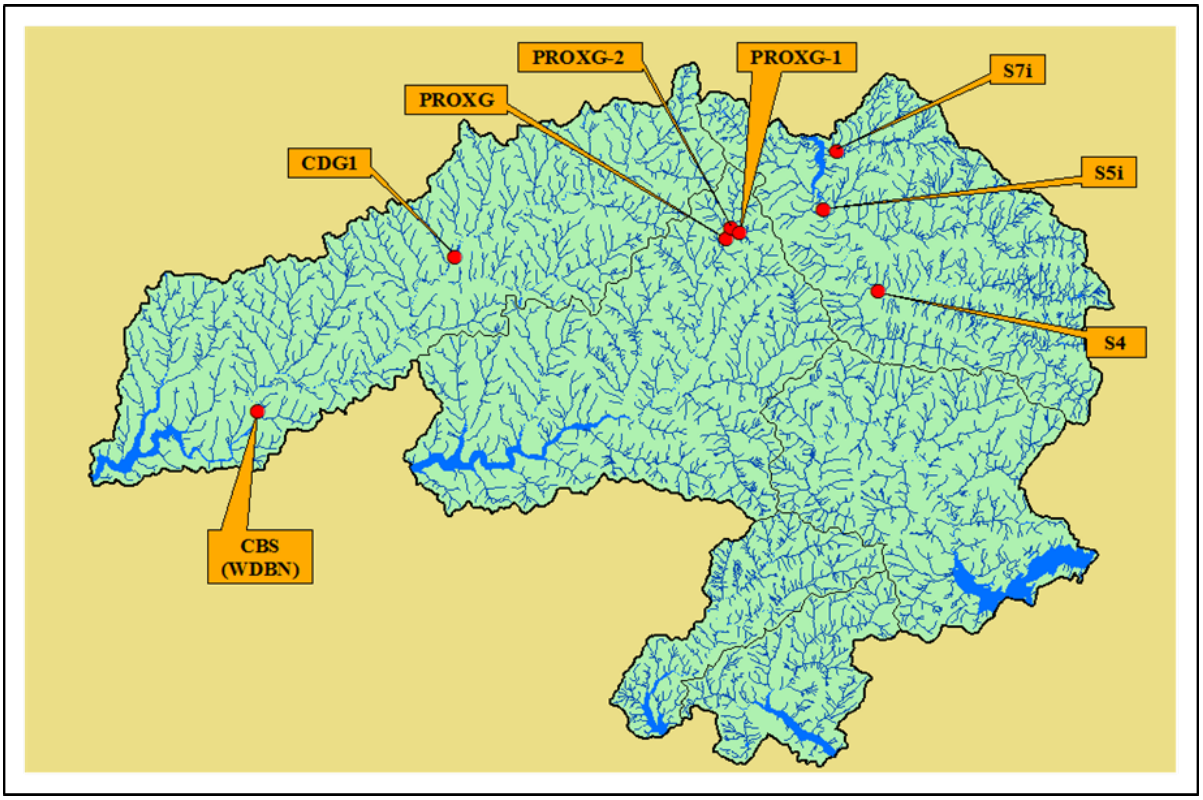


Figure 5.8 WOH stream sites monitored for protozoans in 2017.

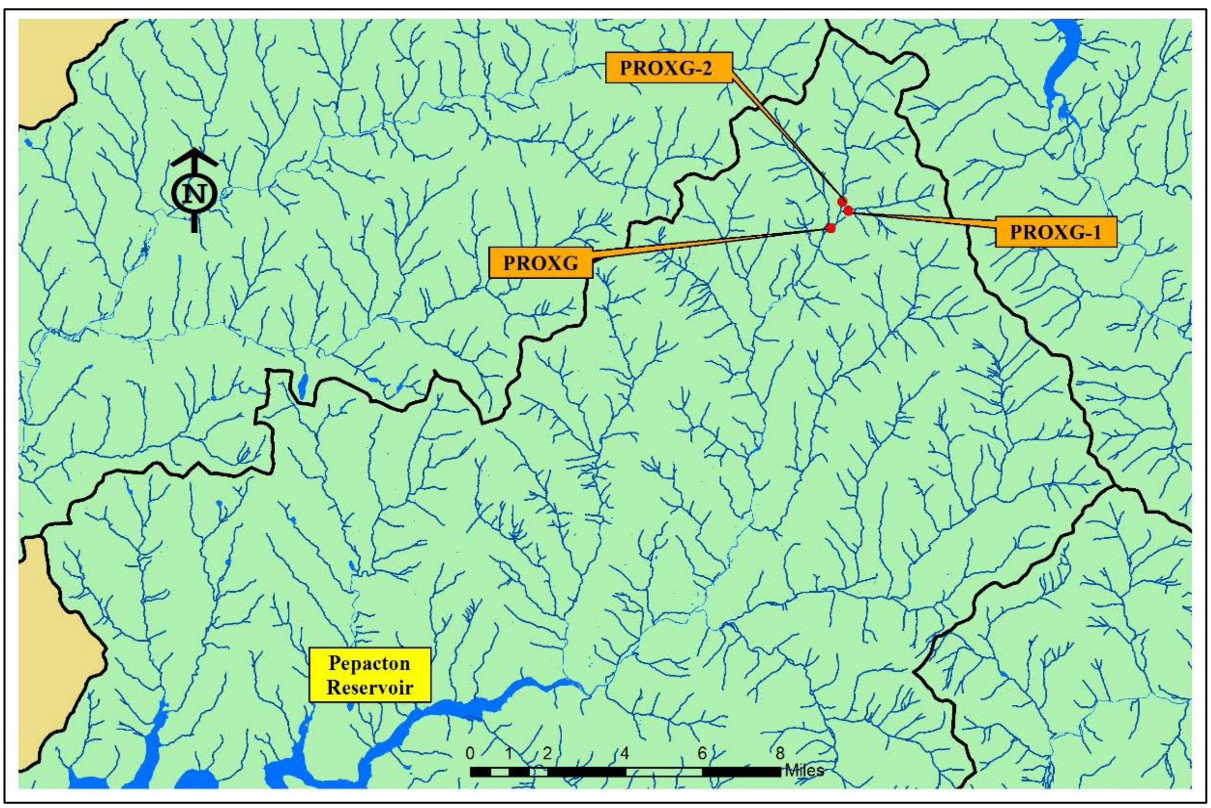


Figure 5.9 New stream sites monitored upstream of PROXG for protozoans in 2017.

Cryptosporidium oocysts were detected in 25 of the 72 WOH stream samples (34.7%) in 2017, lower than in 2016 (46.4%). The percent detection of oocysts ranged from 8.3 - 50.0% at the different stream sites (Table 5.6). All WOH stream sites had mean annual *Cryptosporidium* concentrations less than 2.50 oocysts $50L^{-1}$, and five of the eight sites had means less than one oocyst. CBS had the maximum concentration in an individual sample (12 oocysts $50.8L^{-1}$) in December 2017, and the highest annual mean concentration (2.47 oocysts $50L^{-1}$.)

Table 5.6 Summary of WOH stream protozoan results for 2017.

		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})**
CDG1	6	1.50	50.0%	6 (50.6L)	0.12	79.77	83.3%	246 (50.6L)	4.86
PROXG	12	0.74	41.7%	3 (50.0L)	0.06	132.54	100.0%	566 (50.0L)	11.32
PROXG-1	12	0.17	8.3%	2 (50.1L)	0.04	2.14	58.3%	17 (50.6L)	0.34
PROXG-2	12	0.92	33.3%	5 (48.5L)	0.13	168.84	83.3%	1000 (31.4L)	31.85
S4	6	1.15	50.0%	4 (50.1L)	0.08	64.39	83.3%	143 (50.1L)	2.85
S5	6	0.66	16.7%	4 (50.4L)	0.08	117.57	100.0%	273 (50.7L)	5.38
S7i	12	0.66	41.7%	3 (50.4L)	0.06	109.51	83.3%	493 (44.9L)	10.98
WDBN/ CBS	6	2.47	50.0%	12 (50.8L)	0.24	38.27	100.0%	118 (14.0L)	8.43

[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 61 of the 72 samples (84.7%) taken at WOH streams in 2017, similar to the percent positive in 2016 (87.0%). Only PROXG-1 had a detection rate lower than 80.0%. *Giardia* is generally found more frequently and at a higher concentration than *Cryptosporidium* in the entire NYC Watershed. This pattern holds true in most years and at most sites in the watershed, but is most evident in the WOH streams where the difference between mean cyst and oocyst concentrations at each site can be greater than two orders of magnitude (Table 5.6). PROXG-2 had the highest annual *Giardia* mean (168.84 cysts $50L^{-1}$), and the highest single sample result (1000 cysts in a 31.4L sample in October 2017). Results for this site were much higher than 2016, when the mean was 2.33 cysts $50L^{-1}$ and the highest *Giardia* result was 8 cysts in 38.8L. Likewise the downstream site, PROXG, also had much higher annual mean and maximum in 2017 (132.54 and 500 cysts $50L^{-1}$, respectively) compared to those in 2016 (8.24 cysts $50L^{-1}$and 28 cysts in 50.2L, respectively).

Giardia results at PROXG-2 increased sharply in June 2017, while results at PROXG increased beginning in August. Results remained low at PROXG-1 throughout 2017(results < 20 cysts $50L^{-1}$). While results fluctuated from month to month, mean *Giardia* concentrations at PROXG and PROXG-2 for the latter six months of 2017 (258.62 and 319.24 cysts $50L^{-1}$, respectively) suggest a pathogen source upstream of PROXG-2 (along the main stem of the East Branch of the Delaware River). Monitoring will continue at these sites for at least a portion of 2018 at which point the data and selected sites will be re-evaluated.

West of Hudson WWTPs

Protozoan monitoring of WWTPs is scheduled on a quarterly basis at the eight WOH plants. However, in 2017 there was a sampling exception at the Grahamsville plant where the sample was not collected during the last quarter of 2017, but was instead collected on January 18, 2018. Of the 31 samples taken in 2017, and the one sample in January 2018, three out of 32 samples were positive for *Giardia* (9.7%) at two different plants (Trailside at Hunter and Windham (Table 5.7)). All WOH WWTPs were negative for *Cryptosporidium* in 2017.

Table 5.7 Protozoan detections at WOH WWTPs in 2017.

Date	Site	Plant	Sample Volume (L)	*Cryptosporidium* Result	*Giardia* Result
2/21/2017	Hunter Highlands BD	Trailside at Hunter	50.4	0	10
11/28/2017	Windham WTP	Windham	50.7	0	3
11/29/2017	Hunter Highlands BD	Trailside at Hunter	50.7	0	7

The Trailside at Hunter, LLC plant (Hunter Highlands) was sampled on February 21 and had 10 *Giardia* cysts in the 50.4 L sample. DEP contacted the facility operator to investigate any process irregularities that may have led to the elevated *Giardia* count. Operators notified DEP that around the time of sample, a pressure reduction to 60 psi (normal operating pressure ranges from 100-120 psi) was observed in the portable air compressor to drive the air lift pumps within the Continuously Backwashing Upflow Dual Sand Filters (CBUDSF). This unit had been active since the start of 2017. The CBUDSF remained operational and turbidity readings for the day were not unusual ranging from 0.16 – 0.18 NTU. A new compressor was ordered and put in service on February 23, 2017. The operator also noted that the facility is planning on ordering a permanent, inline compressor to serve their needs. No other mechanical or process abnormalities that could have led to the positive detection were noted by the operators. The following two quarterly samples were negative for *Giardia* cysts; however, the fourth sample for 2017 was positive. This sample was collected on November 29 and there were 7 *Giardia* cysts detected in the 50.7 L sample. Once again DEP contacted the facility operator to identify any potential process irregularities, however, no mechanical or process abnormalities were noted at the treatment plant around the time of sampling.

The Windham plant also had a *Giardia* detection in 2017. Three *Giardia* cysts were found in the 50.7 L sample taken on November 28. The operators of the plant were contacted to investigate any potential issues, however, no abnormal conditions were noted at the Windham plant around the time of sampling. The first three quarterly samples for 2017 were negative for *Giardia*, and this is consistent with the past three years, when one out of the four samples each year was positive for *Giardia.*

East of Hudson Streams

The Kensico perennial streams were monitored at least monthly for protozoans in 2017. In addition to the 96 scheduled samples, eleven additional samples were taken at routine sites to follow-up on elevated results found during routine monitoring, for a total of 107 samples at the eight streams this year.

Cryptosporidium oocysts were detected in 29 out of 96 routine samples (30.0%) at Kensico perennial stream sites in 2017. This was lower than the number of detections found in 2016 (45 out of 96, 46.9%) but still higher than in 2015 (24 out of 94 samples, 25.5%). For the third straight year, N12 had the highest annual mean concentration (5.83 oocysts $50L^{-1}$) as well as the highest concentration in a single sample (49.0 oocysts $50L^{-1}$) (Table 5.8). These were remarkably similar to the mean and maximum concentrations found at N12 in 2016 (5.75 and 43.0 cysts $50L^{-1}$). Annual *Cryptosporidium* means at four of the perennial streams (E9, MB-1, N12, and WHIP) were equivalent to or higher than those found in 2016, which were all more than double those seen in 2015 (Figure 5.10). The annual mean for N5-1 (2.18 oocysts $50L^{-1}$) was lower than in 2016 (2.87 oocysts $50L^{-1}$) but still higher than in 2015 or the prior nine years (2007 – 2015 highest annual mean concentration = 1.00 oocysts $50L^{-1}$). The remaining three streams (BG9, E10 and E11) had means below those found in 2016, more similar to those found in 2015 and the preceding years. It is possible the change in stain in 2015 may account for the increases in detection of oocysts observed at some sites. Additional years of data collection may help to quantify a shift in the data, if one exists.

Table 5.8 Summary of routine Kensico perennial stream protozoan results for 2017.

		Cryptosporidium				*Giardia*			
Site	**n**	**Mean[1] ($50L^{-1}$)**	**% Detects**	**Max ($50L^{-1}$)**	**Max (L^{-1})**	**Mean ($50L^{-1}$)**	**% Detects**	**Max ($50L^{-1}$)**	**Max (L^{-1})**
BG9	12	0.00	0.0%	0	0.00	3.22	41.7%	16	0.32
E10	12	0.42	33.3%	2	0.04	0.89	25.0%	4 (29.0L)	0.14
E11	12	0.92	25.0%	9	0.18	7.20	58.3%	63 (47.0L)	1.34
E9	12	1.80	33.3%	17 (50.5L)	0.34	13.63	66.6%	43 (50.5L)	0.85
MB-1	12	2.70	25.0%	27	0.54	4.13	50.0%	29	0.58
N12	12	5.83	50.0%	49	0.98	19.58	83.3%	188	3.76
N5-1	12	2.18	50.0%	11	0.22	3.33	66.6%	9	0.20
WHIP	12	1.25	25.0%	13	0.26	2.50	58.3%	10	0.20

[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.

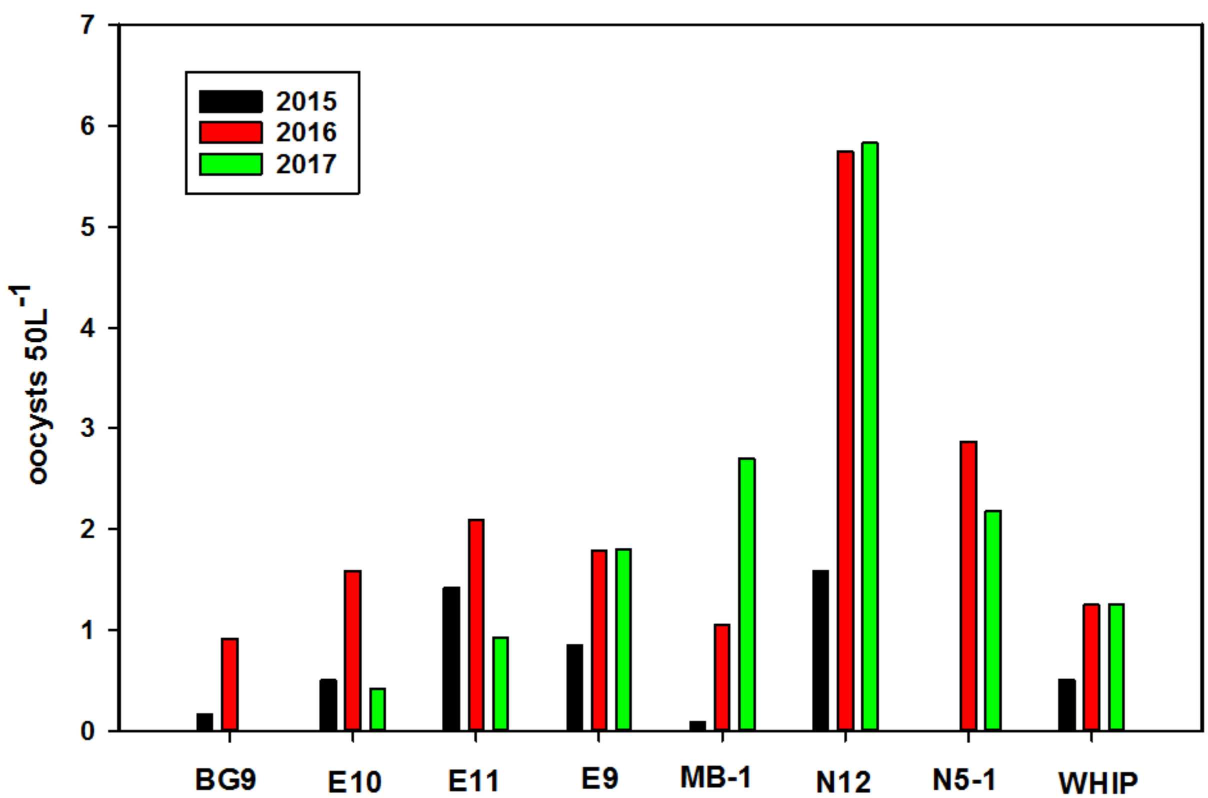


Figure 5.10 Annual mean *Cryptosporidium* concentrations for routine samples taken at the eight Kensico streams in 2015 through 2017.

The *Giardia* detection rate was 56.3% for routine samples at Kensico perennial streams in 2017, similar to that seen in prior years (2012 to 2016 detection rate – 63.3%; annual range - 34.0 - 75.0%). Two sites (BG9 and E11) exhibited increases in annual mean concentrations compared to 2016. Most notably, the 2017 mean for BG9 (3.22 cysts $50L^{-1}$) was significantly higher than the 2016 mean (0.08 cysts $50L^{-1}$) but still much lower than the historical mean for this site (2002-2015, 11.31 cysts $50L^{-1}$). Four sites (E10, MB-1, N5-1, and WHIP) showed decreases in 2017 of the annual mean concentrations when compared to 2016 (change >40% from 2016 value). The remaining two sites (E9 and N12) displayed only a minor increase (change <20% from 2016 value). Changes observed may be due to the potentially selective nature of EasyStain, and that not all *Giardia* in the watershed originate from the same source. (Figure 5.11).

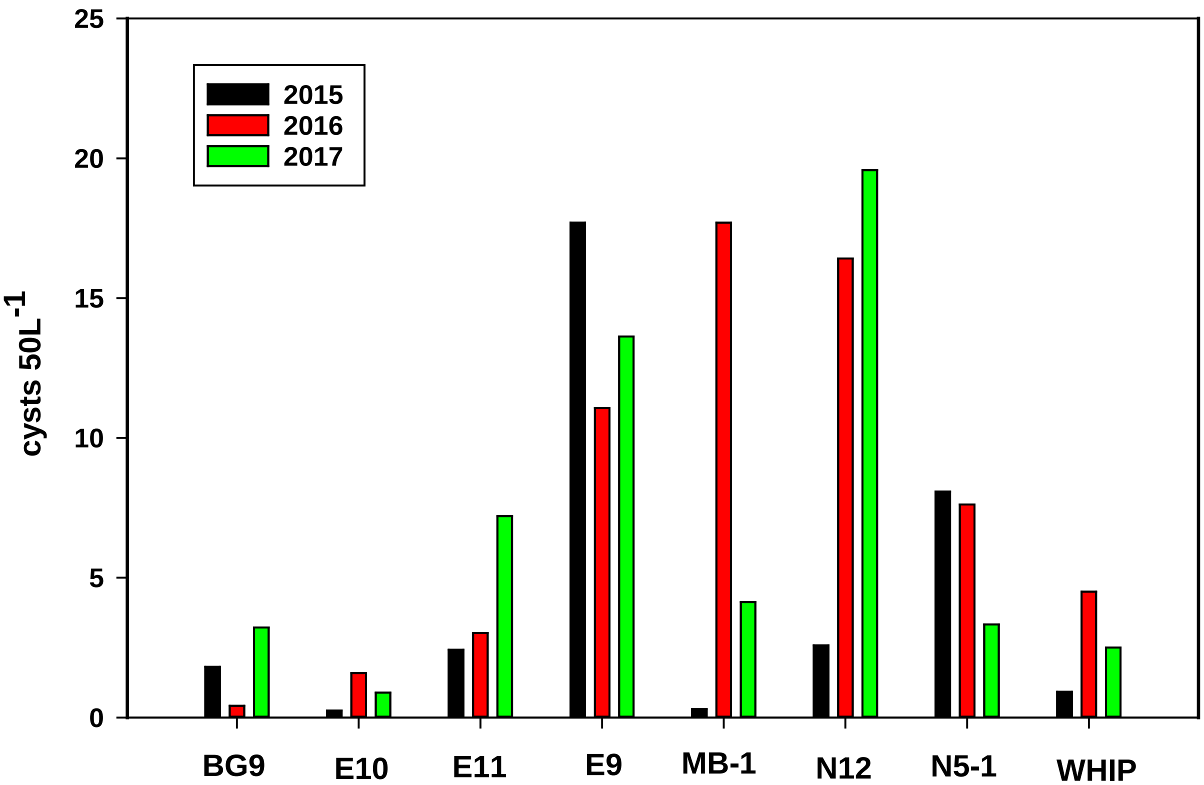


Figure 5.11 Annual mean *Giardia* concentrations for routine samples taken at the eight Kensico streams in 2015 through 2017.

Additional Samples

Eleven additional samples were collected in 2017 as part of follow-up investigations for elevated results. The first additional sample was taken on June 19 at N5-1 after an elevated *Cryptosporidium* result at that site on June 6 (3.0 oocysts $50L^{-1}$). No *Cryptosporidium* and only one *Giardia* were found in the follow-up sample. The second special investigation sample was taken on July 17 at N12, after the routine sample on July 5 was found to have 14 *Cryptosporidium* oocysts and 188 *Giardia* cysts in the 50L sample. These results were well over the historical 95th percentiles for data from this site (5.25 and 17.27 (oo)cysts $50L^{-1}$, respectively). Results for this follow-up sample were below the 95th percentile threshold, at 2 oocysts and 15 cysts 50L^{-1}.

Results from samples taken on November 7 at five of the perennial streams sites (E11, E9, MB-1, N5-1, and WHIP) showed results with elevated *Cryptosporidium* (ranging from 9.00 to 27.00 oocysts 50L^{-1}) and exceeded the 95th percentile calculated using ten years of historical data from each individual site. Follow-up samples were collected at the five sites on November 14 and results for two sites (E11 and MB-1) showed no *Cryptosporidium* in the follow-up samples. The November 14 results at E9 indicated *Cryptosporidium* levels had decreased but were still above the 95th percentile, while results from N5-1 and WHIP showed *Cryptosporidium* had increased (17 oocysts 50.5L^{-1} and 26 oocysts 50L^{-1}, respectively). Another round of follow-up samples were taken on November 27 at three sites (E9, N5-1, and WHIP) and all results were below the 95th percentile (range from 0-3 oocysts 50L^{-1}).

The final special investigation sample taken at the Kensico streams in 2017 was after an elevated *Cryptosporidium* result in the December 5 sample at N12 (49 oocysts 50.5L^{-1}). As noted above, this is greater than the historical 95th percentile threshold for N12 (5.25 oocysts 50L^{-1}), hence a follow-up sample was scheduled for December 11. Results for this follow-up sample (1.00 oocyst 50L^{-1}) indicated *Cryptosporidium* levels at N12 had returned to well below the threshold.

East of Hudson WWTPs

Two EOH WWTPs, Carmel and Mahopac, were sampled quarterly in 2017. All of the WWTP samples at EOH sites were negative for *Giardia* and *Cryptosporidium*.

5.5 Hillview Monitoring

Giardia and *Cryptosporidium* have been routinely monitored weekly at Hillview Reservoir Site 3 since August 2011 as part of the Hillview Administrative Order. In 2017, 52 weekly samples were collected and analyzed using the routine method (Method 1623.1 with EasyStain and heat dissociation) (Figure 5.12 and Figure 5.13). In addition, one 100 liter sample was collected on May 22 as part of another study. As explained in previous editions of this annual report, a decrease in *Giardia* cysts and a potential increase in *Cryptosporidium* detections and concentrations after the April 2015 method change may be occurring. More data will be needed over the next few years to increase confidence in any changes in the database.

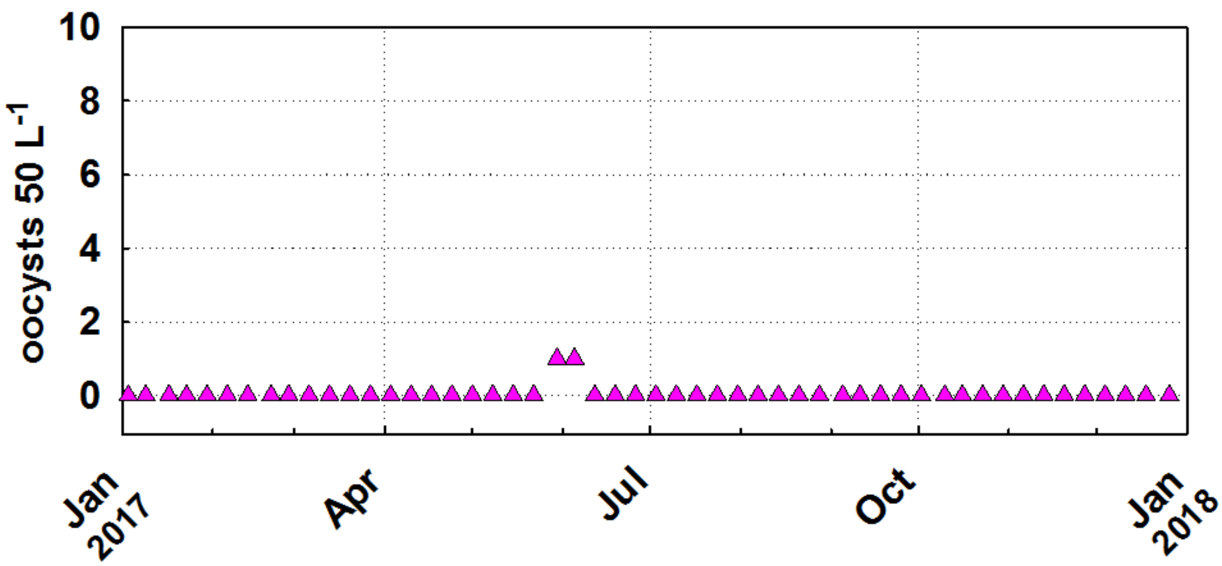


Figure 5.12 *Cryptosporidium* oocyst concentrations for routine samples at Hillview Site 3 in 2017.

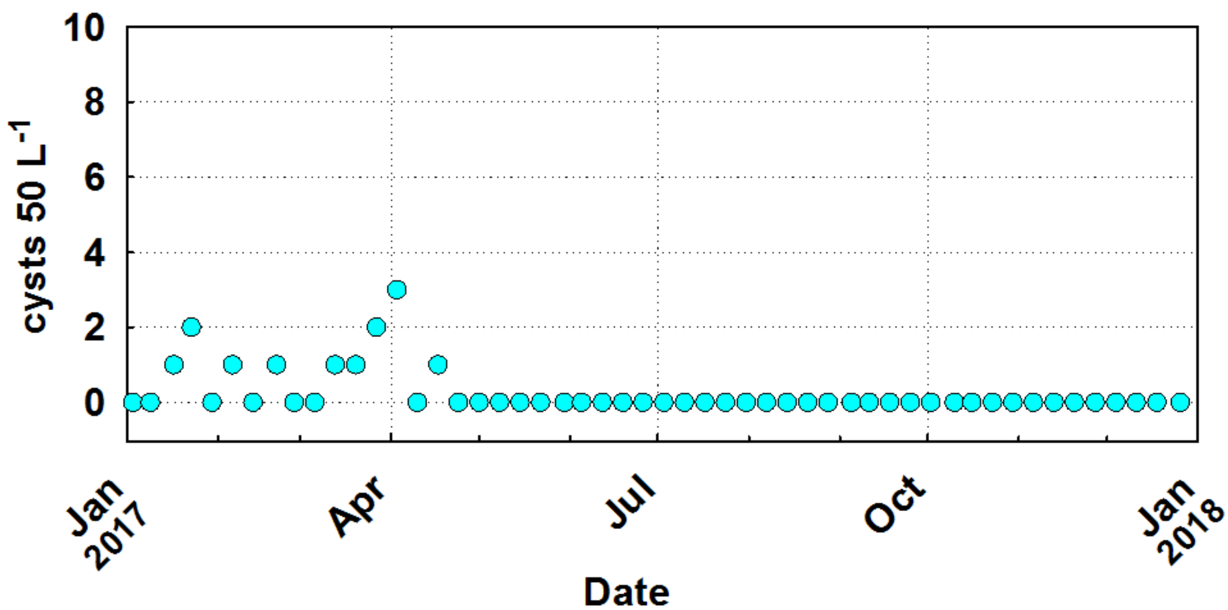


Figure 5.13 *Giardia* cyst concentrations for routine samples at Hillview Site 3 in 2017.

Cryptosporidium was detected in 3.8% of samples and the annual mean concentration was 0.04 oocysts $50L^{-1}$ (Table 5.9). The *Cryptosporidium* detection rates in 2017 were lower than those in 2016 and 2015, and more similar to those observed in years prior to the method change (2013 and 2014; Table 5.10). *Giardia* results were higher in 2017 than those in 2015 and 2016, but lower than most years prior to switching to Method 1623.1 with EasyStain. The slight rise in 2017 could be due to the switch to the alternate heat dissociation step which was intended to improve *Giardia* recovery. The *Giardia* detection rate was 17.3%, and the annual mean concentration was 0.25 cysts $50L^{-1}$. Again, additional years of data are needed to be confident about the causes of these change in detection.

Table 5.9 Hillview Site 3 protozoan monitoring results summary for 2017.

	***Cryptosporidium* oocysts**	***Giardia* cysts**
n	52	52
Number of Detects	2	9
% Detects	3.8%	17.3%
Mean ($50L^{-1}$)	0.04	0.25
Maximum ($50L^{-1}$)	1.00	3.00

Table 5.10 Hillview Site 3 protozoan detections from 2011 to 2017.

	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%

[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 part of research studies at Hillview Reservoir, extra sampling and analyses were performed. The 100L sample, noted in the introduction as being processed with acid dissociation, was negative for both *Cryptosporidium* and *Giardia*. Sixty additional 100-liter samples were taken at Hillview Site 3 as part of an infectivity study using Hillview matrix water and known spike doses of oocysts.

6. Water Quality Modeling

6.1 Overview

The Water Quality Modeling Program 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 section contains an overview of major activities in the Water Quality Modeling Program that took place in 2017.

6.2 West of Hudson Reservoir Bathymetry

The U.S. Geological Survey, working under contract with NYCDEP, completed bathymetric surveys of the six reservoir basins located west of the Hudson River in 2013-2015. Complete information on the survey results, including storage tables, were transmitted to NYCDEP in 2017. An overview of those results is presented here. Comparing the total (gross) reservoir volume determined by USGS to the original as-built volumes, modest reductions have occurred that are consistent with the deposition of sediment in these seven basins. A summary of the results is given in Table 6.1.

Considering total or gross reservoir volume, a 2.4% reduction occurred from original construction to the time of the USGS surveys. The reduction in the available (portion of the total above the lowest intake elevation) and dead storage (portion of the total below lowest intake) components of the total was 2.0 and 13%, respectively. The greatest percent reductions in total storage were at Schoharie (9.0%) and the West Basin of Ashokan (5.3%); in the remaining five basins, the reduction was less than 2.7%. Assuming that the reduction in volume was due to sediment deposition, the average depth of sediment deposition ranged from a low of 18 cm (0.6 ft.) at Pepacton to a high of 162 cm (5.3 ft.) at Schoharie. Rates of storage loss per unit watershed area vary from 0.019 (Pepacton) to 0.073 MG km^{-2} $year^{-1}$ (Ashokan). Applying the individual rates of storage loss for each basin into the future, the West of Hudson reservoirs will experience an additional 1% loss of total storage by 2046 (28 years), 3% loss by 2104 (86 years), 5% loss by 2163 (145 years).

Table 6.1 Summary of bathymetry results from 2013-2015 USGS surveys: change in total (gross) reservoir volume (BG=billion gallons), years in service, loss rate, watershed area, areal loss rate (MG=million gallons), and average deposition depth.

Basin	Volume, billion gallons BG			% Red-uction	Years in Service	Loss Rate % yr^{-1}	Watershed Area, km^2	Areal Loss Rate, MG km^{-2} yr^{-1}	Deposition Depth, cm/feet
	As Built	New USGS	Change						
Ashokan East	80.68	78.53	-2.15	2.6	99	0.027			40 / 1.3
Ashokan West	49.42	46.82	-2.60	5.3	99	0.055			79 / 2.6
Ashokan Total	130.10	125.35	-4.75	3.7	99	0.038	660	0.073	54 / 1.8
Cannonsville	98.62	96.00	-2.62	2.7	47	0.057	1180	0.047	52 / 1.8
Neversink	37.15	36.65	-0.50	1.3	61	0.022	241	0.033	31 / 1.0
Pepacton	149.80	148.69	-1.11	0.7	60	0.012	961	0.019	18 / 0.6
Rondout	52.44	51.77	-0.67	1.3	63	0.020	246	0.043	30 / 1.0
Schoharie	21.55	19.60	-1.95	9.0	88	0.11	816	0.027	162 / 5.3
Total	489.66	478.06	-11.60	2.4					

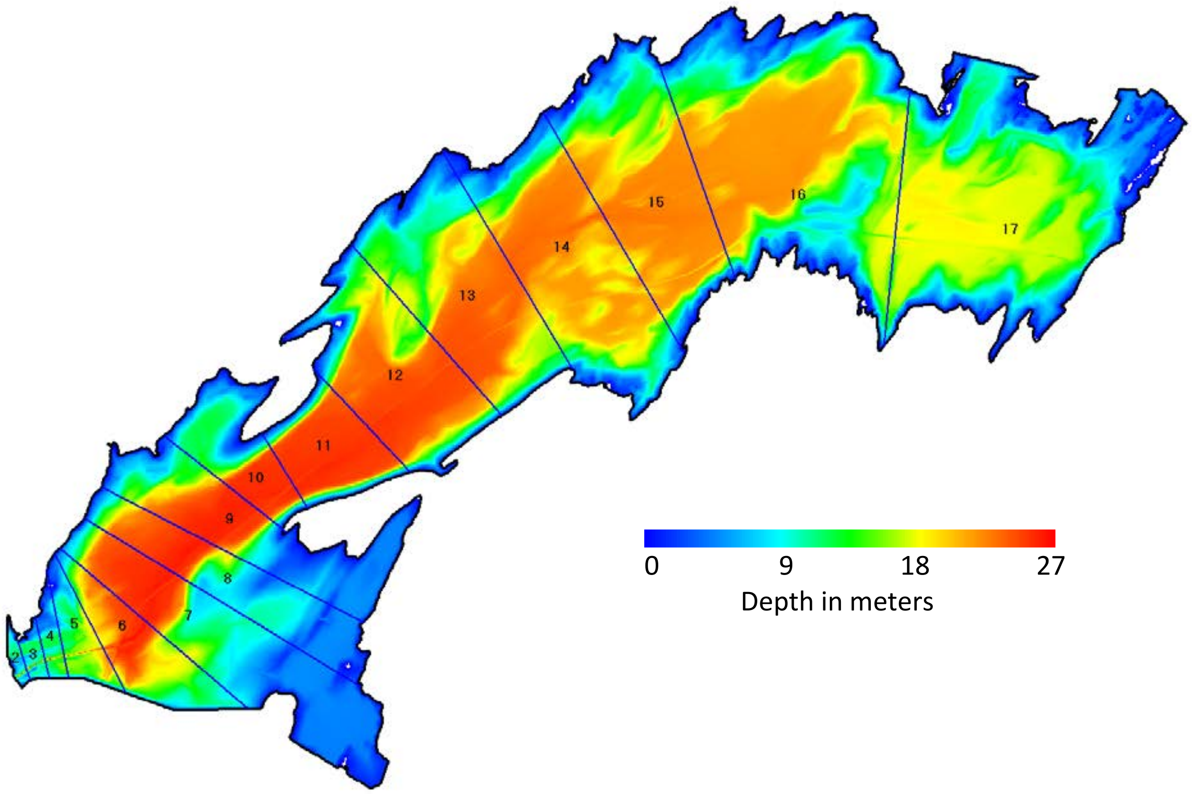


Figure 6.1 Bathymetry of the East Basin of Ashokan Reservoir measured by USGS in May 2014. Depths assume water surface elevation at the spillway crest of 587.1 feet (BWS datum). The 16 segments used in the W2 (two-dimensional) model for this basin, numbered 2 to 17, are shown.

An example of the detailed bathymetric measurements is shown in Figure 6.1 for the East Basin of Ashokan Reservoir. Volume tables for the entire reservoir, and for each of the 16 segments used in the two-dimensional model segments shown in Figure 6.1, were determined from this information.

The new USGS bathymetric information has been implemented in all models of the six West of Hudson reservoir basins used by the Water Quality Modeling group, and in all supporting analyses of data.

6.3 GWLF Streamflow Forecast Automation

To extend the utility of watershed models that have been developed for the six West of Hudson watersheds, the Water Quality Modeling section has developed scripts to automate runs of the Generalized Watershed Loading Function (GWLF) model. The goal of this GWLF automation project is to create scripts that are capable of running the GWLF model simulations in an operational capacity to generate streamflow predictions. The scripts combine historical meteorological data with forecasts to provide a continuous time series to drive GWLF up to 10 days into the future using publicly available, web-accessible data. These daily results and forecasts would then be available as input datasets for reservoir water quality models.

The GWLF-VSA model (Schneiderman et al. 2007) is a lumped parameter hydrological model that simulates daily streamflow at a watershed scale. This model has been applied and validated in previous studies for the West of Hudson watersheds. To drive the simulations, GWLF requires a daily input time series of maximum and minimum air temperature, precipitation amount, relative humidity and solar radiation that is representative for an entire reservoir watershed. The historical input data are obtained from the PRISM (Parameter-elevation Relationships on Independent Slopes Model) dataset. PRISM is a modeled climate product, computed at a 4 kilometer grid cell size for the continental US. The period of record is 1/1/1981–present, with a lag of 1-2 days. PRISM data are considered provisional for approximately 6 months after generation. PRISM data include daily values for minimum and maximum air temperature, and precipitation. For weather forecasting, Weather Underground was used to provide 10-day forecasts. As with the PRISM data, Weather Underground forecasts are a 4-kilometer gridded product at a daily time step. Forecasts are updated hourly, but here we use only the midnight dataset for consistency. To prepare the final datasets, additional data variables (relative humidity and solar radiation) are calculated using MTClim, a microclimate simulation model. MTClim uses minimum and maximum temperature and precipitation from the input datasets, along with other location variables such as latitude and elevation.

The open source Python scripting language is used to drive the entire GWLF workflow. The Python scripts allow DEP to perform batch simulations for the six West of Hudson basins, and provide streamflow forecasts and reports to staff automatically without any need for user input. Figure 6.2 shows the overall process, starting with input data downloads, preparation of time series, invoking external software to run MTClim and GWLF, post-processing GWLF and warehousing results in a server database. In addition to base Python, Pandas and SQLAlchemy are the primary modules used to drive the workflow.

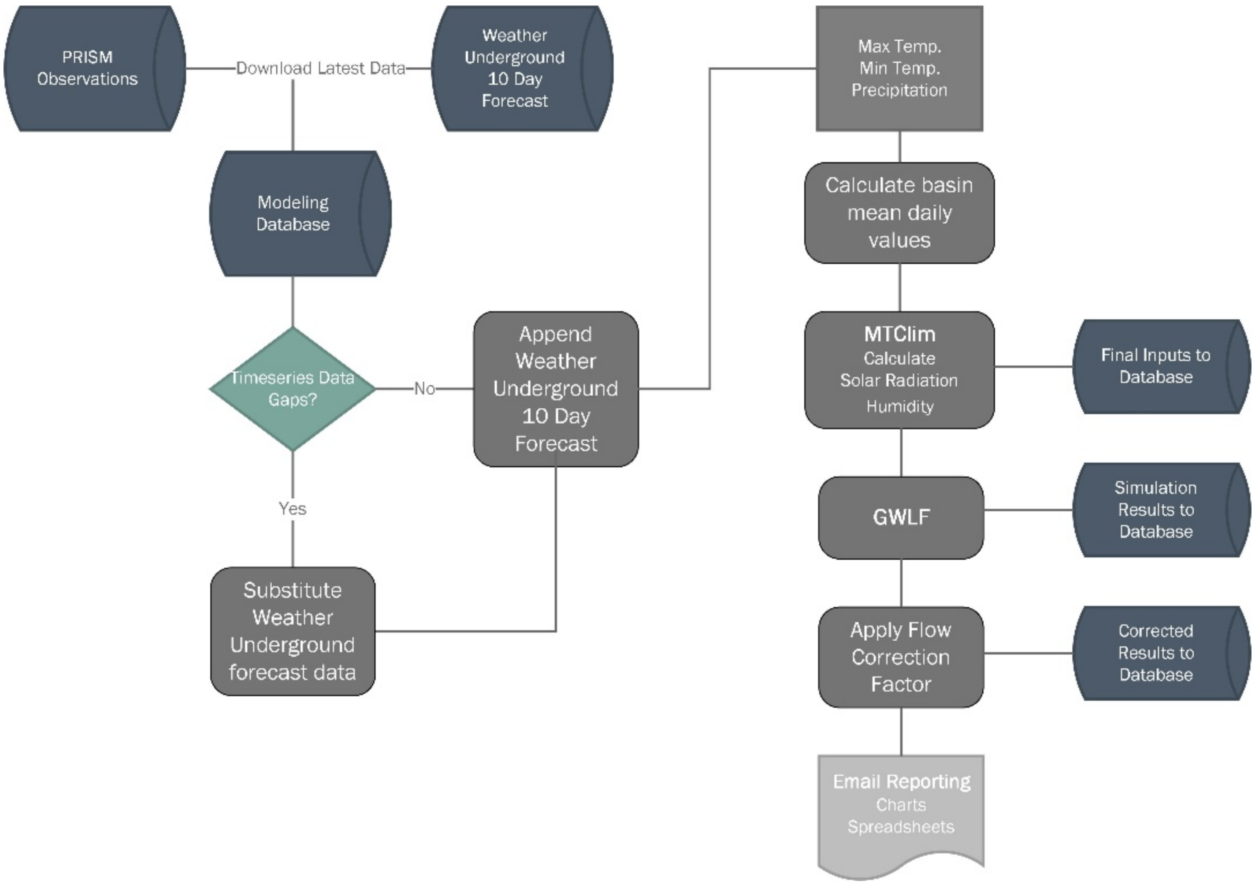


Figure 6.2 Overview Diagram of the GWLF Automation Workflow

To build the time series inputs for GWLF, the mean value for each basin is calculated for each variable from the 4-km grids. With the dataset of air temperature and precipitation compiled for the period of record, MTClim is applied to the entire dataset to generate average daily relative humidity and solar radiation estimates. The final datasets are passed to the GWLF model for simulation. The primary result of the GWLF simulation is a daily streamflow value for each basin at the location of the USGS gage station nearest the reservoir. After the simulations are completed, the Python script reads the GWLF output files and appends recorded streamflow data collected from the USGS gages. To improve model performance, a series of bias correction values have been computed for each watershed. Biases in streamflows simulated by GWLF are computed and corrected using a simple, effective equidistant quantile mapping (EQM) method. For the Ashokan Reservoir watershed, an additional correction is applied to account for the diversions from Schoharie Reservoir through the Shandaken Tunnel into the Esopus Creek. All results are imported to SQL server, and any results based on provisional PRISM data will be overwritten if final PRISM data are available. Once all data are compiled and correction factors are applied, the automation script produces a series of plots comparing the observed flow values at each gage with raw and corrected simulation results (Figure 6.3). These plots are then transmitted by email to a list of recipients.

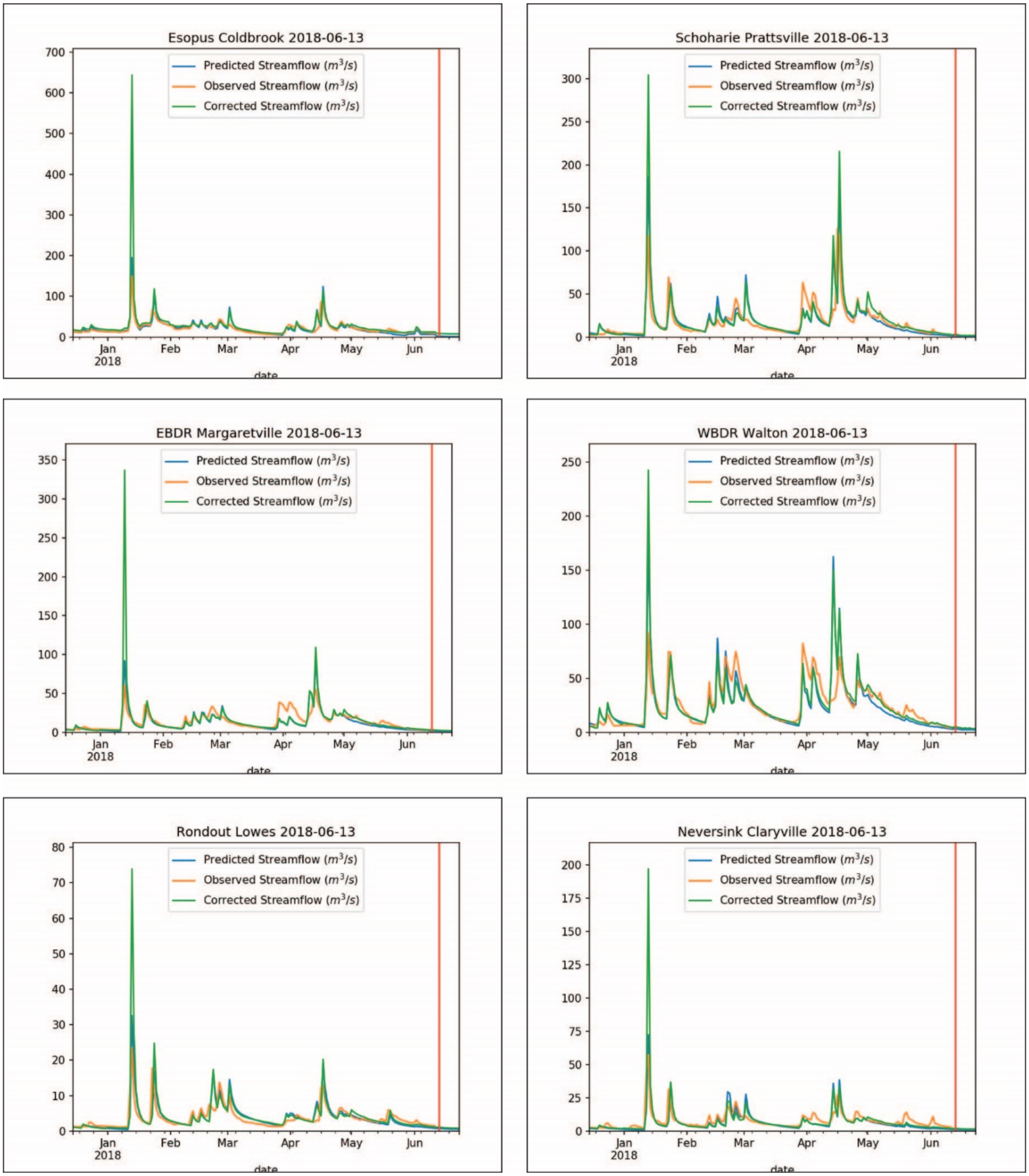


Figure 6.3 Sample results of the GWLF automation process for each of the six basins, showing the observed streamflow from USGS gages (orange), raw predicted streamflow (blue) and corrected streamflow (green). The vertical red line indicates the time at which the input weather data shifts from historical PRISM data to Weather Underground forecasts.

6.4 Neversink Reservoir Turbidity Model

Development and testing of a two-dimensional model for temperature and turbidity for Neversink Reservoir was completed by the Water Quality Modeling section in 2017. The model is based on the hydrodynamic, temperature, and mass transport framework of the CE-QUAL-W2. The turbidity submodel is the same as previously tested and validated for Schoharie, Ashokan, Kensico and Rondout reservoirs during earlier Catskill Turbidity Control and other subsequent studies.

The primary tributary of the reservoir, Neversink River, is gaged at Claryville, NY, capturing runoff from 74% of the mostly forested watershed. Outflow from the reservoir occurs via an aqueduct (Neversink Tunnel) that discharges into Rondout Reservoir, through release works located in the dam, and over the spillway. Water withdrawn from Rondout Reservoir enters an aqueduct for conveyance to a further downstream reservoir where it mixes with water from other parts of the system in Kensico Reservoir before disinfection and supply to NYC, without filtration. An important water quality parameter of concern for the City's water supply is turbidity. Turbidity in Neversink Reservoir is less than 5 NTU 92% of the time (1987-2014), however, higher turbidities have been observed during extreme runoff events, exceeding 20 NTU 1% of the time.

Model calibration was performed using data from 2015, and validation using data from 2013-2014. Extended validation of the model is performed for 1987-2012 interval (26 years). The model performed satisfactorily in simulating turbidity in the reservoir and in the withdrawal (Figure 6.4).

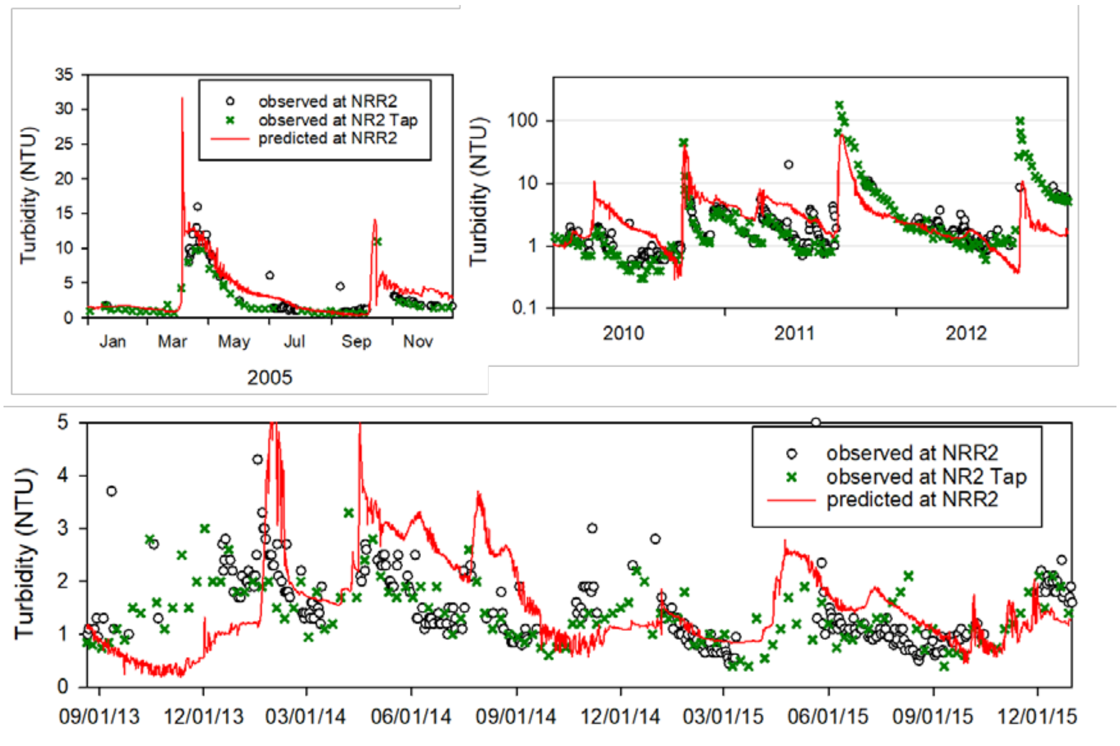


Figure 6.4 Performance of Neversink Reservoir turbidity model for 2005, 2010-2012, and 2013-2015, with respect to withdrawal turbidity. Observations at NR2 Tap location are also shown, a site that closely corresponds to the typical withdrawal elevation location.

The validated model was used to simulate the dispersion of a conservative constituent spill and time of travel by conducting a “numerical” tracer study. A known quantity of a hypothetical soluble conservative tracer was injected for a short duration (15 min), once every two weeks (1987-2011), at the mouth of Neversink River, in a total of 679 model simulation runs. By conducting these runs over a large range of variability in model drivers (e.g., meteorology, hydrology, and reservoir operations), the variability in the travel time response is considered. For each of the runs, dispersion of the constituent was tracked and time of travel to the intake location was computed. The resulting distribution of the time of travel of the arrival of the leading edge at the intake location is depicted in Figure 6.5. The median of the distribution was 178 hours (7.4 days), which is substantially higher than values determined for Schoharie (6 hours) and Ashokan East Basin (75 hours) reservoirs. Table 6.2 presents a comparison of time of travel from influent (mouth of major stream inflow) to intake location as measured in terms of leading edge, peak level, and trailing edge for four reservoirs.

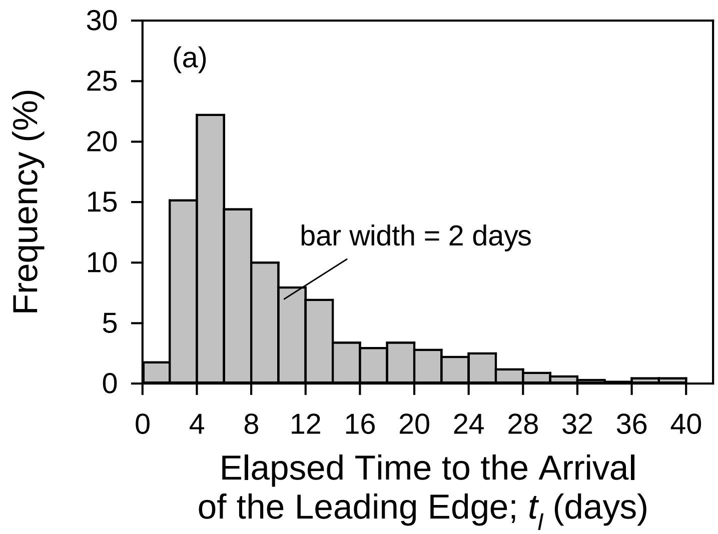


Figure 6.5 Distribution of time of travel from Neversink River mouth to the water supply intake.

Table 6.2 Comparison of time of travel from influent location to intake location as measured in terms of leading edge, peak level, and trailing edge for four reservoirs.

Reservoir	Time of travel		
	Leading edge	Peak concentration	Trailing edge
Neversink	178 hours	22 days	687 days
Schoharie	6 hours	1.5 days	125 days
Ashokan East	75 hours	22 days	512 days
Kensico – CATALUM	15 hours	3.5 days	117 days
Kensico – DEL17	32 hours	12 days	178 days

6.5 Routine Water Quality Forecasts Using Operations Support Tool (OST)

The Water Quality Modeling section has completed development of software tools to generate water quality forecast reports for the Directorate of Water Quality, Bureau of Water Supply (BWS). With the help of these tools and the Operations Support Tool (OST), water quality model runs are now conducted on a regular schedule, providing BWS with the ability to quickly respond to watershed storm events and adjust water supply operations effectively and efficiently. An example of the summary report generated by this software is shown in Figure 6.6. Predictions of turbidity at three important keypoints in the system, the water supply diversion from Rondout (RDRRCM), Ashokan (EARCM), and Kensico (DEL18DT) reservoirs, are generated in a probabilistic format indicating the probabilities of exceedance of selected levels of turbidities that are appropriate for a keypoint at the time of forecast. The forecasts are typically generated weekly, with a forecast duration of 2 weeks. Note that the summary report in Figure

6.6 does not contain results for the diversion turbidity from Rondout Reservoir because the turbidity model for Rondout was not integrated into OST in 2017. That integration will be completed in 2018.

Water Quality Forecast Summary — Division of Water Quality Science & Research

Forecast Period: 10/31/2017 - 11/13/2017 — Bureau of Water Supply

Kingston, NY

Rondout Reservoir

	31-Oct	1-Nov	2-Nov	3-Nov	4-Nov	5-Nov	6-Nov	7-Nov	8-Nov	9-Nov	10-Nov	11-Nov	12-Nov	13-Nov
Inflow, MGD	131	98	116	101	106	89	101	101	94	96	102	106	99	114
Div., MGD	700	700	700	700	700	700	700	700	700	700	700	700	700	700
WSE, ft	836	836.1	836.1	836.3	836.4	836.4	836.4	836.5	836.5	836.7	836.7	837	837.1	837.2
Diversion Turbidity (RDRR): Probability of Exceedance (%)														
1 NTU														
1.5 NTU														
2 NTU														
3 NTU														
4 NTU														
5 NTU														
Hist. Med.,NTU	1	1	1	0.9	0.9	0.8	0.9	1	1	0.9	0.9	0.9	0.9	0.9
Hist. 95^{th},NTU	1.9	1.9	1.7	1.7	2	1.4	1.5	2.1	2	1.7	1.8	1.9	1.7	1.9

Ashokan Reservoir

	31-Oct	1-Nov	2-Nov	3-Nov	4-Nov	5-Nov	6-Nov	7-Nov	8-Nov	9-Nov	10-Nov	11-Nov	12-Nov	13-Nov
Inflow, MGD	55	364	85	290	293	311	405	468	107	517	139	470	246	692
Div., MGD	425	425	425	425	425	425	425	425	425	425	425	425	425	425
WSE, ft (EB)	578	577.7	577.4	577.2	576.9	576.6	576.3	576.1	575.8	575.5	575.3	575	574.7	574.5
Diversion Turbidity (EARCM): Probability of Exceedance (%)														
1 NTU	96	91	98	100	91	89	87	85	94	91	91	94	96	91
2 NTU	60	49	79	64	40	36	17	6	11	9	9	11	11	11
3 NTU	2				2	2	2	4	4	9	9	11	11	11
5 NTU								2		6	4	6	6	6
7 NTU										2	4	6	4	4
10 NTU											2	2	4	4
Hist. Med.,NTU	3	3	3.1	3.2	3	3.1	3.3	3.4	3.2	3.8	3.7	4.5	3.3	3.6
Hist. 95^{th},NTU	10	13	16	5.9	9.5	9.1	8.5	13.4	14.3	14.8	12	10	7.3	8.9

Kensico Reservoir

	31-Oct	1-Nov	2-Nov	3-Nov	4-Nov	5-Nov	6-Nov	7-Nov	8-Nov	9-Nov	10-Nov	11-Nov	12-Nov	13-Nov
Inflow, MGD	1095	1128	1119	1119	1116	1113	1112	1108	1108	1107	1108	1100	1096	1096
Div., MGD	1093	1075	1075	1075	1075	1075	1075	1075	1075	1075	1075	1075	1075	1075
WSE, ft	356	356	356.1	356.1	356.2	356.2	356.2	356.3	356.4	356.4	356.4	356.4	356.4	356.4
Diversion Turbidity (DEL18DT): Probability of Exceedance (%)														
0.5 NTU	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1 NTU							2	6	11	6	9	9	13	11
1.5 NTU														2
2 NTU														
2.5 NTU														
4 NTU														
Hist. Med.,NTU	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.8	0.9	0.8	0.9	0.9	0.9	0.9
Hist. 95^{th},NTU	1.2	1.2	1	1.1	1.2	1.1	1.1	1.3	1.2	1.2	1.1	1.2	1.1	1.2

Currently planned operations.

Run Name: 2017-11-01_WQ_CO_COX3_PA_Baseline_161224_RKG_v01
Run Short Description:
Run Execution Date: 11/1/2017 12:38:59 PM
Run Executed By: GRakesh on 11/1/2017 12:54:38 PM

Figure 6.6 Example of a water quality forecast summary report for three keypoint locations in the water supply system.

An example of verification of the routine forecasts of turbidity is presented in Figure 6.7, which depicts the turbidity of the diversion from Ashokan Reservoir (EARCM). The results of

11 weekly forecasts, each of 14-day duration, are shown. On each day there are 48 predictions (traces) of diversion turbidity, reflecting the uncertainty in future weather conditions that is a key feature of the "position analysis" forecasts that are generated by OST. In almost all cases, the turbidity observed after the time of the forecasts falls within the range of the forecasts traces. These results illustrate the validation and utility of the forecasts, in the context of the dynamic nature of Ashokan Reservoir operations.

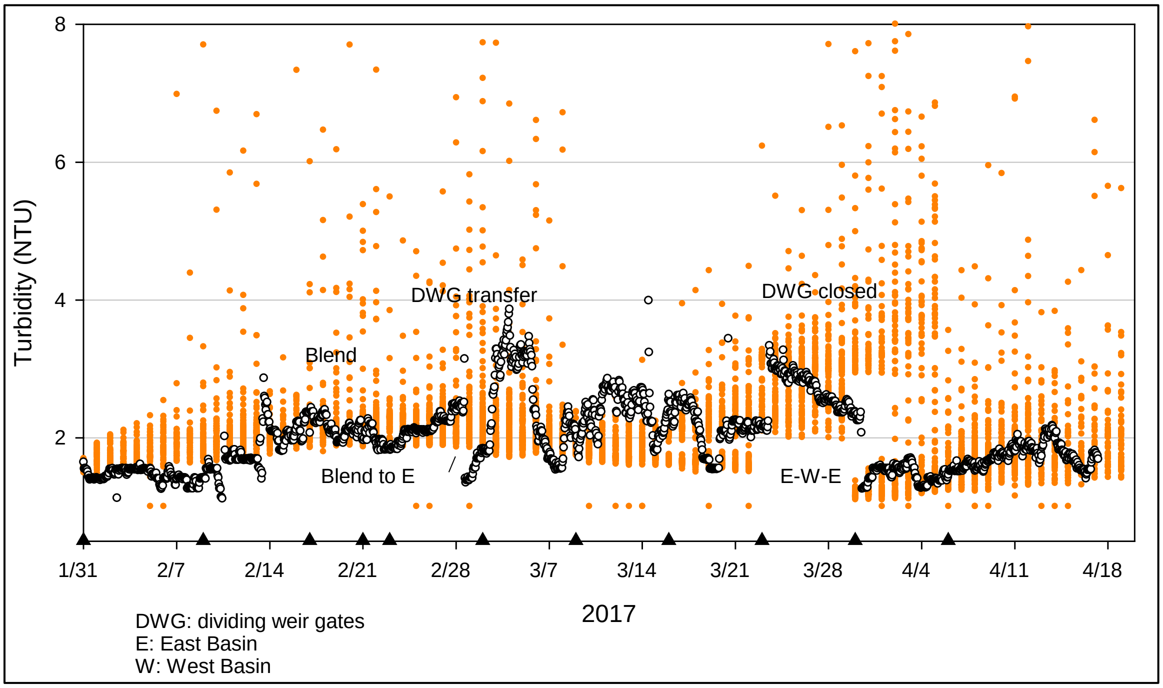


Figure 6.7 Verification of turbidity forecasts for the drinking water diversion from Ashokan Reservoir (EARCM). The triangles show the dates on which forecasts were made; the orange dots immediately following a forecast date are predicted diversion turbidities, with the range of turbidity reflecting the uncertainty in future weather at the time of the forecast. The black circles are the observed diversion turbidity.

6.6 Review of Operations Support Tool (OST) by National Academy of Sciences Expert Panel

The National Academy of Sciences has convened an Expert Panel to review NYCDEP's Operations Support Tool (OST) and the use of OST. This Expert Panel began its work early in 2017 and held several meetings at which DEP staff made presentations on various aspects of the capabilities and application of OST. In addition to assembling and providing background material on OST, staff from the Water Quality Modeling section made several technical presentations to the Expert Panel covering topics related to OST and its use. Two topics that were a focus of those presentations are summarized here.

One of these presentations was about “water quality rules” related to turbidity in OST. These turbidity rules generally define turbidity values at various points in the system that, when exceeded, act as thresholds or triggers to modify operations. For example, if the turbidity in the diversion from Schoharie Reservoir to the Shandaken Tunnel exceeds 100 NTU and no variances are in effect, then a penalty is applied to the Esopus Creek-West Ashokan flow, which makes it unlikely that diversion from Schoharie Reservoir to the Shandaken Tunnel will occur. If there is a turbidity event in the Catskill System, then the target value for Delaware Aqueduct diversion target is maximized. Water quality rules in OST are based on regulatory limits including: (a) Shandaken Tunnel State Pollutant Discharge Elimination System (SPDES) Permit, 2011; (b) New York Codes, Rules, and Regulations (NYCRR) Part 670: Reservoir Releases Regulations: Schoharie Reservoir–Shandaken Tunnel–Esopus Creek; (c) New York State Department of Environmental Conservation/New York City Department of Environmental Protection (DEC/DEP) Interim Release Protocol (IRP) for Ashokan Reservoir; (d) Catskill Aqueduct Influent Chamber SPDES Permit, 2007; and (e) the experience and institutional knowledge of DEP operating staff.

During 2017, the Expert Panel requested verification of the ensemble hydrologic forecasts generated by OST in the form of rank histograms. Rank histograms provide a simple measure of conditional reliability and involves determining the fraction of observations that fall between any two ranked ensemble members in the distribution of forecast values. Water quality modeling staff conducted the analysis using “reforecast” data for a historical period, typically 1951–1996. This output from the hydrology model component of OST was generated every five days, e.g., starting from January 1, 1951, January 6, 1951, January 11, 1951, and so on. Each run generated forecasts for 364 days in future; e.g., January 1, 1951 run would generate a forecast for every day up to December 31, 1951. Each day’s forecasts consist of an ensemble of 46 members. Multiple lead-time forecast ensembles were generated for a particular day. For example, for January 12, 1951, a run started on January 1, 1951 would generate an ensemble (n=46) with an 11-day lead-time, a run started on January 6, 1951 would generate an ensemble with a 6-day lead-time, and a run started on January 11, 1951 would generate an ensemble with a 1-day lead-time. Observations included total inflows as derived from gaged inflows, changes in water surface elevation, gaged outflows, and estimated evaporation, consistent with the forecasts. Results showed that the probability that an observation fell between any two ranked ensemble members was approximately uniform, implying that the forecasting system was reliable.

6.7 Rondout West Branch Tunnel Shutdown Evaluation

DEP’s current plan is that in 2022, the Rondout West Branch Tunnel (RWBT) will be shut down for a period of six months (October 1-March 31) in order to make the final connections of the new bypass tunnel under the Hudson River currently under construction. During the period of this shutdown, the majority of the supply to Kensico Reservoir will be from the Catskill system. Based upon historical turbidity levels in the Catskill Aqueduct, it is likely that alum will be needed to treat the Catskill System water at some point during the shutdown in order to maintain compliance with Surface Water Treatment Rule regulations for turbidity. In an abundance of caution, DEP intends to be proactive and treat with alum at lower levels than in the past in order to minimize baseline levels of turbidity in Kensico Reservoir.

Though unlikely, it is possible that an interruption of alum treatment (a “treatment gap”) may occur during the course of the shutdown period. Such a treatment gap could occur because of interruption of the supply of alum. To evaluate the impact of such a gap, an array of simulation runs were conducted with the Kensico Reservoir turbidity model. All combinations of the following conditions were investigated: three alum treatment gap durations (1, 3, 7 days), two levels of Catskill Aqueduct flow reduction during the gap (no reduction, reduction from 636 to 275), two Catskill Aqueduct turbidity scenarios, and three turbidity levels in Kensico Reservoir at the start of the treatment gap. It was assumed that the treatment gap would occur in mid-March. Table 6.3 summarizes the conditions considered in these model runs.

Table 6.3 Run matrix to evaluate impact of a gap in alum treatment of Catskill Aqueduct inflow at Kensico Reservoir.

Alum gap (Days)	Catskill Aqueduct Inflow (MGD) before/during/after gap	Catskill Aqueduct Inflow Turbidity (NTU) before/during/after gap	Initial Turbidity in Kensico (NTU)
Baseline			
no gap	636 / 636 / 636	2 / 2 / 2	1
Scenarios			
1	636 / 636 / 636*	2 / 5 / 2	0.5
3	636 / 275 / 636	3 / 20 / 3	1
7			2
N=3	N=2	N=2	N=3

**no reduction in flow during alum treatment gap*
Delaware Aqueduct: 175 MGD, 2.0 NTU (all runs)
Total Runs = 3 × 2 × 2 × 3 = 36

The model predictions were evaluated in terms of the number of days that the projected daily median turbidity at DEL18DT was greater than 1, 2, 3, and 5 NTU, and when the projected daily maximum turbidity was greater than 5 NTU. The results for the baseline conditions and for all 36 scenarios are summarized in Table 6.4. For all scenarios, the daily median turbidity and the daily maximum turbidity are predicted to be less than 5 NTU. The predicted turbidity time series at DEL18DT for the baseline and scenarios 15 and 33 are shown in Figure 6.8.

Table 6.4 Summary of Kensico turbidity model runs for a simulated gap in alum treatment.

RWBT shutdown scenarios									
Run Scenario Number	Alum gap (Days)	Catskill Aqueduct Inflow (MGD) before/during/after gap	Catskill Aqueduct Inflow Turbidity (NTU) before/during/after gap	Initial Turbidity (NTU)	No. of days (3/13 - 5/31) when projected daily median turbidity is > 1 NTU	> 2 NTU	> 3 NTU	> 5 NTU	No. of days (3/13 - 5/31) when projected daily maximum turbidity > 5 NTU
Base	*no gap*	*636 / 636 / 636*	*2 / 2 / 2*	*1*	*77*	*0*	*0*	*0*	*0*
Effect of alum gap with no flow reduction and low inflow turb and varying initial conditions									
1	1	636 / 636 / 636	2 / 5 / 2	0.5	55	0	0	0	0
2	3	636 / 636 / 636	2 / 5 / 2	0.5	58	0	0	0	0
3	7	636 / 636 / 636	2 / 5 / 2	0.5	69	0	0	0	0
4	1	636 / 636 / 636	2 / 5 / 2	1	77	0	0	0	0
5	3	636 / 636 / 636	2 / 5 / 2	1	77	0	0	0	0
6	7	636 / 636 / 636	2 / 5 / 2	1	77	0	0	0	0
7	1	636 / 636 / 636	2 / 5 / 2	2	80	0	0	0	0
8	3	636 / 636 / 636	2 / 5 / 2	2	80	8	0	0	0
9	7	636 / 636 / 636	2 / 5 / 2	2	80	18	0	0	0
Effect of alum gap with no flow reduction and high inflow turb and varying initial conditions									
10	1	636 / 636 / 636	3 /20 / 3	0.5	71	12	0	0	0
11	3	636 / 636 / 636	3 /20 / 3	0.5	75	14	0	0	0
12	7	636 / 636 / 636	3 /20 / 3	0.5	75	57	0	0	0
13	1	636 / 636 / 636	3 /20 / 3	1	78	19	0	0	0
14	3	636 / 636 / 636	3 /20 / 3	1	78	26	0	0	0
15	7	636 / 636 / 636	3 /20 / 3	1	78	73	0	0	0
16	1	636 / 636 / 636	3 /20 / 3	2	80	77	0	0	0
17	3	636 / 636 / 636	3 /20 / 3	2	80	77	0	0	0
18	7	636 / 636 / 636	3 /20 / 3	2	80	77	15	0	0
Effect of alum gap with flow reduction and low inflow turb and varying initial conditions									
19	1	636 / 275 / 636	2 / 5 / 2	0.5	53	0	0	0	0
20	3	636 / 275 / 636	2 / 5 / 2	0.5	55	0	0	0	0
21	7	636 / 275 / 636	2 / 5 / 2	0.5	57	0	0	0	0
22	1	636 / 275 / 636	2 / 5 / 2	1	77	0	0	0	0
23	3	636 / 275 / 636	2 / 5 / 2	1	77	0	0	0	0
24	7	636 / 275 / 636	2 / 5 / 2	1	77	0	0	0	0
25	1	636 / 275 / 636	2 / 5 / 2	2	80	0	0	0	0
26	3	636 / 275 / 636	2 / 5 / 2	2	80	0	0	0	0
27	7	636 / 275 / 636	2 / 5 / 2	2	80	8	0	0	0
Effect of alum gap with flow reduction and high inflow turb and varying initial conditions									
28	1	636 / 275 / 636	3 /20 / 3	0.5	68	10	0	0	0
29	3	636 / 275 / 636	3 /20 / 3	0.5	72	12	0	0	0
30	7	636 / 275 / 636	3 /20 / 3	0.5	73	15	0	0	0
31	1	636 / 275 / 636	3 /20 / 3	1	78	19	0	0	0
32	3	636 / 275 / 636	3 /20 / 3	1	78	23	0	0	0
33	7	636 / 275 / 636	3 /20 / 3	1	78	26	0	0	0
34	1	636 / 275 / 636	3 /20 / 3	2	80	77	0	0	0
35	3	636 / 275 / 636	3 /20 / 3	2	80	77	0	0	0
36	7	636 / 275 / 636	3 /20 / 3	2	80	77	0	0	0

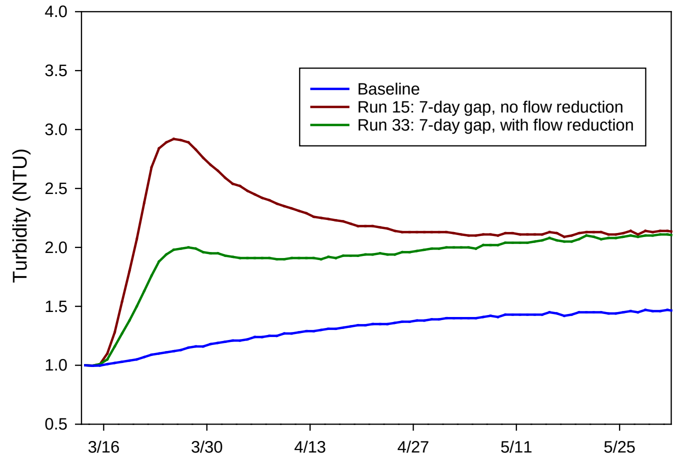


Figure 6.8 Model simulation of turbidity at DEL18DT showing effect of reducing Catskill Aqueduct inflow, from 636 MGD to 275 MGD, during an alum treatment gap of seven days and inflow turbidity of 20 NTU.

6.8 Modeling Streamflow Sensitivity to Climate Change using a Stochastic Weather Generator

A modeling study was carried out to simulate the impact of climate change on streamflow using a stochastic weather generator (SWG) model developed for the region (Acharya et al. 2017), the Generalized Watershed Loading Function (GWLF) watershed model (Schneiderman et al. 2007), and downscaled global climate model (GCM) scenarios with secondary bias correction (Gelda et al. 2018). Streamflow simulations using future climate from 20 CMIP5 GCMs (Table 6.5) for the Esopus Creek watershed indicate the potential for changes in hydrology in this region. The models indicate a shift in the timing of spring melt runoff from a distinct peak in late March and April under historical (1950-2009) conditions towards earlier in the year for mid-century (2041-2060) period (Figure 6.9). Results indicate that the region may experience an overall increase in mean streamflow in the future due to the combined effect of decreasing spring runoff peak and increasing streamflow during other seasons. These findings are consistent with earlier studies using historical observations and simulations using CMIP3 projections (Zion et al. 2011). Compared to the historical period representing current conditions, a majority of the scenarios generated using the SWG indicated an increase in frequency and magnitude of extreme hydrological events for the future time slice considered (Figure 6.10). Using a validated SWG in this analysis generated hydrologic scenarios that incorporated climate variability not found in historical record, nor in GCM projections. The use of a SWG also made it possible to investigate scenarios based on multiple realizations of current and future climate from a limited time series of observed weather or time slices of future weather based on GCMs. The general approach described here can be broadened to allow evaluation of the potential impact of climate change on both the quantity and quality of water in NYC water supply and its implications on water supply management and planning in the future.

Table 6.5 List of CMIP5 GCMs used in this study and projected mid-century (2041-2060) average annual change in precipitation (%) and air temperature (ºC) for the Esopus Creek watershed region compared to historical period (1950-2005) based on RCP 8.5 emission scenario.

GCM ID	GCM name (Country)	Change in air temperature (ºC)	Change in precipitation (%)
GCM1	bcc-csm1-1 (China)	+3.3	+13.3
GCM2	bcc-csm1-1-m (China)	+3.1	+24.5
GCM3	BNU-ESM (China)	+4.0	+10.1
GCM4	CanESM2 (Canada)	+3.8	+11.9
GCM5	CCSM4 (USA)	+2.8	+11.5
GCM6	CNRM-CM5 (France)	+3.2	+8.9
GCM7	CSIRO-Mk3-6-0 (Australia)	+3.1	+15.8
GCM8	GFDL-ESM2G (USA)	+2.7	+11.5
GCM9	GFDL-ESM2M (USA)	+2.5	+11.0
GCM10	HadGEM2-CC365 (United Kingdom)	+4.3	+19.2
GCM11	HadGEM2-ES365 (United Kingdom)	+4.4	+8.6
GCM12	inmcm4 (Russia)	+1.8	+2.5
GCM13	IPSL-CM5A-LR (France)	+3.6	+11.1
GCM14	IPSL-CM5A-MR (France)	+3.4	+10.6
GCM15	IPSL-CM5B-LR (France)	+3.4	+9.3
GCM16	MIROC5 (Japan)	+4.3	+13.9
GCM17	MIROC-ESM (Japan)	+4.5	+6.1
GCM18	MIROC-ESM-CHEM (Japan)	+4.9	+9.3
GCM19	MRI-CGCM3 (Japan)	+2.2	+3.1
GCM20	NorESM1-M (Norway)	+3.0	+16.2
	Average	**+3.4**	**+11.4**

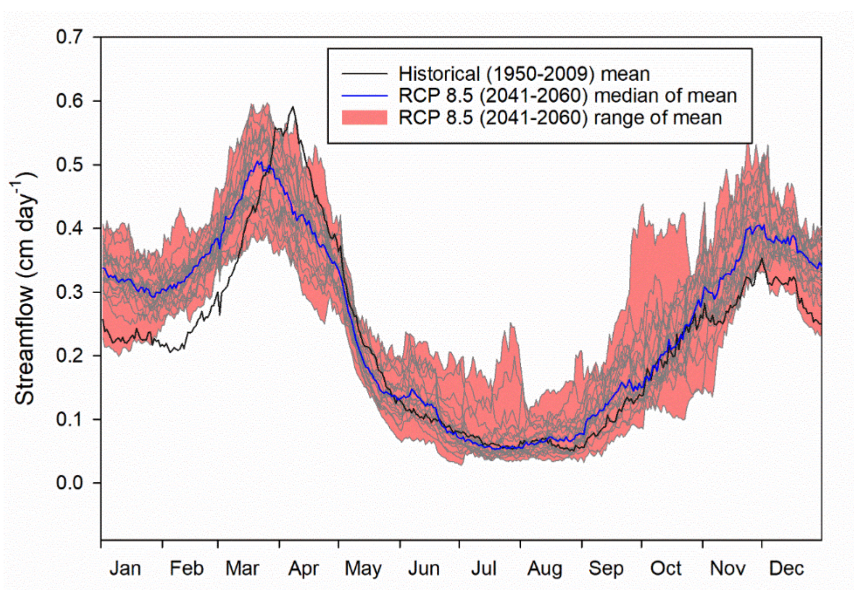


Figure 6.9 Projected change in annual streamflow hydrograph for the Esopus Creek watershed. Historical mean daily values are based on long-term simulations (n=1980 years) using synthetic weather generated using observed weather statistics for the period 1950-

2009. Each future scenario (gray lines) is based on a 2000-year long simulation using synthetic weather generated using weather statistics from 20 GCMs for the period 2041-2060.

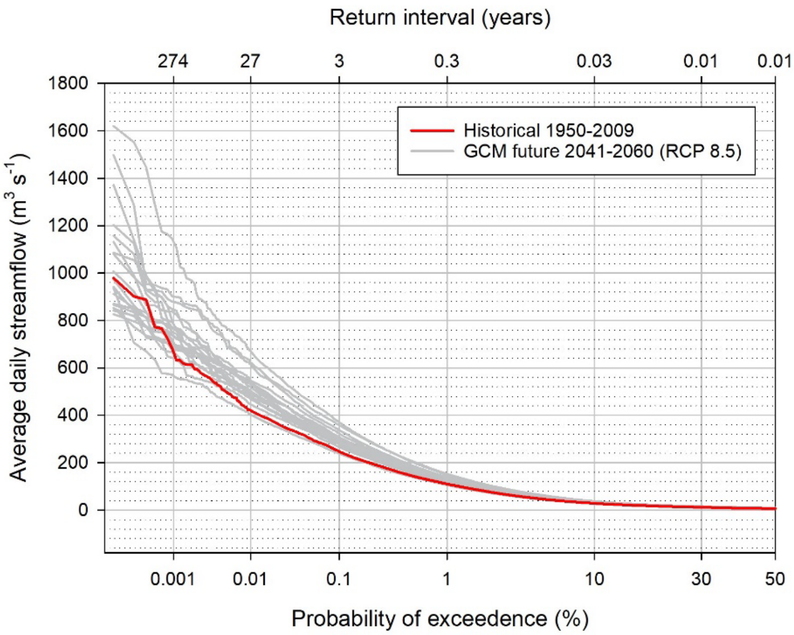


Figure 6.10 Projected changes in extreme streamflow in the Esopus Creek watershed for the mid-century period compared to historical period. Weather scenarios were determined using the stochastic weather generator, historical weather, and predictions from 20 GCMs.

6.9 Projected Changes in Esopus Creek Stream Turbidity under Climate Change Scenarios

The impact of changes in hydrology on turbidity and sediment loads are often modeled using sediment rating curves, empirical relationships that predict suspended sediment concentration or turbidity based on stream discharge. A shortcoming of this method is its failure to describe the uncertainty associated with the high degree of scatter that is common in a relationship between turbidity (or sediment concentration) and streamflow. For the purposes of turbidity projections under future climate change, alternative rating curve methods are needed that can better account for the complex behavior between discharge and turbidity. To address this problem, we investigated the use of quantile regression. The quantile regression approach has been used to model turbidity-discharge relationships but has not been used for long-term planning applications under changing climate conditions. Regression relationships determined for various quantiles were applied to streamflows simulated using the GWLF model for the Esopus Creek watershed to predict stream turbidity under observed historical climate conditions and future climate conditions derived from 20 GCMs. Future scenarios using quantile regression in combination with these GCMs and a stochastic weather generator indicated an increase in the frequency and magnitude of hydrological events that may generate high stream turbidity, and cause potential water quality challenges to the water supply (Figure 6.11). Events that produce the highest turbidity are projected to occur predominantly in the fall season (Figure 6.12). Threshold streamflow in Esopus Creek that could trigger alum treatment in the terminal Kensico Reservoir was determined based on historical records. The probability of exceeding this threshold is projected to increase by a factor of 2.3 under future climate compared to the current climate, suggesting that alum treatment will be required more frequently in the future.

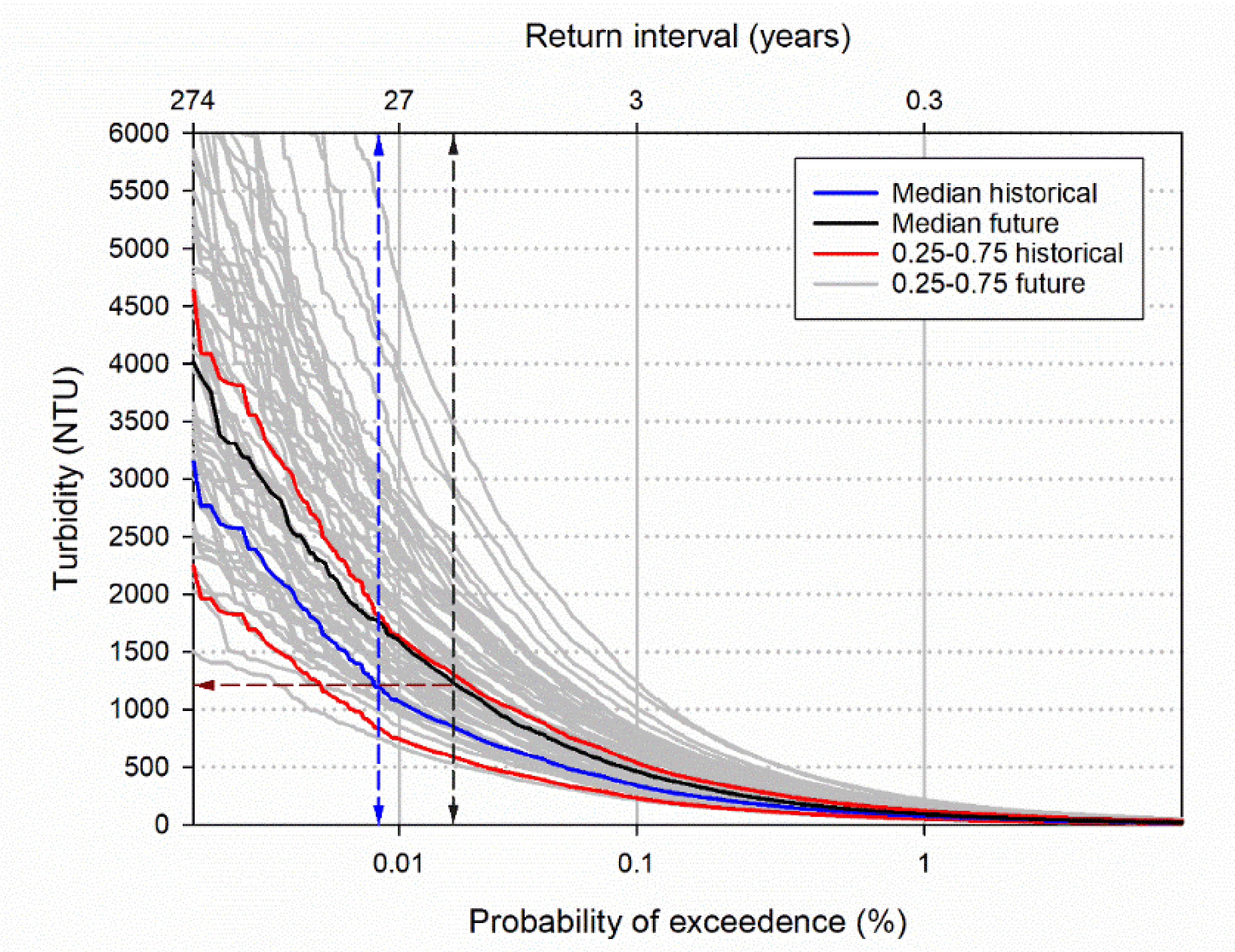


Figure 6.11 Projected changes in extreme (< 5% probability) stream turbidity values (daily average) in the Esopus Creek watershed for the mid-century period (2041-2060) compared to historical period (1950-2009). Probability of exceeding 1,200 NTU threshold (horizontal dash line) under historical (vertical blue dash line) and future (vertical black dash line) period is shown.

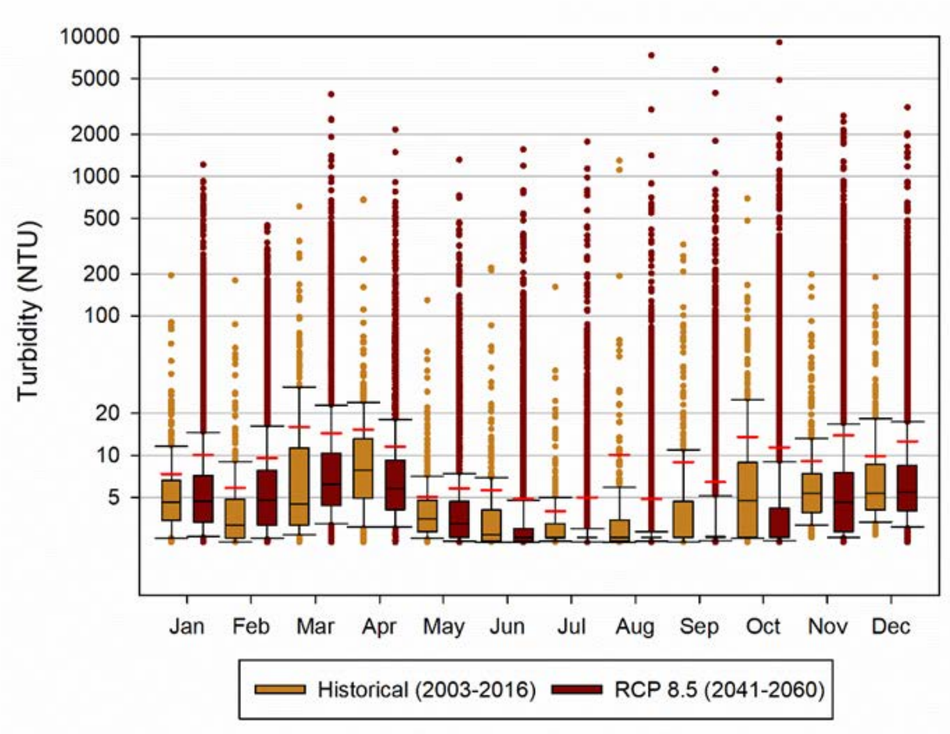


Figure 6.12 Comparison of simulated turbidity for Esopus Creek under historical (2003-2016) and future (2041-2060) climate using 20 GCMs. Red line is the mean. Outliers include all values above the 95th percentile.

6.10 Application of the Hydro-Ecologic Model RHESSys to simulate Streamflow, Organic Carbon, and Nitrate in Biscuit Brook

Understanding the sources, fate, and transport of dissolved organic carbon (DOC) in the NYC water supply watersheds remains an important area of study in the Water Quality Modeling section. A subset of the compounds that make up DOC in the source waters are precursors of disinfection by-products (DBPs). The DBPs are regulated compounds in the drinking water supplied to customers. Predicting the magnitude and variability of DOC over multiple time scales is important for managing water quality in the water supply system. DEP has supported the testing and application of the Regional Hydro-Ecological Simulation System (RHESSys) (Tague and Band 2004), a hydro-ecologic process-based model that is capable of predicting streamflow and DOC concentration/fluxes at multiple time scales. RHESSys includes spatially distributed and coupled water, carbon, and nitrogen cycling and transport. The model provides the spatial and temporal discrimination of sources in the watershed that are dependent on ecosystem composition and patterns, weather conditions, and disturbance. RHESSys is a physically based, spatially explicit model, and integrates forest ecosystem, hillslope hydrology, and DOC production, its mobilization and transport to stream. RHESSys has the ability to simulate the impact of various forest management practices, and the impact of invasive species in forested areas. An overview of the application of this model to Biscuit Brook, a 9.2-km^2 forested headwater catchment in the Neversink Reservoir watershed, is described here.

Three different setups of RHESSys that combine two levels of complexity for simulating ecosystem phenology and two assumptions regarding hydrologic connectivity were tested to find an appropriate model structure that yielded good predictions of streamflow and DOC export to streams. The first setup (Setup-1) assumes that the intra-annual vegetation phenology pattern is static from year to year with a fixed timing of green-up and senescence every year, and delivers deep groundwater directly to the stream channel without interaction with riparian zones. In the second setup (Setup-2), vegetation was simulated using a dynamic phenology calculation to simulate the inter-annual variations of intra-annual phenology pattern, i.e., different timing of green-up and senescence every year, depending on the environmental conditions. The final setup (Setup-3) includes the dynamic phenology calculation, and connectivity between deep groundwater storage and riparian zone, in which deep groundwater transports to riparian subsurface, maintaining higher subsurface flow to stream and shallower water table in the riparian zone. Nine hydrologic parameters in RHESSys were calibrated by comparing the simulated and measured streamflow. The predictive performance of the model is evaluated using three accuracy measures: a) Nash-Sutcliffe efficiency (NSE) coefficient for stream discharge, b) NSE coefficient for the log of discharge, (logNSE) and c) the percent error in the predicted volume of streamflow (PerErr).

Model comparison showed that incorporating dynamic phenology (Setup-2) improved model agreement with streamflow and DOC in the fall, compared with a static phenology approach (Setup-1). Incorporating the connectivity of riparian zone and deep groundwater storage with dynamic phenology (Setup-3) improves summer flow/DOC, compared with Setup-2. For daily DOC fluxes, Setup-3 showed higher model accuracy in daily DOC fluxes (Table 6.6). The time series of observed and simulated DOC in Biscuit Brook for two water years (1993 and 1997) using the three setups is shown in Figure 6.13. Based on this work Setup 3 will be used for this watershed.

Table 6.6 Accuracy of daily streamflow predictions for the Biscuit Brook watershed for three alternative setups of RHESSys.

Period	Accuracy	Setup-1	Setup-2	Setup-3
Calibration (Water Year 1993-1995)	NSE	0.30~0.58	0.30~0.59	0.30~0.60
	logNSE	0.30~0.68	0.30~0.73	0.30~0.72
	PerErr	-15.0~-10.6	-11.6~-1.3	-11.9~-1.7
Validation (Water Year 1996-2000)	NSE	0.30-0.42	0.30~0.44	0.30~0.46
	logNSE	0.31-0.67	0.55~0.71	0.45~0.74
	PerErr	1.4~4.4	11.7~14.8	6.7~14.8

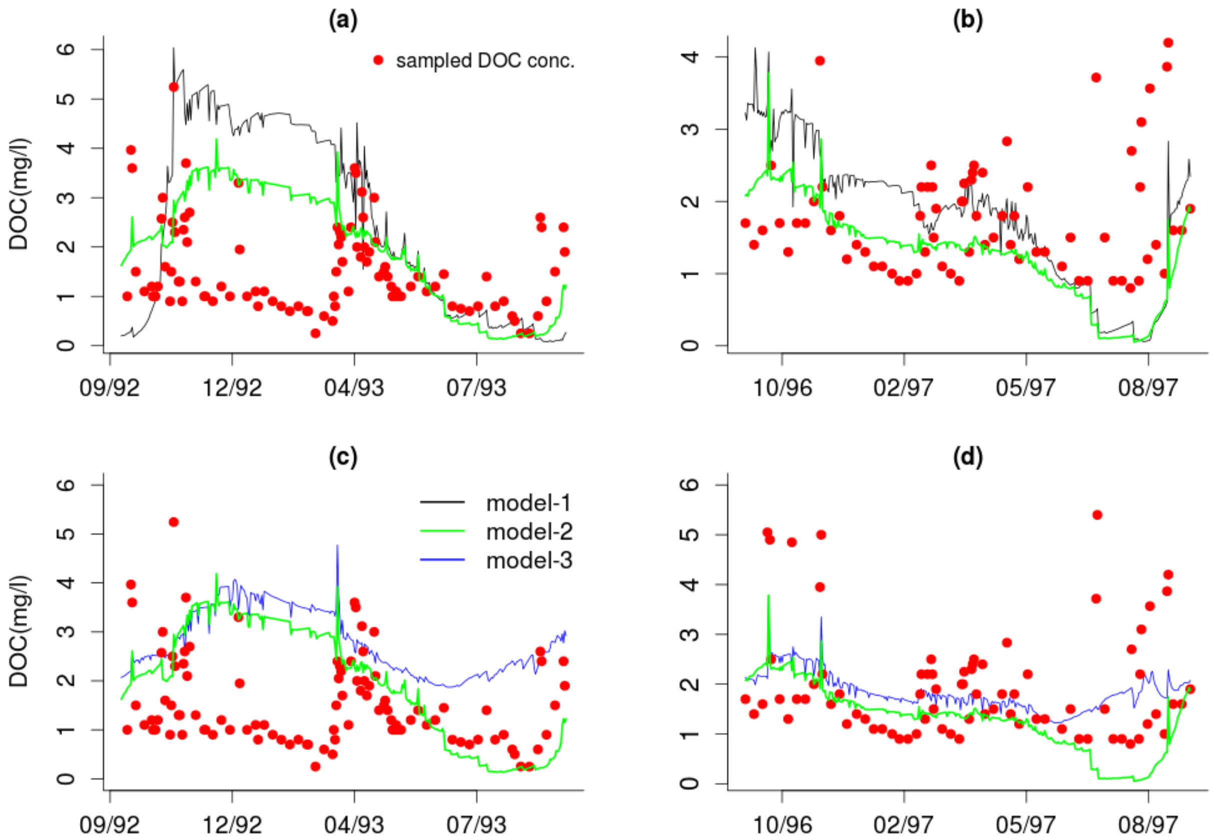


Figure 6.13 Comparison of the simulated and observed DOC concentration in water years 1993 and 1997: (a) and (b) comparison of Setup-1 and Setup-2 in 1993 and 1997, respectively, (c) and (d) comparison of Setup-2 and Setup-3 in 1993 and 1997, respectively. The simulation for each setup was made using the parameter set with the best streamflow accuracy.

6.11 Application of the General Lake Model/Aquatic Ecodynamics Model to Cannonsville Reservoir

The General Lake Model (GLM), a one-dimensional hydrothermal lake/reservoir model coupled with the water quality model Aquatic Ecodynamics (AED), was used to simulate the dynamics of temperature and water quality in Cannonsville Reservoir. The goal of this work was to validate the ability of GLM/AED to simulate the dynamics of eutrophication-related water quality that have occurred in Cannonsville Reservoir over the period of DEP’s watershed protection programs.

The model simulation period for this work was 1995-2010. Model inputs for the simulation of this historical period included updated bathymetry data (Section 6.2), meteorological data measured at the Cannonsville Dam, daily stream discharge, temperature, water quality data, and operations of the reservoir (drinking water diversion, intake depth, and dam release). Inflow from minor unmonitored streams was derived from a reservoir water balance. The model was operated at a daily time step. Observations of temperature and water quality in the water column and drinking water diversion during the open water season were used for calibration. Water column measurements of the following parameters were generally available at a bimonthly frequency: temperature, dissolved oxygen, chlorophyll, soluble reactive phosphorus, ammonia, nitrate and dissolved organic carbon. Model calibration was performed manually, using visual inspection of predictions and observations, as well as quantitative metrics for goodness-of-fit. Example simulations with the calibrated model are shown in Figure 6.14. The model captured the observed dynamics of soluble reactive phosphorus (SRP) and chlorophyll *a* over the 16-year period.

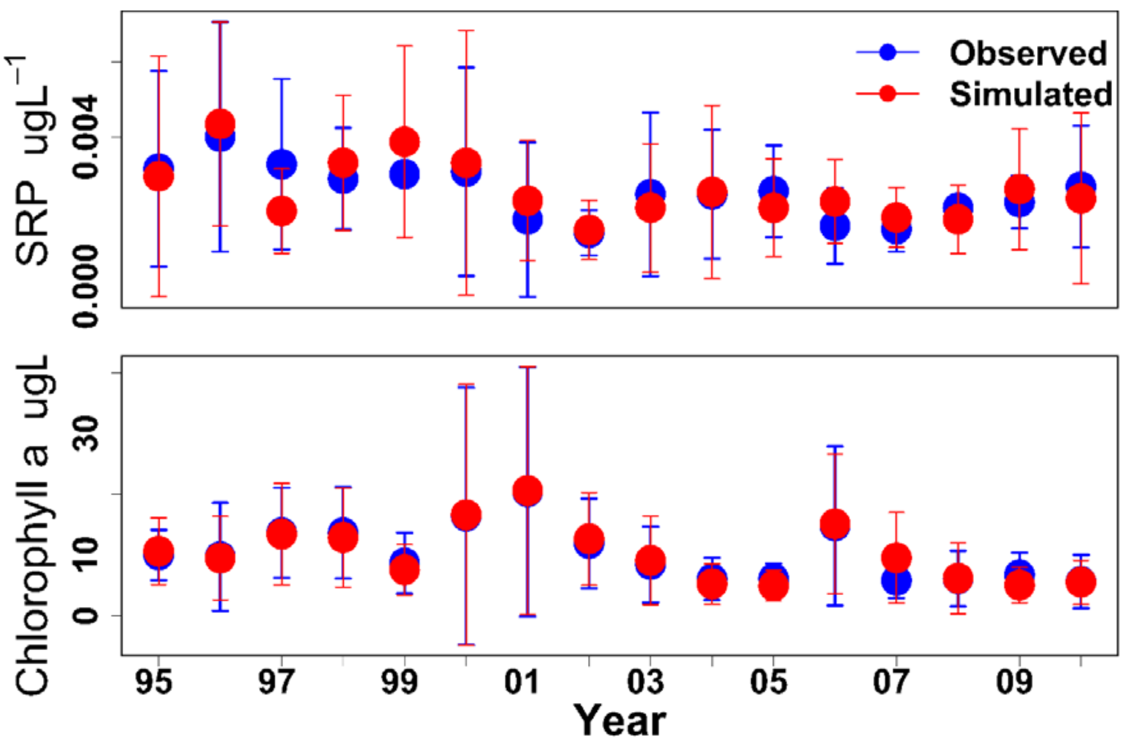


Figure 6.14 Observations and model simulations of soluble reactive phosphorus and chlorophyll *a* in the water column of Cannonsville Reservoir averaged over the depth and over each of the 16 years (circles) and the standard deviation in the depth-average concentrations over each year (bars).

The impact of nutrient reductions due to watershed protection are seen more clearly in the model predictions of sediment oxygen demand (SOD) and sediment release of SRP over the simulation period, which decreased over the simulation period.

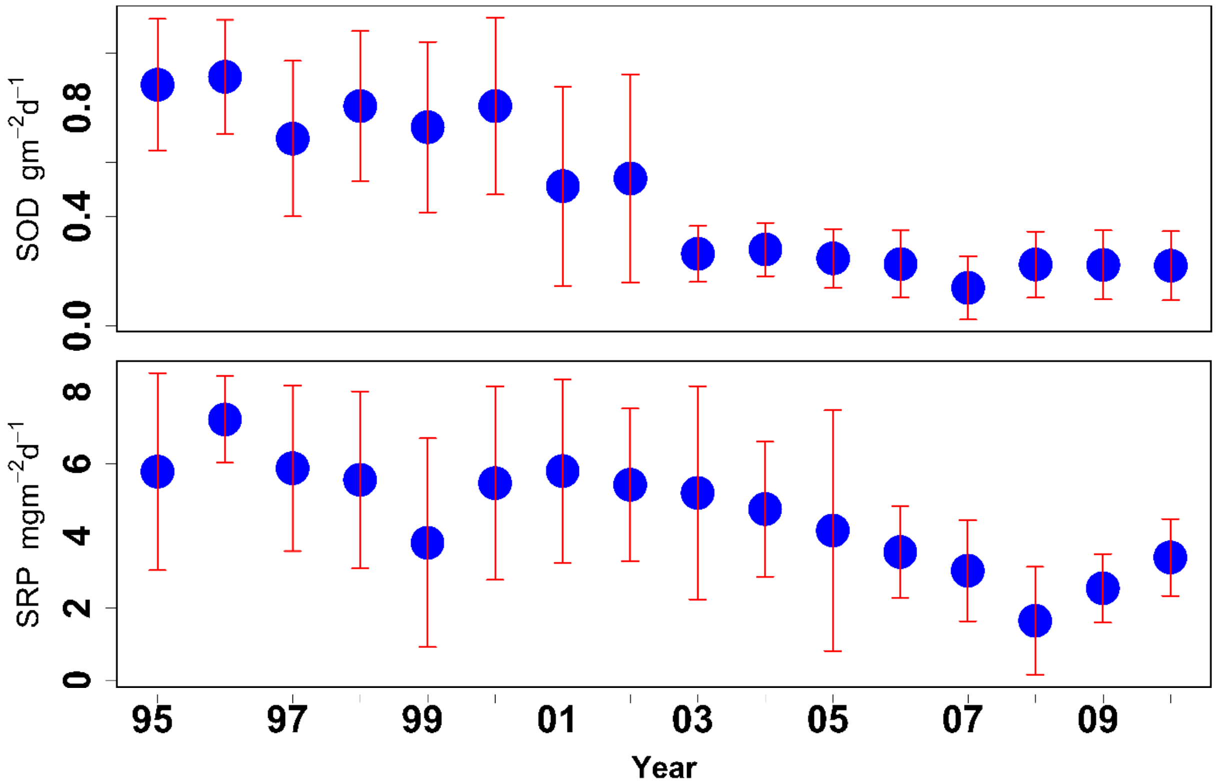


Figure 6.15 Model predictions of sediment oxygen demand (SOD) and sediment release of SRP over the period of simulation: circles are annual averages, bars represent the standard deviation over each year.

6.12 Regionalization Analysis of Observed Precipitation in the West of Hudson Watersheds

This research described here is a part of DEP's efforts to understand the potential impacts of climate change on the hydrologic cycle in the watersheds of the New York City water supply. The geographical and meteorological features of the Catskill region contribute to complex seasonal and spatial patterns of precipitation. In the context of regional impact studies, information on the spatial distribution of precipitation at a sufficiently high resolution is essential to allow calculation of local values of hydrologic variables, such as streamflow, using watershed models such as GWLF, Soil and Water Assessment Tool (SWAT), and RHESSys. Due to the high spatial variability of precipitation and relatively low density of rainfall or meteorological monitoring stations, the estimation and prediction of hydrologic variables is challenging.

Regionalization methods have been employed to understand the spatial pattern of precipitation, and to provide a basis to effectively transfer precipitation information from a location with sufficient observations to another where available records are scarce. More specifically, regionalization methods have been developed and employed with two main objectives: (1) identification of the extent of spatial dependency (homogeneity) in precipitation, and (2) reducing uncertainty in the estimation of precipitation processes at locations with short or no observations. Regionalization attempts to identify regions where spatial variations in precipitation are small; if two or more stations have similar statistical characteristics, then those stations are identified to belong to a delineated homogenous group. Regionalization has been found to be a powerful tool in the effort to improve the accuracy of precipitation estimation. Regionalization, the evaluation of the similarity of observed precipitation series at different locations, is a first step in this process.

Most existing regionalization methods determine the similarity of the statistical properties of precipitation at different locations based on the spatial correlation of precipitation amount. A limitation of conventional approaches based on precipitation amounts is that the resulting identified regions do not include information on spatial variation in precipitation occurrence (wet or dry). An improved regionalization technique based on the similarities of both rainfall occurrence and amount is described here, using the serial application of Principal Component Analysis (PCA) and Ordinal Factor Analysis (OFA). In particular, the use of OFA applied to precipitation occurrence adds spatial information that is unavailable from the use of PCA on precipitation amount alone. OFA is particularly appropriate for the analysis of binary or ordinal data, such as precipitation occurrence. The application of OFA here employs a tetrachoric correlation matrix to identify the spatial patterns of daily precipitation occurrence.

Data from precipitation stations in the Catskill region (Figure 6.16), within an area of about 31,000 km^2, were used here. The topography in this region includes ridges oriented from the southwest to northeast, as well as a southeast-to-northwest oriented escarpment defining the northeastern boundary of the region. Historical precipitation data from stations in this region were obtained from the Northeast Regional Climate Center and National Climatic Data Center. Precipitation data from the 11-year period from 1949-1959 were used here; this being the period of sufficiently long duration that had the largest number of active precipitation stations. PCA, followed by OFA, were applied to the 80 daily precipitation time series in order to identify homogeneous groups of daily precipitation stations. In the first step, four groups of stations were identified by PCA. OFA was then performed on each PCA group independently. The results of this two-step process are summarized in Figure 6.16. The 11 climatic regions (OR1 to OR11) are identified, where OR denotes regions defined by the two-step analysis. The watersheds of the West of Hudson water supply reservoirs fall within the first six regions (OR1 to OR6). It may be noted that the boundaries of the first six regions are reasonably consistent with the watershed boundaries of the six West of Hudson reservoirs. However, the identification of regions in this analysis considered no information on the location or elevation of the precipitation stations; only the time series of observed precipitation was used. The results from this analysis lay the groundwork for the development of a procedure to estimate precipitation at ungauged or partially gauged sites in and around the watersheds of the West of Hudson reservoirs.

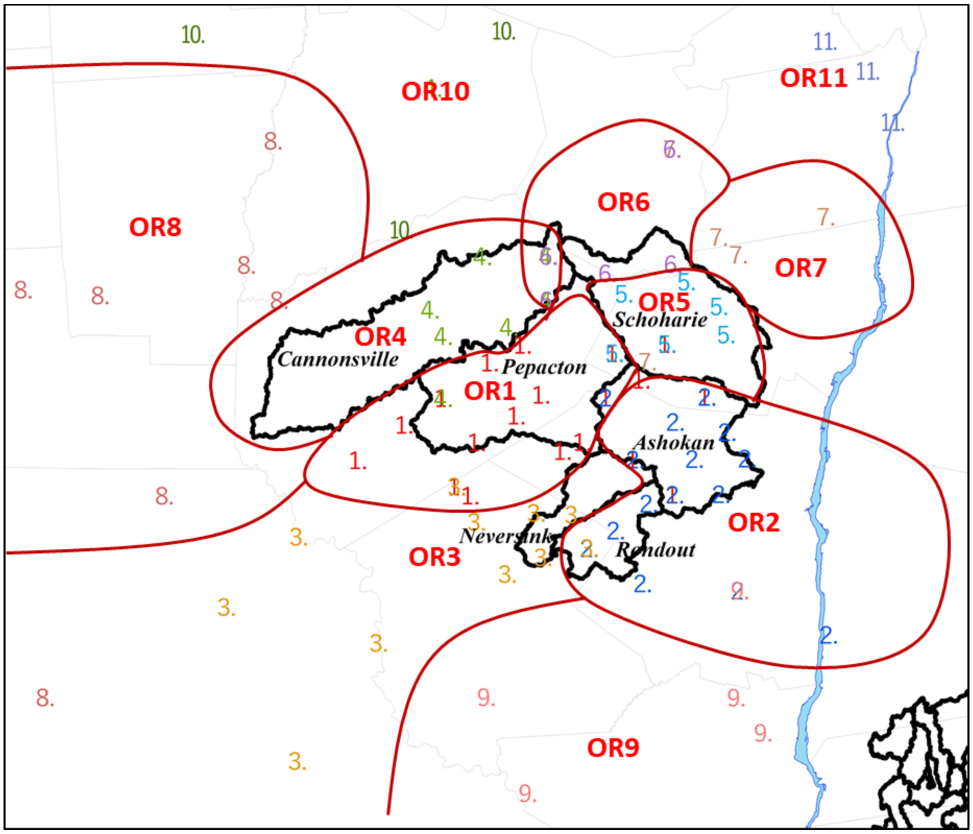


Figure 6.16 Regions of homogeneous daily precipitation as delineated by PCA/OFA, using precipitation data for 1949-1959. The numbers indicate the location of a precipitation gaging station, with the value of the number indicating the region in which the station is located. The red lines are the approximate boundaries between adjacent regions, numbered OR1 through OR11.

6.13 Application of SWAT-HS to Evaluate Watershed Protection in the Cannonsville Watershed

The successful testing of the SWAT-HS watershed model for the Town Brook catchment in the headwaters of the West Branch Delaware River was completed in 2016. In 2017, the model was scaled up in order to simulate the entire watershed of Cannonsville Reservoir. The Cannonsville watershed was delineated into 14 sub-basins using digital elevation data at a 10-meter resolution. Eight of the 14 sub-basin outlets were at locations of gauging stations operated by USGS, at water quality stations operated by DEP, or both. The seven USGS flow gauging stations are shown in Figure 6.17.

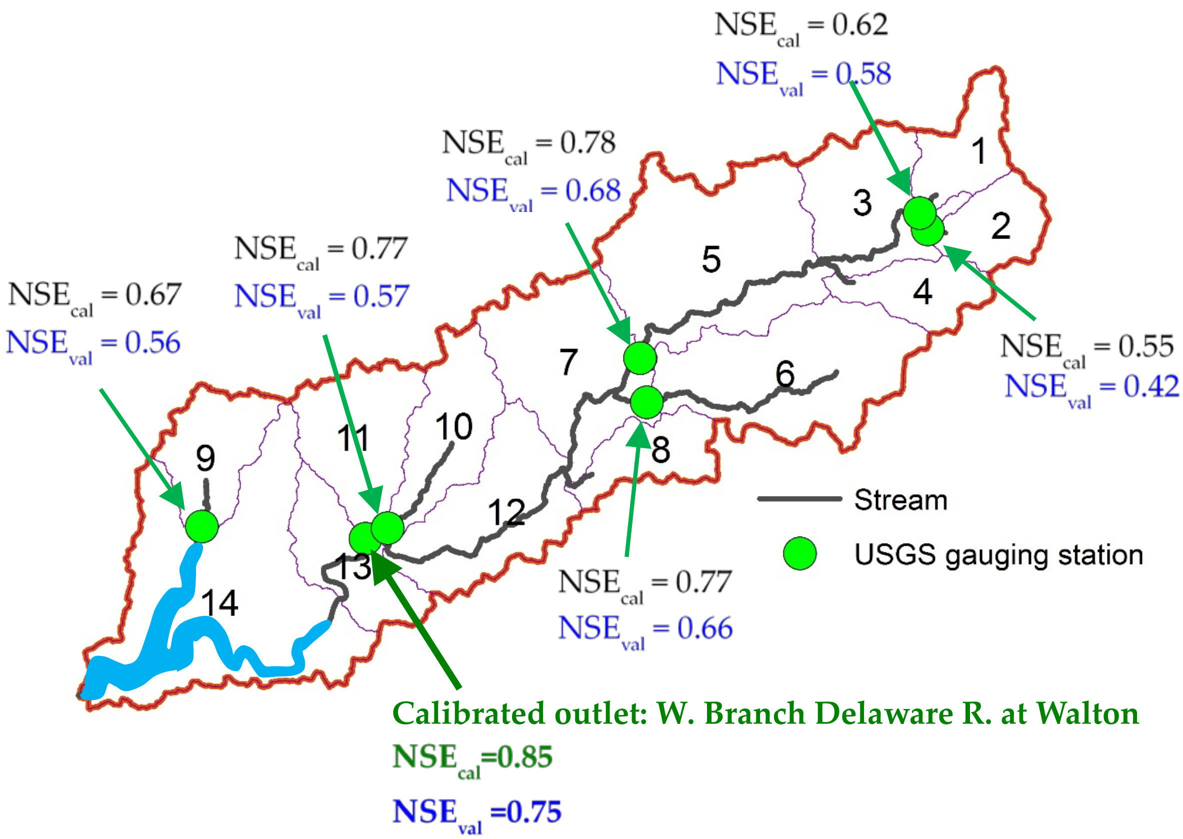


Figure 6.17 Goodness of fit of SWAT-HS simulations represented by Nash-Sutcliffe Efficiency (NSE) values at the calibrated station (at Walton) and at six other USGS stations during the calibration (NSE$_{cal}$) and validation (NSE$_{val}$) periods.

In the setup of SWAT-HS for the Cannonsville watershed, soil properties were derived from the Soil Survey Geographic (SSURGO) database. The dominant soil type in each wetness class (used by SWAT-HS to quantify variable soil moisture capacity) of a subbasin was chosen as the representative soil type of the wetness class. With this assumption, the setup of SWAT-HS for the Cannonsville watershed used eight soil types distributed over the watershed. Land use information was extracted from a land use map derived from 2009 aerial photography data. The Cannonsville watershed land use consists of forest (64%), agriculture (19%), shrubland (10%), residential areas (5%) and water bodies (2%). Agricultural lands were further categorized into three classes: pasture, cropland, and woodland covering 58%, 23% and 19% of the agricultural land, respectively. The Parameter-elevation Relationships on Independent Slopes Model (PRISM) climate data, available on a 4-km grid, were used for precipitation and air temperature inputs to drive the model. Model simulations were made for the period 1998 through 2012 in this study. The accuracy of the model predictions of daily streamflow at the seven USGS gaging stations in the watershed, including the West Branch Delaware River (the largest stream inflow to Cannonsville Reservoir) is shown in Figure 6.17. These results are generally judged very good.

Phosphorus (P) is known to be the limiting nutrient for phytoplankton growth in Cannonsville Reservoir. Streams in the Cannonsville watershed receive phosphorus from a variety of point and nonpoint sources. Point source P loads are from five publicly owned wastewater treatment plants (WWTPs; Stamford, Hobart, South Kortright, Delhi and Walton) and two small industrial plants. The Walton WWTP, which receives both domestic wastewater and food waste from a dairy processing facility, is the largest point source in the watershed. As a component of the Watershed Protection Program, upgrades to advanced (tertiary) wastewater treatment systems went online at these facilities in 2003 (Figure 6.18).

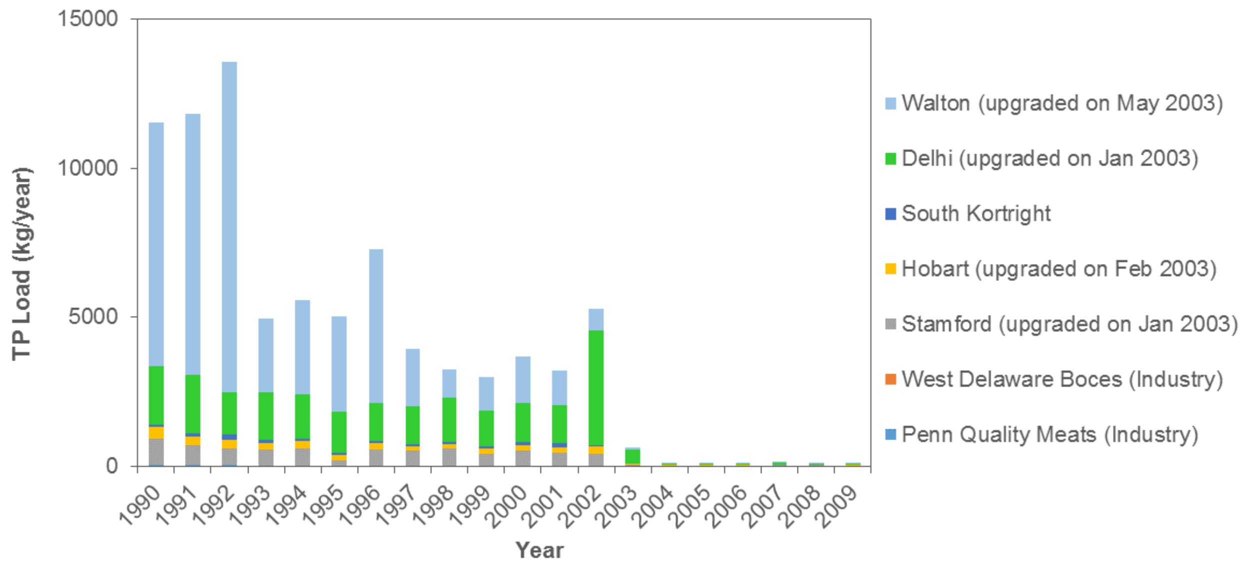


Figure 6.18 Total phosphorus load in effluent from WWTPs in the Cannonsville watershed from 1990-2009.

Two important nonpoint sources of P associated with dairy farming were specifically considered in this study: (i) fertilizer and manure applied to croplands, and (ii) manure deposited on the landscape by cattle. Best management practices to reduce P loading from these two sources were implemented as a part of whole farm plans. The initial phase of this implementation occurred from 1995 to 2001, with implementation continuing at present. The model inputs to SWAT-HS allow each of these two sources and the impact of management practices on the magnitude of these sources, to be quantified. A detailed description of this setup of the model is given in Hoang et al 2018. The accuracy of predictions of soluble and total P at the water quality monitoring station at Beerston on the West Branch Delaware River over the simulation period are shown in Table 6.7.

Table 6.7 Accuracy of SWAT-HS model predictions of soluble and total phosphorus (P) at Beerston, West Branch Delaware River, using three measures of accuracy.

Monthly loads	**Calibration**			**Validation**		
	NSE	KGE	r	NSE	KGE	r
Soluble P	0.76	0.74	0.88	0.36	0.27	0.82
Total P	0.90	0.74	0.97	0.56	0.70	0.76

NSE: Nash Sutcliffe Efficiency; KGE: Kling-Gupta Efficiency; r: correlation coefficient

Using the calibrated model, P contributions from point and nonpoint sources, and from nonpoint sources originating from different land uses in the watershed are quantified for the period 2001 to 2005 (Table 6.8). Nonpoint sources contribute approximately 97% of the soluble and particulate P load. Among nonpoint sources based on different types of land use, pasture and forest are the two dominant sources contributing 38% and 36% soluble P to the stream, respectively. These same results were used to determine the percent reduction in soluble, particulate, and bioavailable P loading that is due individually to point and nonpoint source management (Table 6.9). Due in large part to the dominant contribution of nonpoint sources over the 2001-2007 time interval, the nonpoint source controls on P load were predicted to have had the greatest impact on both soluble and particulate P loading.

Table 6.8 Loading of soluble and particulate phosphorus (P).

		Land use types	**Areal percentage (%)**	**Soluble P**		**Particulate P**	
				Load (ton/year)	*Percent (%)*	*Load (ton/year)*	*Percent (%)*
Point sources			-	0.37	3.22	1.49	2.48
Nonpoint sources	**Farm areas**	Cropland	4.42	0.78	6.78	19.7	32.8
		Pasture	11.0	4.39	38.2	21.8	36.2
		Woodland	3.67	0.25	2.17	6.52	10.8
	Non-farm areas	Forest	63.7	4.16	36.2	3.24	5.39
		Shrubland	10.3	0.73	6.35	2.65	4.41
		Urban	4.87	0.48	4.17	2.70	4.49
		Septic system	0.05	0.01	0.09	0.01	0.02
		Water bodies	2.11	0.33	2.87	2.05	3.41
P load from nonpoint sources				11.1		58.7	
P load from point and nonpoint sources				11.5		60.4	

Table 6.9 Simulated average reduction in soluble, particulate, and bioavailable P loads during the period 2001-2007, considering upgrades at wastewater treatment plants (point source reductions) and two components of nonpoint source watershed protection.

Average load (ton/month)	**Point and nonpoint**	**Point source only**	**No WPP**	**Percent of P reduction (%) by**	
				Point source reductions	*Nonpoint source WP*
Soluble P	0.76	0.98	1.04	6	21
Particulate P	5.87	9.19	9.40	2	35
Bioavailable P	2.87	4.29	4.42	3	33

6.14 A Comparison of SWAT and RHESSys Hydrologic Model Predictions for Town Brook and Biscuit Brook

A model inter-comparison study was completed in order to compare streamflow simulations from two watershed models that have been applied and tested by the Water Quality Modeling section. The two models are: (1) RHESSys, a hydrologic modeling framework that requires detailed spatial input and high computational requirement, and (2) SWAT-HS, a semi-distributed model requiring less detailed spatial input as well as lower computational requirements. Both models were setup for Biscuit Brook, a 9.2-km^2 forested catchment in the Neversink watershed, and Town Brook, a 37-km^2 catchment in the Cannonsville watershed with a significant portion (32%) of agricultural land. Results of streamflow simulations by the two models and comparison with observed streamflow are presented in Figure 6.19, Table 6.10, Figure 6.20, and Table 6.11.

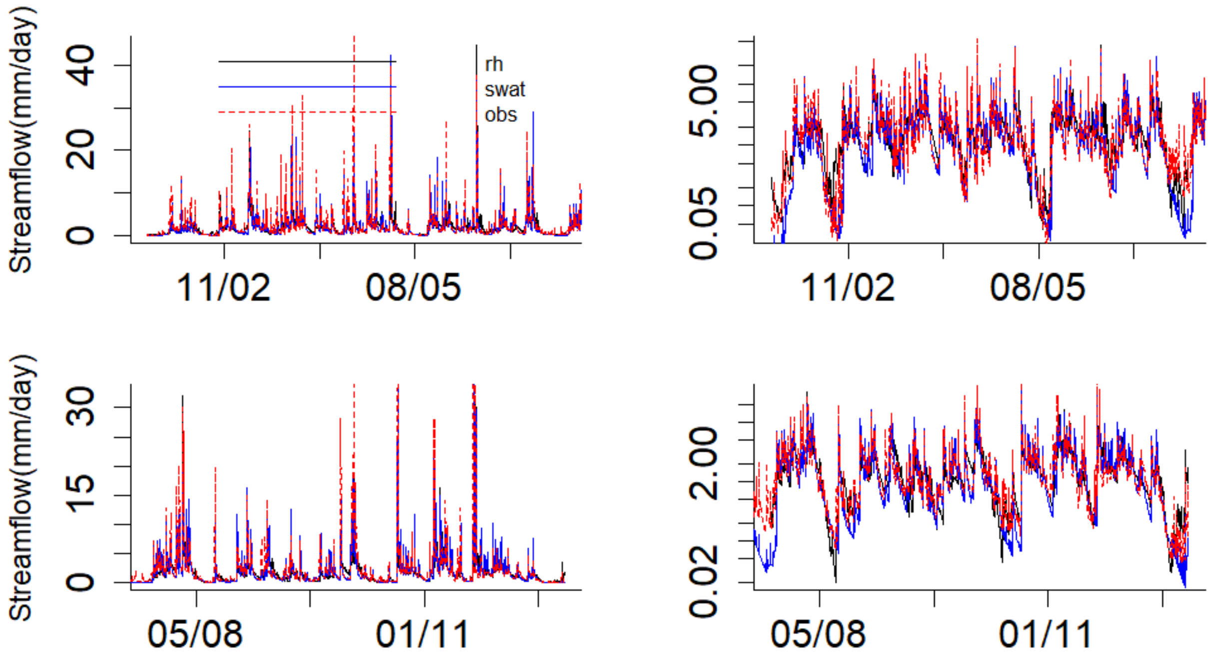


Figure 6.19 Streamflow predictions for Town Brook using SWAT-HS and RHESSys during (a) calibration period and (c) validation period. Streamflow is also shown on a log-scale for the (b) calibration and (d) validation period.

Table 6.10 Model performance statistics for daily streamflow prediction in Town Brook.

Period	**Statistic**	**SWAT-HS**	**RHESSys**
Calibration	NSE	0.68	0.55
(WY 2002-2007)	NSE log	0.66	0.69
	Volume error (%)	-16	-13
Validation	NSE	0.56	0.46
(WY 2008-2012)	NSE log	0.70	0.70
	Volume error (%)	-7	-13

NSE: Nash-Sutcliffe Efficiency

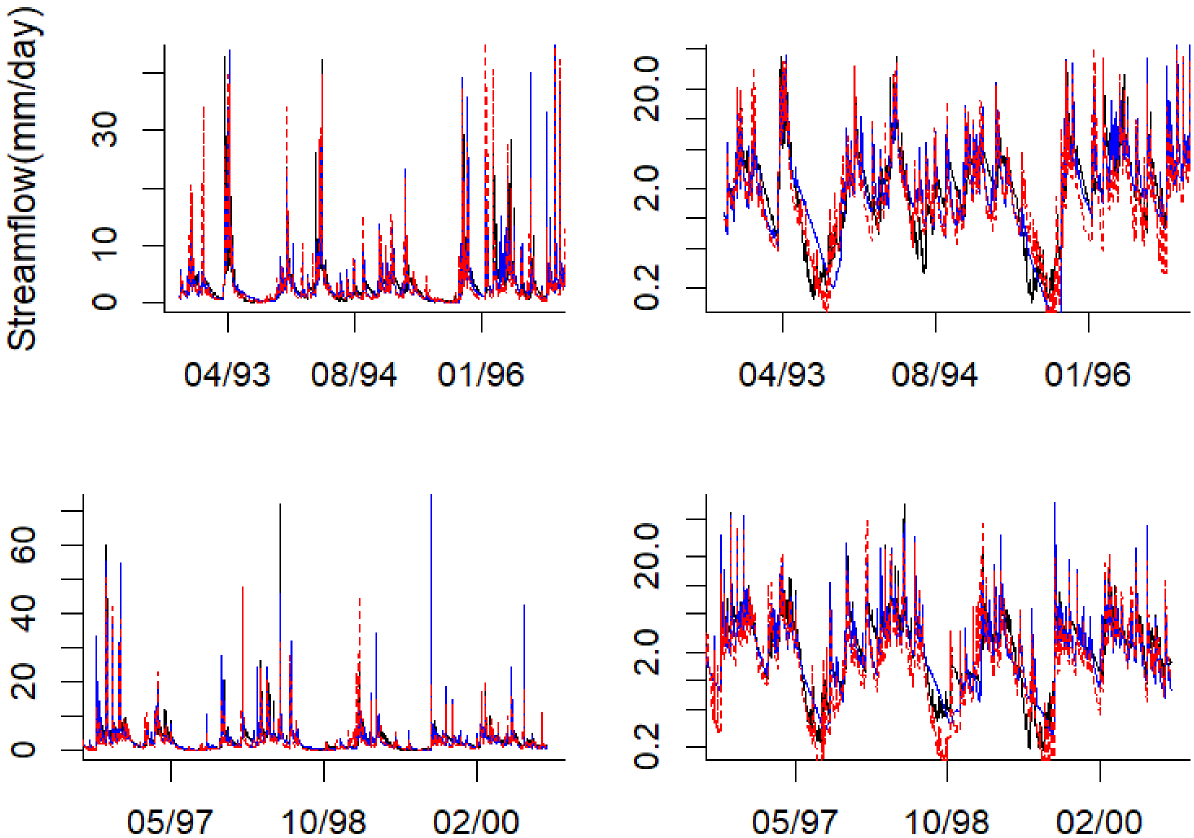


Figure 6.20 Streamflow predictions for Biscuit Brook using SWAT-HS (blue) and RHESSys (black) during (a) calibration period and (c) validation period. Streamflow is also shown on a log-scale for the (b) calibration and (d) validation period. Observed streamflow is shown in red.

Table 6.11 Model performance statistics for daily streamflow prediction in Biscuit Brook.

Period	**Statistic**	**SWAT-HS**	**RHESSys**
Calibration	NSE	0.63	0.40
(WY 1993-1995)	NSE log	0.74	0.62
	Volume error (%)	5.0	3.0
Validation	NSE	0.42	0.45
(WY 1996-2000)	NSE log	0.70	0.67
	Volume error (%)	12	15

NSE: Nash-Sutcliffe Efficiency

The model inter-comparison exercise showed that overall SWAT-HS gave more accurate predictions of streamflow than RHESSys (Table 6.10 and Table 6.11) although both models were able to capture the magnitude of variation in streamflow (Figure 6.19 and Figure 6.20). There are specific areas where RHESSys performed better than SWAT-HS such as simulation of low flow and overall streamflow accuracy in summer and fall for Biscuit Brook when the timing and magnitude of forest water use and phenology are important.

Modeling using RHESSys in NYC watersheds so far has been limited to Biscuit Brook (drainage area 9.2 km^2), Town Brook (37 km^2), and Shelter Creek (1.61 km^2). Part of the reason for this is the need for detailed model input and the computational resources needed to run the model. Scaling-up to the six West of Hudson (WOH) watersheds having drainage areas in the range of 100 to 900 km^2 can thus be challenging. This is an important issue that needs to be resolved if RHESSys is to be used in simulating DOC loading into reservoirs for subsequent predictions of DBP formation potential. On the other hand, recent developments in the SWAT model include the ability to simulate stream DOC. Another issue is that compared to all other watershed/reservoir models currently being used by DEP that run on a standard Windows operating system, RHESSys model set up and simulation has to be done in the Linux or Mac-OS operating system. This brings in the additional challenge of non-transferability of models for making simulations in other machines/modeling servers. The detailed results from the model inter-comparison study, which were summarized here, will be used to help decide how RHESSys will be used in the future work in the Water Quality Modeling section.

6.15 Annual Water Quality Modeling Progress Meeting with Regulators

A requirement for the Water Quality Modeling program that is included in the new 2017 Filtration Avoidance Determination is to hold an annual progress meeting with state and federal regulators to present and discuss water quality modeling results. The first of these annual meetings was held on November 8, 2017, at the Kingston office of DEP. Four representatives from NYSDOH and one from USEPA attended the meeting. The agenda for that meeting was:

1. Overview of the Water Quality Modeling Program
    a. Staff and CUNY Post-Doctoral Researcher Introductions
    b. Current Status and Future Plans – CUNY-NYCDEP contract to support water quality modeling
    c. New FAD requirements: this meeting; Annual modeling report to become a part of Watershed Water Quality Annual Report (next submission July 2018)
    d. National Academy of Sciences Expert Panel Reviews: (1) Operations Support Tool (current); (2) Watershed Protection Programs (to begin in 2018)
    e. Status report on individual models
    f. Status of Climate Change Integrated Modeling project (CCIMP)
2. Climate: Stochastic Weather Generator – Chris Yeo
3. Application of GWLF to West of Hudson Watersheds using Stochastic Weather – Rajith Mukundan
4. Application of Soil Water Assessment Tool (SWAT) to Town Brook and the Cannonsville Watershed –Linh Hoang

5. Application of Regional Hydro-Ecologic Simulation System (RHESSys) to Biscuit Br. and Shelter Cr. – Kyongho Son
6. Bathymetric Data Collection: West of Hudson (completed); East of Hudson (underway) – Jordan Gass
7. Turbidity Model Development for Rondout and Neversink Reservoirs –Rakesh Gelda
8. Regular Operations Support Tool (OST) Model Runs – Rakesh Gelda
9. Organic carbon model for Cannonsville and Neversink Reservoirs – Theo Kpodonu
10. Mass balance analysis and modeling approaches for THM precursors – Emmet Owens

6.16 Water Quality Modeling: Publications and Presentations in 2017

6.16.1 Peer-Reviewed Publications

The following papers written by members of the Water Quality Modeling section were published in peer-reviewed journals in 2017:

Acharya, N., A. Frei, J. Chen, L. DeCristofaro, and E. M. Owens, 2017. Evaluating Stochastic Precipitation Generators for Climate Change Impact Studies of New York City's Primary Water Supply, *Journal of Hydrometeorology* 18:879-896.

Hoang, L., E.M. Schneiderman, R. Mukundan, K. E. Moore, E. M. Owens, and T. S. Steenhuis, 2017. "Predicting saturation-excess runoff distribution with a lumped hillslope model: SWAT-HS" *Hydrologic Processes* 31(12):2226-2243.

Frei, A., and P. Kelly-Voicu, 2017. Hurricane Irene and Tropical Storm Lee: how unusual were they in the Catskill Mountains? *Journal of Extreme Events*, Vol. 4, No. 2 (2017),
DOI: 10.1142/S2345737617500099.

6.16.2 Conference Presentations

Members of the Water Quality Modeling section made the following presentations at scientific and professional conferences and workshops in 2017:

Son, K., E. M. Owens, L. Lin and L. E. Band: "RHESSys model predictions of streamflow dissolved organic carbon and forest leaf dynamics in a New York City water supply watershed". Gordon Research Conference, Lewiston, Maine, June 2017.

Owens, E. M., and A. Frei. "Modeling the Effect of Climate Change on the New York City Water Supply" American Water Resources Assoc. Conference, Climate Change Solutions: Collaborative Science Policy and Planning, Tysons VA, June 2017.

Hall, D., N. DiGirolamo, and A. Frei. Contribution of Lake-Effect Snow to the Catskill Mountains Snowpack, Proceedings of the 74th Eastern Snow Conference, Ottawa, Ontario, Canada, June 2017.

Son, K., E. M. Schneiderman, E. M. Owens, L. Lin and L. E. Band: " Impact of forest harvesting on streamflow in Neversink Reservoir streams, New York City", Watershed Science and Technical Conference, Saugerties, NY, September 2017.

Gelda, R. K. "Development and Testing of a Turbidity Model for Neversink Reservoir, Watershed Science and Technical Conference, Saugerties, NY, September 2017.

Mukundan, R., R.K. Gelda, and E. M. Owens. "A framework for "bottom-up" based climate change impact assessment for NYC watersheds". Watershed Science and Technical Conference Saugerties, NY, September 2017.

Owens, E. M. "A Model of the Internal Seiche in Schoharie Reservoir", Watershed Science and Technical Conference Saugerties, NY, September 2017.

Kpodonu, T. "Modeling of Dissolved Organic Carbon in Cannonsville and Neversink Reservoirs using GLM-AED", presented at DOC/DBP Workshop, 19th Meeting of the Global Lake Ecological Observatory Network, Mohonk NY, November 2017.

Owens, E. M. "Modeling Approaches for Disinfection Byproduct Precursors in NYCDEP Reservoirs", presented at DOC/DBP Workshop, 19th Meeting of the Global Lake Ecological Observatory Network, Mohonk NY, November 2017.

Mukundan, R., M. Scheerer, R.K. Gelda, and E. M. Owens. Probabilistic Estimation of Stream Turbidity under Climate Change Scenarios. American Geophysical Union Fall Meeting, New Orleans, LA, December 2017.

L. Hoang, R. Mukundan, K. E. Moore, E. M. Owens, and T. S. Steenhuis, "Evaluating watershed protection programs in New York City's Cannonsville Reservoir source watershed using SWAT-HS", American Geophysical Union Fall Meeting, New Orleans, LA, December 2017.

7. Further Research

The analytical, monitoring, and research activities of DEP are supported through a variety of contracts, 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 Observation Network (GLEON). 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. The on-going contracts and projects in which WQD is involved are described below.

7.1 Contracts Managed by the Water Quality Directorate in 2017

In 2017, the WQD managed 10 water quality-related contracts to enhance its ability to monitor and model the watershed. The contracts supported surveillance, model development, and management goals. A brief description of each contract is provided below.

7.1.1 Laboratory Analytical Support Contracts

Eurofins Eaton Analytical Inc. (EEA): EEA conducts various analyses to support monitoring efforts of DEP laboratories. In 2017, EEA analyses for DEP included algal toxins on aqueduct and reservoir samples; total and volatile solids on some aqueduct samples, volatile organic carbon (VOC), semivolatile organic carbon (SVOC) and glyphosate analyses on selected aqueduct samples. Total Kjeldahl nitrogen, methylene blue active substance (MBAS), total dissolved solids (TDS), low level mercury, cyanide, and purgeable organics analyses were performed on wastewater samples. This contract is managed by DEP's Distribution Water Quality Operations Laboratory.

Source Molecular Laboratories: As part of studying routine samples and storm events, which had elevated fecal coliform or protozoan levels, samples were sent to this laboratory for microbial source tracking analysis.

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 results were used to calculate metrics and Biological Assessment Profile scores for each stream as reported here.

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

DEP contracted with the United States Geological Survey (USGS) for a project titled, "Water Quality Operation and Maintenance for the Hydrological Monitoring Network." Under this agreement, the USGS measures stage and discharge at 58 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 stream flow; 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 stream flow data, and (6) preparing an annual summary report. The data support DEP's development of multi-tiered water quality models, which is a requirement of the revised 2007 Filtration Avoidance Determination (FAD) (NYSDOH 2014). The data also support the following FAD-mandated 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 Support

Work continued on the four-year water quality modeling support contract between DEP and the City University of New York-Research Foundation (CUNY-RF) in 2017. This contract provides support for the Water Quality Directorate in the analysis and use of water quality data, development of new models, enhancement of existing models, and application of models for water quality management and water system operation. The contract supports four post-doctoral researchers who work full-time in the NYCDEP Water Quality Modeling office in Kingston, and four associated faculty advisors.

The topics that are the focus of work by the researchers and associated faculty advisors are the following:

- Climate data analysis and modeling
- Watershed runoff and nutrient modeling
- Ecohydrologic modeling of forested watersheds
- Reservoir modeling of organic carbon, precursors of disinfection byproducts, and eutrophication

The four post-doctoral positions were filled for nearly all of 2017; the reservoir modeling post doc started work in min-January 2017, while the climate modeling post doc began in early February 2017. This contract has been very successful, leading to significant progress in all four research areas. In 2017, three peer-reviewed publications and five conference presentations were made by the post-doctoral researchers and advisors. These publications and presentations are included in the listings for the Water Quality Modeling program in Section 6.

7.1.4 Waterfowl Management

The Waterfowl Management Program (WMP) was developed in response to seasonal elevations of fecal coliform bacteria 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 re-bid 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), with Henningson, Durham & Richardson, requires staffing of up to 25 contractor personnel annually to cover waterfowl management activities at several upstate reservoirs. It is intended to run through July 30, 2018 with an option to renew under the same terms for an additional two years through July 30, 2020.

7.1.5 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. West of Hudson reservoirs are monitored less frequently (July and October) due to lower calcium levels and less chance of colonization. The current lab, APTIM, examines integrated (0-5m) pump and plankton net samples to monitor for veligers as well as solid substrate and bridal veil substrates to monitor for juveniles and adults. The contract laboratory analyzes the samples and provides a monthly report to the project manager indicating whether or not zebra mussels have been detected. To date, no infestations have been found.

7.1.6 Bathymetric Surveys of Reservoirs

Under an inter-governmental agreement with United States Geological Survey (USGS), bathymetric surveying work was conducted on the six WOH reservoirs from 2013-2015. The USGS employed a single-beam echosounder to survey evenly spaced transects across each reservoir, with an average spacing between transects of between 100-150 meters. Additional, more closely spaced overlapping transects were completed near reservoir spillways and intakes to improve local data quality in those areas. In 2017, USGS submitted the draft report to DEP for review and comment. DEP requested additional information on the accuracy assessment of the project prior to final publication, which was scheduled for 2018.

A separate inter-governmental agreement with the USGS was initiated in 2015 to survey the bathymetry of the 13 EOH reservoirs and three controlled lakes. The contract was registered in 2018, and fieldwork commenced in May. During the field season, USGS staff were able to complete initial data collection for 10 of the 16 reservoirs and controlled lakes, as well as eagle nesting protection areas on the remaining 6 reservoirs. The USGS began data cleaning and processing in the late fall and winter of 2017. All field work should be completed in 2018, and final data delivery is due by 2020. The EOH reservoirs will be surveyed using a multibeam echosounder, which will improve accuracy throughout the reservoir with better coverage than transect-based surveys. The spatial data and information delivered under these contracts will help DEP to more accurately regulate storage in the reservoirs and to improve water-quality models used in reservoir management.

7.1.7 WISKI Software Support Contract

DEP has continued to expand and enhance usage of the WISKI software to collect and view fixed point as well as continuous on-line data 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 systems that supply 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 7.4.5, and the new ESRI Portal is operational with plans to upgrade to portal 10.6. New work will allow for creating "Heat Maps" of select datasets on the Portal to better represent areas of interest. New weather stations in the distribution system along with Doppler radar are aiding in tracking flooding and scheduling of BWSO crew work during heavy rain events. Harbor Buoy monitoring build out is nearing completion.

7.1.8 *Cryptosporidium* Infectivity Analysis for Hillview; University of Texas Public Health Laboratory Contract

The current method DEP uses for determining the presence of *Cryptosporidium* in water (USEPA Method 1623.1 with EasyStain) does not determine viability, infectivity, or the genotype of the oocysts observed within samples. The oocysts are conservatively counted and recorded. This, however, may lead to an overestimation of risk to public health since oocysts counted may be dead, non-infectious, or not a genotype associated with human illness.

Based on the data analysis completed in 2017, CC-IFA infectivity testing of both *C. parvum* and *C. hominis* in the Hillview sample matrix has indicated comparability to control samples and the ability to detect low levels of oocysts. While seasonal effects may need to be studied during various times of the year, the results indicate that this method is appropriate for further evaluation of the infectivity of oocysts at Hillview Reservoir.

7.2 Water Research Foundation Project Participation by WQD in 2017

The Water Research Foundation (www.waterrf.org) is "the leading research organization advancing the science of all 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 Participating Utility in order to remain current with cutting-edge research for the benefit of the City’s drinking water. The current projects in which WQD is involved are described below.

7.2.1 WRF Project 4386: Decision support program for reducing Endocrine Disrupting Contaminants (EDCs) and Pharmaceutical Products (PPCPs) in Drinking Water

The objective of this project is to develop a computerized decision support system to guide water and wastewater utilities in determining the most cost-effective measures for reducing consumer exposure to endocrine disrupting compounds, pharmaceuticals, and personal care products (EDCs/PPCPs) in drinking water. WRF & Arcadis are in the process of setting up the online tool to be publicly accessible and WRF has purchased a domain name for it. The online tool and user’s manual are the final products for this project. C. Glaser is a member of the Project Advisory Committee (PAC) for this project.

7.2.2 WRF Project 4568: Evaluation of Innovative Reflectance-Based UV for Enhanced Disinfection and Enhanced Oxidation

This project began June 30, 2014. The objective of the project was to evaluate the NeoTech Aqua Solutions, Inc. (NeoTech) reflectance-based UV technology to determine the effectiveness and energy efficiency (energy use per volume of treated water) on the inactivation of microorganisms. Additionally, a specific comparison of the energy efficiency observed with the NeoTech reactor as compared to the existing UV system at the EBMUD Walnut Creek Water Treatment Plant (WTP) that hosted the biodosimetric testing, and other available UV systems was done. This is relevant to DEP because the City operates a large UV plant and any advances in technology, or reduction in energy usage would be something for the agency to consider. The final report was published in 2017 (WRF, 2017). It stated: “the innovative reflectance-based UV system from NeoTech shows promise for energy efficient disinfection.” It is recommended that UV reactors that rely on wall reflections for UV dose delivery monitor and account for changing wall reflections. The potential benefits of wall reflections should be explored further as the technology continues to develop.” C. Glaser, was a member of the PAC for this project.

7.2.3 WRF Project 4590: Wildfire Impacts on Drinking Water Treatment Process Performance: Development of Evaluation Protocols and Management Practices

The objective of this project is to expand the knowledge base regarding the effects of wildfire on drinking water quality, treatment, plant performance, and operations. Specifically, this project will address three important components: (1) assess the impact that a wildfire has on source water quality within a recently-impacted watershed, (2) develop and apply a lab-based approach to simulate the effects of a wildfire on water quality (e.g., disinfection by-products and turbidity) and treatability, and (3) evaluate the implications of a wildfire for full-scale operation and design of treatment systems. To date all soil and forest litter samples have been collected, processed, and analyzed. The final report is expected to be published in 2018. R. Van Dreason is a member of the PAC for this project.

7.2.4 WRF Project 4616: Hospital Discharge Practices and Contaminants of Emerging Concern in Water

This project began January 1, 2016. The research team continued work on a literature review to evaluate the current regulatory status for controlling discharges of Contaminants of Emerging Concern (CECs) in hospital wastewater, the wastewater treatment technologies currently employed in healthcare facilities, and best available technologies for managing CECs in hospital wastewater. In addition, the research team continues its effort to increase the number of responses to their survey from WWTPs and hospitals. A time extension was requested in order to obtain additional data. S. Neuman is a member of the PAC for this project.

7.2.5 WRF Project 4663: Upgrading Workforce Skills to Meet Demands of an Intelligent Water Network

This project began in February 2016 and over the past year the scope was refined to focus on intelligent water operations. The project efforts are expected to meet the following key objectives: 1) articulate anticipated changes in water industry that will materially affect the workforce; 2) understand the industry's views on the future of the industry and workforce and resulting changes to workforce-related processes, and; 3) give recommendations on how to address them and facilitate collaboration between utilities and key stakeholders. A workshop was held in 2017. The final product will be a report that contains a state of the industry review, proposed worker profiles, identification of workforce gaps, and proposed solutions to workforce gaps. L. Emery is a member of the PAC for this project.

7.2.6 WRF Project 4664: Customer Messaging on Plumbing Systems

The objective of this project, which began in July 2016, is to develop customer messaging for water utilities about the potential risks of opportunistic pathogens in plumbing systems. On May 3-4, 2017, participants from 19 organizations across the country met at a Water Research Foundation sponsored workshop to discuss utility communication strategies for the development of a basic messaging system for the assessment, prevention and treatment of *Legionella* in building water systems. The aim was to develop a message platform for reducing the risk of *Legionella* depending on the target audience which included single family residential, multifamily residential, commercial, retail, industrial, institutional, healthcare, hospitality, etc. Guidance was provided to address the challenges of reaching target audiences and developing relationships/outreach opportunities between utilities and building/facilities managers. The project is scheduled for completion summer 2018. A. Capetanakis is a member of the PAC for this project.

7.2.7 WRF Project 4713 Full Lead Service Line Replacement Guidance

An RFP was issued for this project in 2016, and submissions were due May 17, 2017. The objective of this project is to evaluate strategies to reduce lead exposure after conducting full lead service line replacements. The City is currently only responsible for the replacement of lead service lines at City-owned properties, but long term revisions to the Lead and Copper Rule may change the requirements. Additionally, DEP is interested in being proactive when it comes to protecting customers from at-the-tap lead exposure, and is investigating options to mitigate lead exposure, including possibly subsidizing and/or offering loans for lead service line replacement. Conwell Engineering was selected for the project in July 2017. The 2nd Periodic Report and PowerPoint presentation Protocols were completed. C. Glaser is a member of the PAC for this project.

7.3 Water Utility Climate Alliance (WUCA): Piloting Utility Modeling Applications (PUMA)

In 2017, DEP continued its participation in the Water Utility Climate Alliance (WUCA), a consortium of 12 large water utilities in the United States that are concerned with climate impacts on their drinking water supply. DEP has been a member of WUCA since its inception in 2007. During 2017, Austin Texas Water and the Philadelphia Water Department joined WUCA and are now members along with Central Arizona Water, Denver Water, Metropolitan Water District of Southern California, DEP, Portland Water Bureau, San Diego County Water Authority, San Francisco Public Utilities Commission, Seattle Public Utilities, Southern Nevada Water Authority, and Tampa Bay Water. WUCA was formed with the goal of enhancing climate change research and improving water management decision-making to ensure water utilities will be positioned to respond to climate change and protect our water supplies. The group provides leadership and collaboration on climate change issues. DEP benefits from this information exchange among utilities by keeping current with climate change information and evaluation and in long-term planning in the context of water supply. DEP's designated representative to WUCA is Alan Cohn from the Bureau of Environmental Planning and Analysis (BEPA). Staff from Water Quality Science and Research regularly participate in WUCA activities.

Alan Cohn and Emmet Owens (Water Quality Modeling Section Chief) made presentations at the American Water Resources Association (AWRA) Summer Specialty Conference: Climate Change Solutions, Collaborative Science, Policy, and Planning for Sustainable Water Management, held June 26-28 in Tysons, VA. Alan Cohn made a presentation titled "Preparing for Extreme Rain Events: NYC's Cloudburst Resiliency Planning Study", which described DEP's efforts to evaluate the impact of extreme rain events on urban stormwater systems in NYC. In addition, Emmet Owens presented "Modeling the Effect of Climate Change on the NYC Water Supply", an overview of DEP's past efforts to model the impacts of climate change and of future plans to refine and improve those model projections. Emmet Owens also served as a panelist in the panel discussion titled "From Science to Decisions: Lessons in

Climate Assessment and Planning from the Water Utility Climate Alliance: Co-Producing Actionable Science for Water Utility Climate Assessments". The other panelists were Kavita Heyn from Portland Water, Paul Fleming from Seattle Public Utilities, and Tirusew Asafa from Tampa Bay Water. Alan Cohn and Emmet Owens also attended the WUCA mid-year "retreat", a regular meeting of WUCA members that was held as a part of the AWRA Climate Conference. Water Quality modeling staff held individual telephone meetings with colleagues from Philadelphia Water staff, and Portland Water Bureau. These meetings generally discussed DEP's program to use models to evaluate the impact of climate change on our water supply. DEP plans to remain an active participant in WUCA in the coming years.

7.4 Global Lake Ecological Observation 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. To date, DEP staff have attended GLEON "All-Hands" meetings since 2014 (GLEON16, Orford, Québec; GLEON17, Chuncheon, South Korea; GLEON18, Gaming, Austria; GLEON19, New Paltz, New York).

In 2017, the annual meeting at Mohonk Mountain House in New Paltz, New York provided an opportunity to follow up on existing projects and discuss potential future collaborations. GLEON19 included a workshop on carbon, natural organic matter (NOM) and Disinfection By-Product (DBP) concerns for drinking water organized by DEP staff. The workshop covered a wide range of issues associated with the formation, fate, and transport of organic carbon and DBP precursors in lakes and reservoirs. Speakers from Australia, Sweden, Spain and the USA presented and a new project formed for continued collaboration on the DBP topic as it pertains to monitoring and modeling precursors in drinking water sources (http://gleon.org/research/projects/pipe-monitoring-and-modeling-disinfection-product-precursors-drinking-water).

Some additional highlights for 2017 follow. Ongoing projects without major milestones are not included here as some projects initiated at these meetings take some time to develop.

7.4.1 Temperature Sentinels in Northeastern North America (NENA): In-depth Study of Lake Thermal Responses to Climate Change in Northeastern North America

The primary intent of this study was to examine subsurface water temperature profiles from lakes and reservoirs across the northeastern region of North America to determine how water temperature responds to regional-scale climatic drivers. This project culminated in 2017 with a paper titled *Trends in lake surface and deep water temperature and stratification in northeastern North America (1975-2012)* (Richardson et al., 2017). DEP contributed data from four reservoirs to this study of 231 lakes and reservoirs.

7.4.2 Salting Our Waters: Global Trends in Chloride

In 2015, DEP contributed long-term chloride data from 10 reservoirs to a study of 529 lakes and reservoirs in the GLEON graduate fellowship "SALT" project. The project resulted in a synthesis of data that identified the northeastern United States as a "salinization hotspot" and found that impervious surface was the best predictor of chloride trend. DEP data are included in Dugan et al., 2017: *Long-term chloride concentrations in North American and European freshwater lakes* published in *Scientific Data*, an open-access journal that provides descriptions of scientifically valuable datasets and promotes sharing and reuse of data.

7.4.3 LAGOS Database

The ***LA****ke multi-scaled* ***G****e*__*OS*__*patial & temporal database* is a multi-scale spatial/temporal database of lake chemistry and landscape characteristics for over 49,000 lakes in a 17-state area in the northeastern and midwestern United States. This initiative led by Dr. Pat Soranno at Michigan State University and colleagues in the Cross-Scale Interactions (CSI) Limnology research consortium built the LAGOS database, one of the largest known spatially explicit lake water chemistry and landscape databases. DEP joined GLEON collaborators to provide data published in GigaScience (Sorrano et al., 2017).

7.4.4 Long-term Dissolved Oxygen (DO) Concentrations in Lakes and Reservoirs

This project focuses on using long-term dissolved oxygen profiles to identify trends in dissolved oxygen at different depths, for lakes with different watershed features, and in lakes of different trophic status. Project goals include exploring the response of dissolved oxygen concentrations to changing temperatures and examining how temperature and productivity interact to influence dissolved oxygen. DEP contributed data to this project initiated in 2016 by GLEON's Climate Sentinels Working Group. The focus for 2017 was on compilation of data for over 100 lakes and reservoirs.

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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).

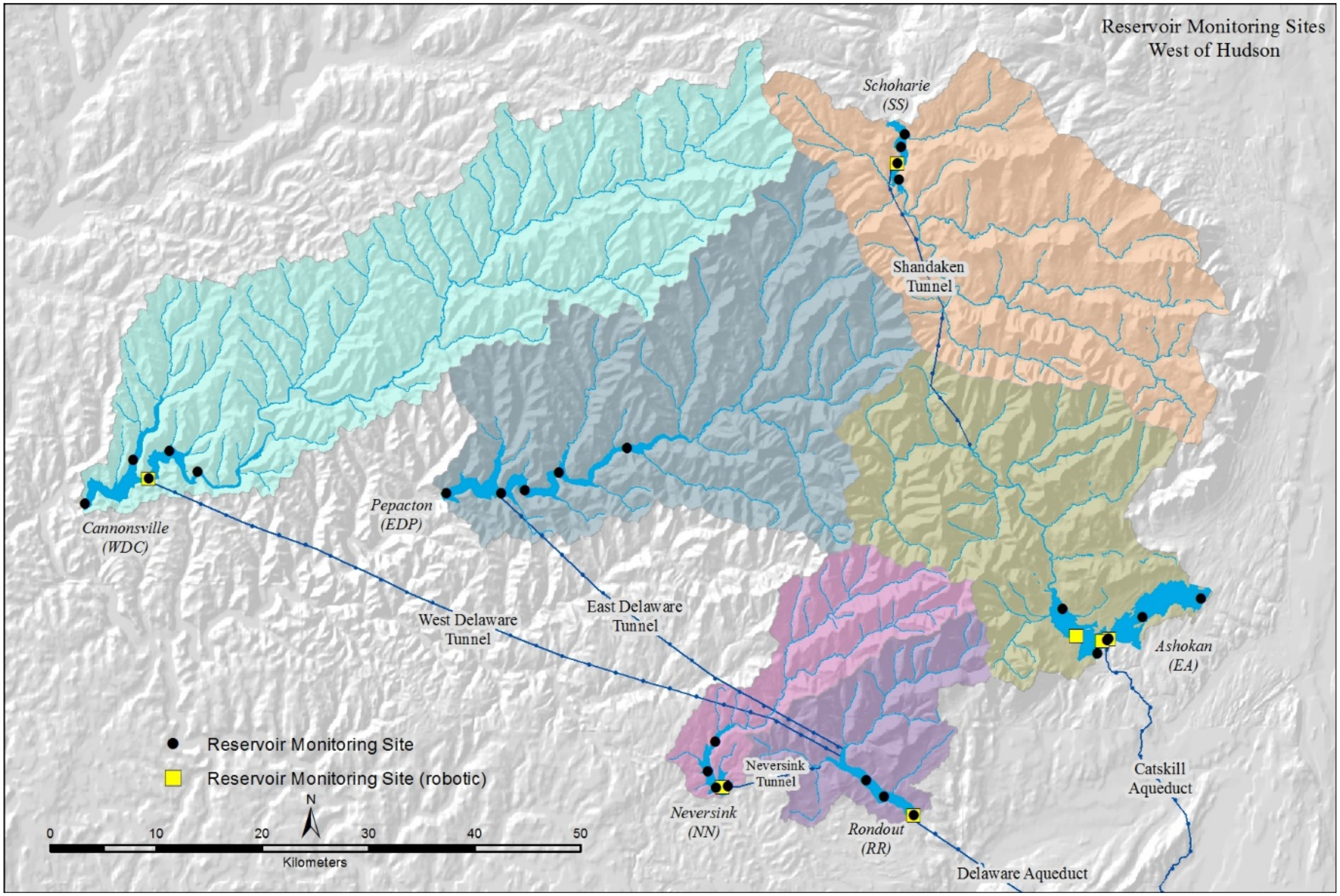
Site	Location	System	Water Type	Parameters
SRR1CM	Schoharie Intake Chamber	Catskill	Raw	Turb, pH, Temp, SpCond
SRR2CM	Shandaken Tunnel Outlet	Catskill	Raw	Turb, pH, Temp, SpCond
EARCM	Catskill Aqueduct	Catskill	Raw	Turb, pH, Temp, SpCond,
M-1	Ashokan Release Channel	Catskill	Raw	Turb
AEAP	Esopus Creek 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	Active Elevation All Taps	Delaware Delaware	Raw Raw	Turb, pH, Temp, SpCond Temp, Turb
CDIS4-DEL[1]	Cat/Del Interconnect at Shaft 4 (Catskill)	Catskill	Raw	
CDIS4-CAT[1]	Cat/Del Interconnect at Shaft 4 (Delaware)	Delaware	Raw	
CDIS4-Combined[1]	Cat/Del Interconnect at Shaft 4 (Catskill)	Catskill	Raw	
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

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

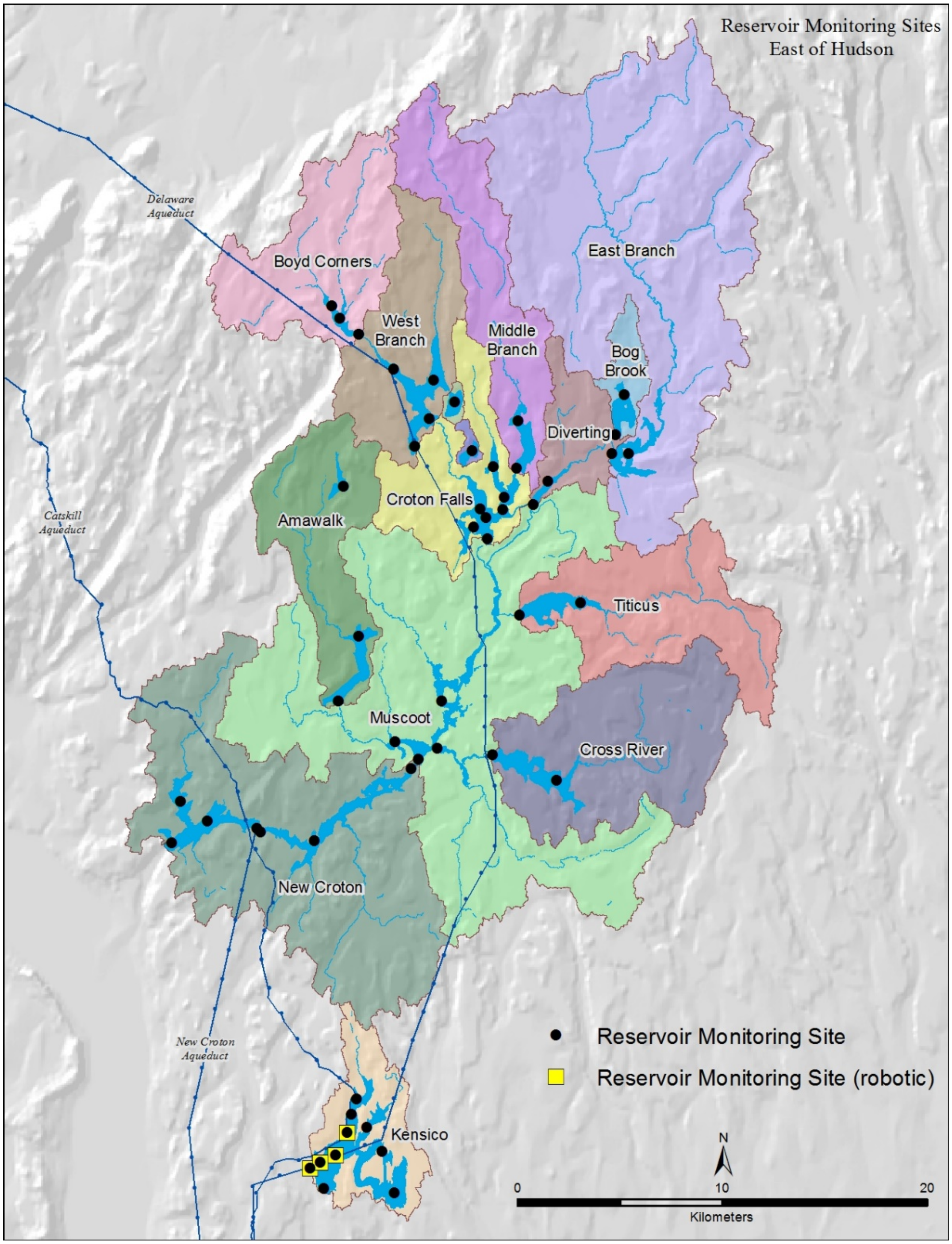
Site	Location	System	Water Type	Parameters
DEL10	Delaware Shaft 10	Delaware	Raw	Turb, pH, Temp, SpCond, Elev
DEL17	Delaware Shaft 17	Delaware	Raw	Turb, pH, Temp, SpCond, TCR, Dechlor, DO
DEL18DT	Delaware Shaft 18 Downtake	Cat/Del	Raw	Turb, pH, Temp, SpCond, Flow, Elev
DEL19	Delaware Shaft 19	Cat/Del	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
Catskill_Flow_Total	CDUV Catskill Flow	Cat/Del	Pre-Treated	Flow
CDUV_TOTAL_FLOW	CDUV Total Flow	Cat/Del	Pre-Treated	Flow
Del_Aqueduct_Total	CDUV Delaware Total Flow	Cat/Del	Pre-Treated	Flow

[1] Site not operational in 2017.

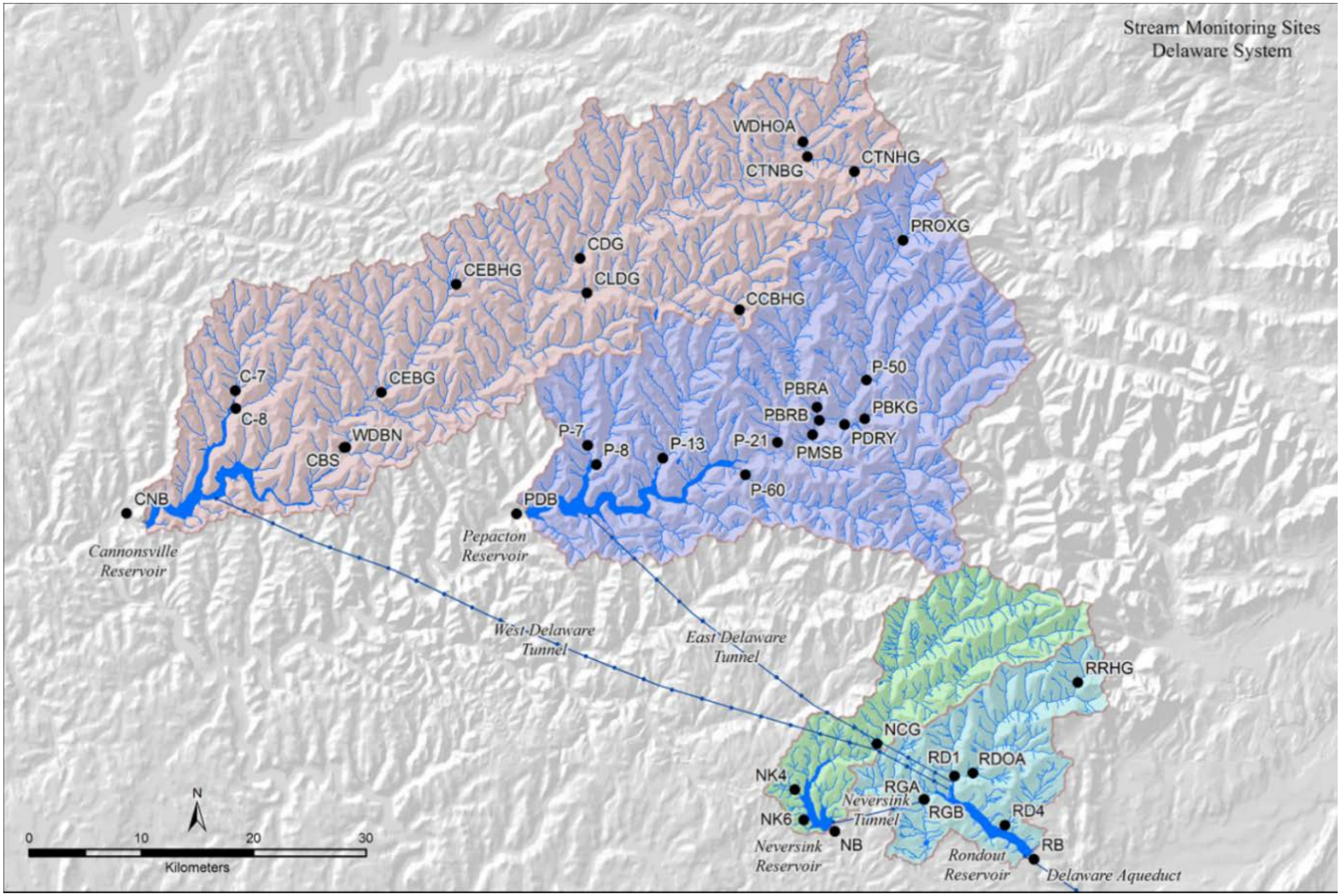
Appendix B. Sampling Locations



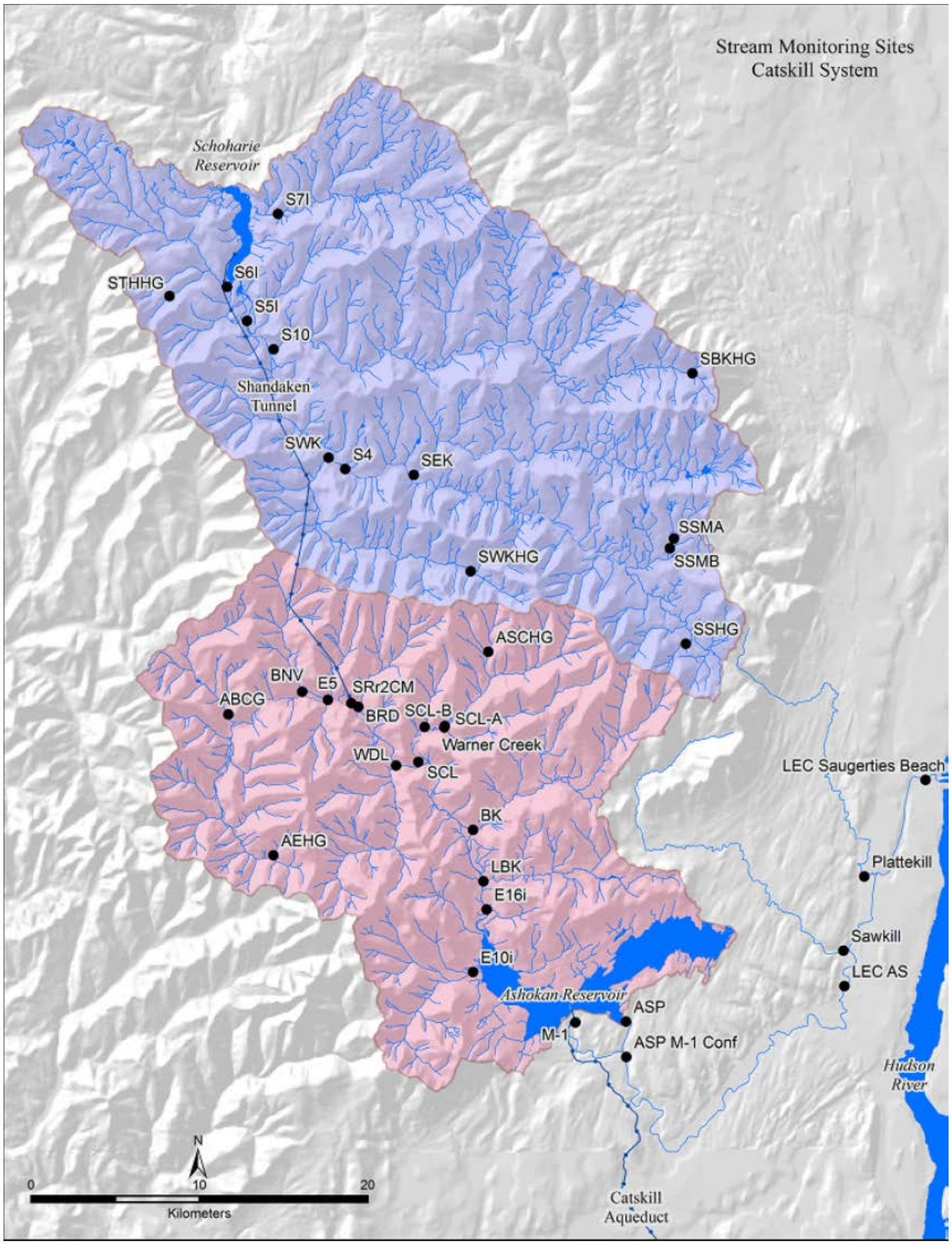
Appendix Figure 1 WOH reservoir monitoring sites [see 2016 WWQMP (DEP 2016a) for detailed maps].



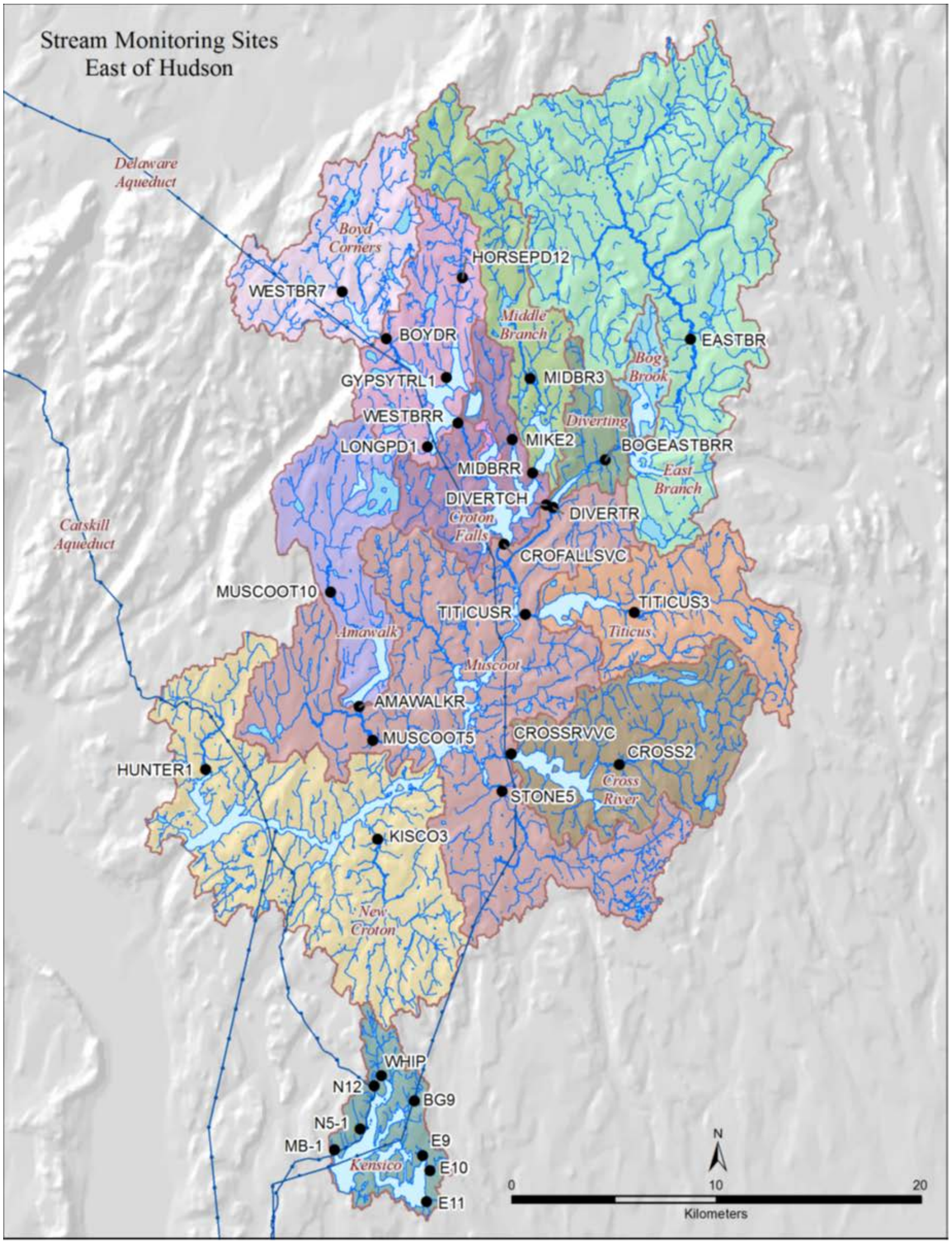
Appendix Figure 2 EOH reservoir monitoring sites [see 2016 WWQMP (DEP 2016a) for detailed maps].



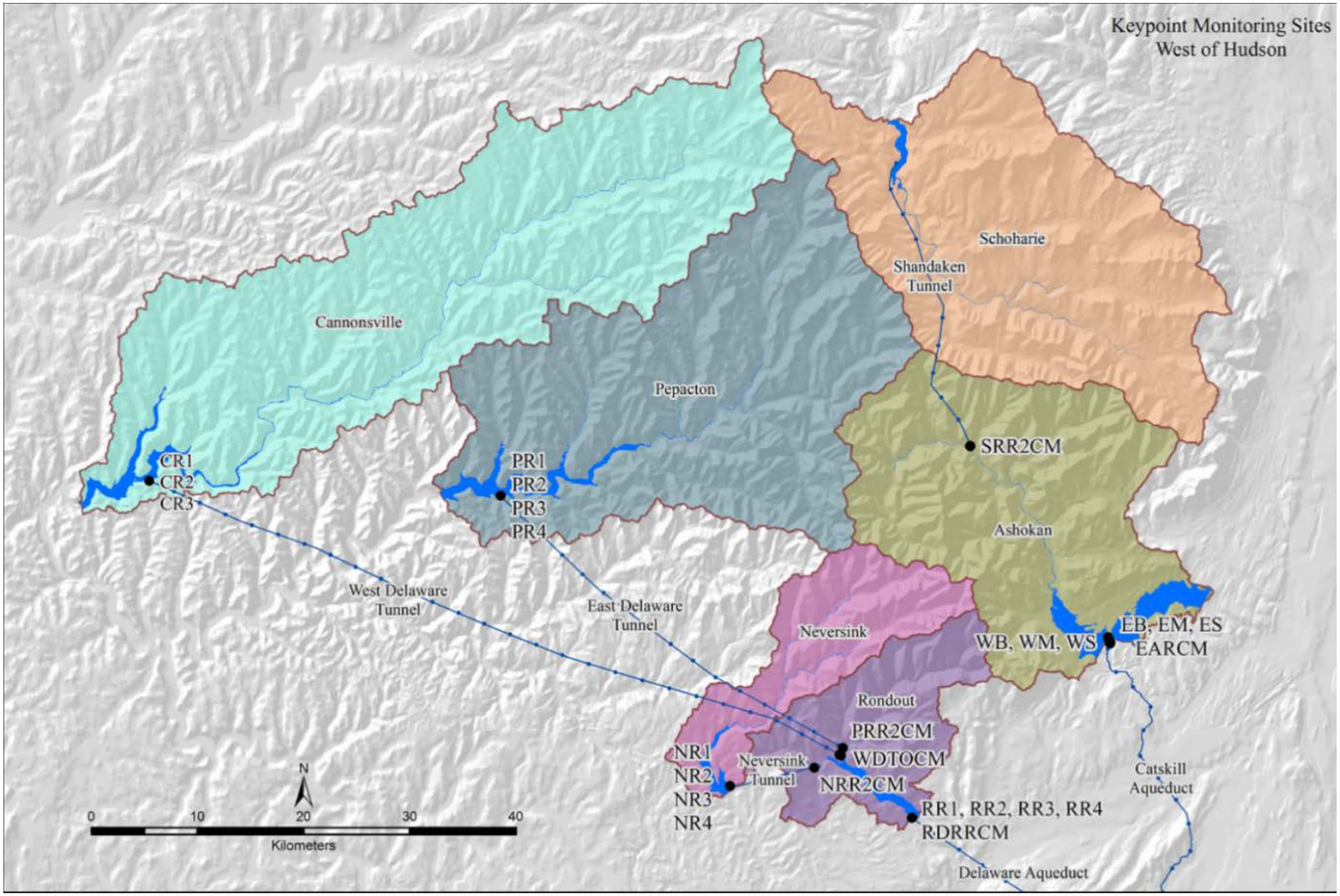
Appendix Figure 3 Delaware System stream monitoring sites [see 2016 WWQMP (DEP 2016a) for detailed maps].



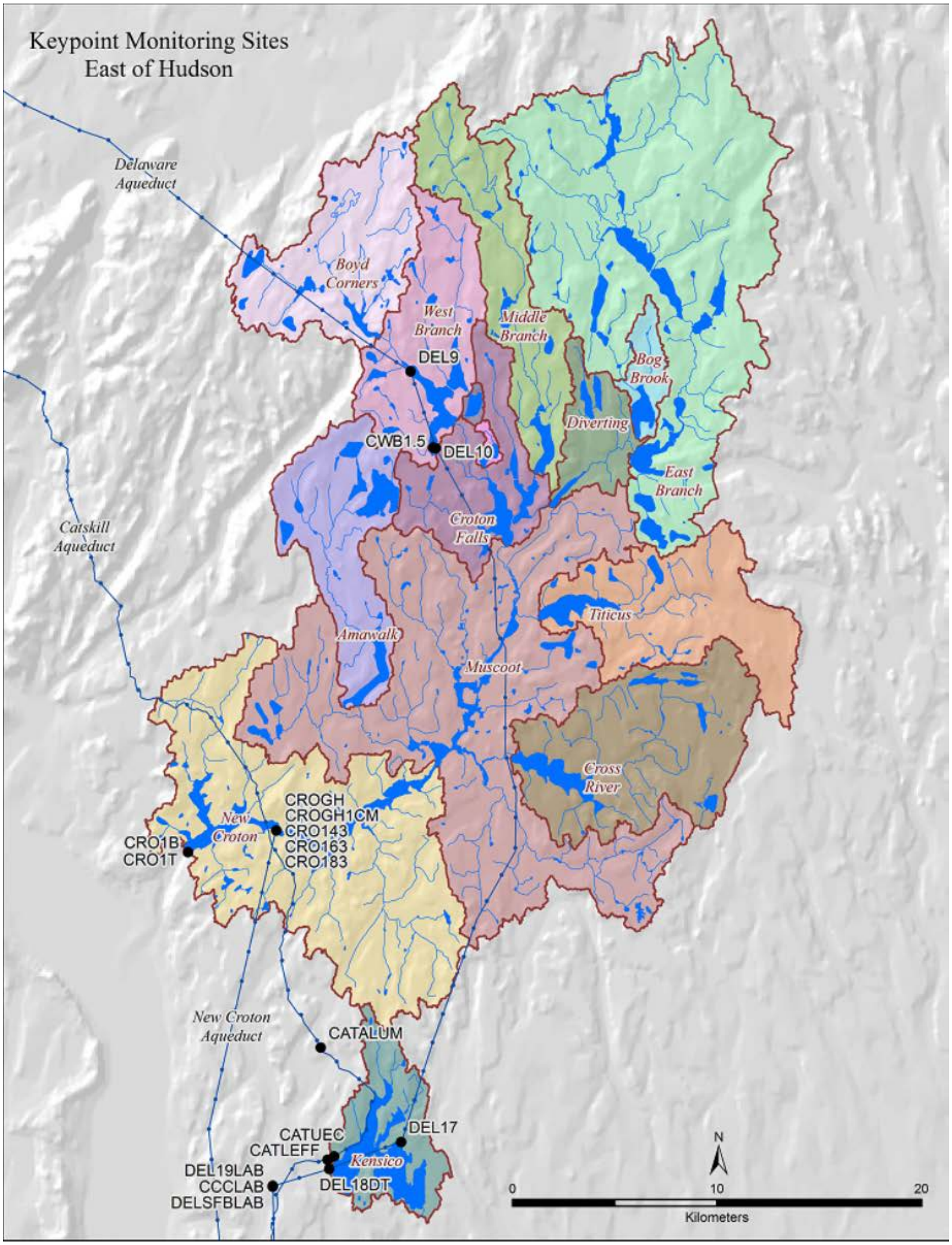
Appendix Figure 4 Catskill System stream monitoring sites [see 2016 WWQMP (DEP 2016a) for detailed maps].



Appendix Figure 5 EOH stream monitoring sites [see 2016 WWQMP (DEP 2016a) for detailed maps].

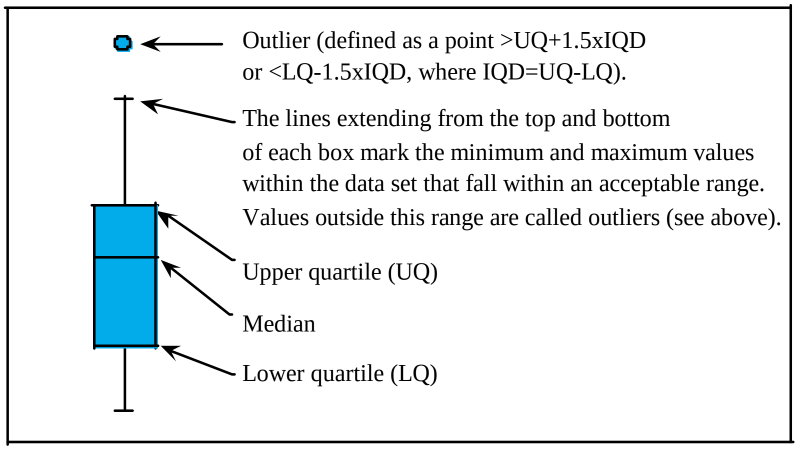


Appendix Figure 6 WOH aqueduct keypoint monitoring sites [see 2016 WWQMP (DEP 2016a) for detailed maps].



Appendix Figure 7 EOH aqueduct keypoint monitoring sites [see 2016 WWQMP (DEP 2016a) 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 samples)	Collection Month	N	Median Total Coliform (coliforms 100 mL^{-1})	Percentage > Standard
Amawalk	A (2400, 5000)	Apr-17	5	20	0
		May-17	5	60	0
		Jun-17	5	40	0
		Jul-17	5	40	0
		Aug-17	5	50	0
		Sep-17	5	50	0
		Oct-17	5	60	0
		Nov-17	5	60	0
Bog Brook	AA (50, 240)	Apr-17	5	20	0
		May-17	6	20	0
		Jun-17	5	20	0
		Jul-17	5	130	0
		Aug-17	6	>=<20	0
		Sep-17	5	<100	20
		Oct-17	5	<50	0
		Nov-17	6	20	0
Boyd's Corners	AA (50, 240)	Apr-17	7	40	0
		May-17	7	110	0
		Jun-17	7	25	0
		Jul-17	7	250	57
		Aug-17	7	<100	14
		Sep-17	6	100	0
		Oct-17	5	50	20
		Nov-17	7	50	0
Croton Falls	A/AA (50, 240)	Apr-17	8	20	0
		May-17	8	5	0
		Jun-17	8	5	0
		Jul-17	8	5	0
		Aug-17	8	>=E30	12
		Sep-17	8	40	12
		Oct-17	8	20	25
		Nov-17	8	85	12

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

Reservoir	Class & Standard (Median, Value not > 20% of samples)	Collection Date	N	Median Total Coliform (coliforms 100 mL $^{-1}$)	Percentage > Standard
Cross River	A/AA (50, 240)	Apr-17	6	18	0
		May-17	6	40	0
		Jun-17	6	<10	0
		Jul-17	6	30	17
		Aug-17	6	60	0
		Sep-17	6	20	0
		Oct-17	6	415	67
		Nov-17	6	10	0
Diverting	AA (50, 240)	Apr-17	5	220	40
		May-17	5	100	0
		Jun-17	5	1600	100
		Jul-17	5	100	40
		Aug-17	5	100	20
		Sep-17	5	100	40
		Oct-17	5	300	60
		Nov-17	5	80	0
East Branch	AA (50, 240)	Apr-17	5	10	0
		May-17	6	30	0
		Jun-17	5	10	0
		Jul-17	5	500	60
		Aug-17	6	>=<20	0
		Sep-17	5	<200	0
		Oct-17	5	<100	0
		Nov-17	6	<50	0
Lake Gilead	A (2400, 5000)	Apr-17	5	<5	0
		May-17	5	<5	0
		Jun-17	5	E10	0
		Jul-17	5	<10	0
		Aug-17	5	<10	0
		Sep-17	5	<5	0
		Oct-17	5	<50	0
		Nov-17	5	20	0
Lake Gleneida	AA (50, 240)	Apr-17	5	<1	0
		May-17	5	<2	0
		Jun-17	5	10	0
		Jul-17	5	<10	0
		Aug-17	5	5	0
		Sep-17	5	>=<5	0
		Oct-17	10	15	0
		Nov-17	5	10	0

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

Reservoir	Class & Standard (Median, Value not > 20% of samples)	Collection Date	N	Median Total Coliform (coliforms 100 mL $^{-1}$)	Percentage > Standard
Kirk Lake	B (2400, 5000)	Apr-17	5	25	0
		May-17	5	<5	0
		Jun-17	5	40	0
		Jul-17	5	20	0
		Aug-17	5	20	0
		Sep-17	5	20	0
		Oct-17	5	100	0
		Nov-17	5	80	0
Muscoot	A (2400, 5000)	Apr-17	6	45	0
		May-17	7	180	0
		Jun-17	7	1800	0
		Jul-17	6	150	0
		Aug-17	6	E50	0
		Sep-17	7	50	0
		Oct-17	7	50	0
		Nov-17	7	20	0
Middle Branch	A (2400, 5000)	Apr-17	5	30	0
		May-17	5	40	0
		Jun-17	5	4000	20
		Jul-17	5	100	0
		Aug-17	5	200	0
		Sep-17	5	50	0
		Oct-17	5	150	0
		Nov-17	5	20	0
Titicus	AA (50, 240)	Apr-17	5	>=E30	0
		May-17	5	100	40
		Jun-17	5	>=<20	0
		Jul-17	5	20	20
		Aug-17	5	60	0
		Sep-17	5	10	0
		Oct-17	5	500	80
		Nov-17	5	50	0
Cannonsville	A/AA (50, 240)	Apr-17	15	18	0
		May-17	15	22	0
		Jun-17	15	E60	7
		Jul-17	14	100	43
		Aug-17	14	40	7
		Sep-17	13	<50	0
		Oct-17	12	10	0
		Nov-17	12	22	0

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

Reservoir	Class & Standard (Median, Value not > 20% of samples)	Collection Date	N	Median Total Coliform (coliforms 100 mL $^{-1}$)	Percentage > Standard
Neversink	AA (50, 240)	Apr-17	13	8	0
		May-17	13	5	0
		Jun-17	11	8	0
		Jul-17	13	<20	0
		Aug-17	12	1	0
		Sep-17	12	5	0
		Oct-17	11	2	0
		Nov-17	12	10	0
Pepacton	A/AA (50, 240)	Apr-17	16	<1	0
		May-17	16	2	0
		Jun-17	16	4	0
		Jul-17	16	<20	6
		Aug-17	16	8	0
		Sep-17	15	<10	0
		Oct-17	14	2	0
		Nov-17	15	22	0
Schoharie	AA (50, 240)	Apr-17	12	71	0
		May-17	12	20	0
		Jun-17	12	56	0
		Jul-17	11	5	0
		Aug-17	10	3	0
		Sep-17	8	2	0
		Oct-17	0	Site inaccessible	NA
		Nov-17	11	100	9

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	**2012 μg L^{-1}**	**2013 μg L^{-1}**	**2014 μg L^{-1}**	**2015 μg L^{-1}**	**2016 μg L^{-1}**	**2017 μg L^{-1}**
Non-Source Waters (Delaware System)						
Cannonsville Reservoir	12.4	15.0	13.1	14.9	17.0	15.4
Pepacton Reservoir	8.4	7.9	7.8	9.0	10.8	10.3
Neversink Reservoir	9.7	6.0	6.2	6.5	8.0	7.3
Non-Source Waters (Catskill System)						
Schoharie Reservoir	20.0	15.0	15.3	11.9	12.5	12.2
Non-Source Waters (Croton System)						
Amawalk Reservoir	22.3	22.3	19.4	19.3	29.8	26.3
Bog Brook Reservoir	27.9	20.0	14.4	19.4	28.4	27.8
Boyd's Corners Reservoir	10.1	10.7	9.0	9.0	11.3	15.1
Diverting Reservoir	26.8	29.5	29.1	25.8	37.4	31.6
East Branch Reservoir	28.5	27.5	24.2	21.3	23.5	25.1
Middle Branch Reservoir	37.6	32.5	35.3	27.4	34.1	28.4
Muscoot Reservoir	31.5	29.9	28.7	28.5	30.6	36.5
Titicus Reservoir	24.4	24.4	24.8	19.5	23.7	25.2
Lake Gleneida	25.1	22.2	19.8	35.0	27.0	25.5
Lake Gilead	16.4	26.7	32.8	27.1	34.6	33.6
Kirk Lake	34.6	24.9	32.8	30.8	27.3	23.3
Source Waters (all systems)						
Ashokan West Basin	10.2	7.3	8.1	8.8	12.6	8.2
Ashokan East Basin	8.4	6.4	7.5	7.9	10.3	8.1
Cross River Reservoir	17.0	15.4	17.6	15.7	19.0	23.2
Croton Falls Reservoir	18.7	23.0	19.9	19.4	18.0	23.2
Kensico Reservoir	6.4	6.2	5.7	7.4	7.6	8.8
New Croton Reservoir	18.7	17.0	16.0	16.8	22.1	22.5
Rondout Reservoir	7.2	7.2	6.6	7.9	10.0	9.0
West Branch Reservoir	11.8	12.6	11.2	11.3	13.4	14.2

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	2017 Mean[1]
Croton System						
Amawalk Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	80
Chloride (mg L^{-1})	40	0			30	
Chlorophyll a (µg L^{-1})	15	16	4	25	10	13.7
Color (Pt-Co units)	15	38	37	97	na	na
Dissolved organic carbon (mg L^{-1})[2]	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	34	6	18	na	na
Sodium, undig., filt. (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})[3]	175	38	38	100	150	412
Total phosphorus (µg L^{-1})	15	38	37	97	na	na
Total phytoplankton (ASU mL^{-1})	2000	16	3	19	na	na
Primary genus (ASU mL^{-1})	1000	16	4	25	na	na
Secondary genus (ASU mL^{-1})	1000	16	1	6	na	na
Total suspended solids (mg L^{-1})	8.0	9	0	0	5	2.4
Turbidity (NTU)	5	38	2	5	na	na
Bog Brook Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	75
Chloride (mg L^{-1})	40	9	9	100	30	72.8
Chlorophyll a (µg L^{-1})	15	8	0	0	10	5.3
Color (Pt-Co units)	15	21	16	76	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	21	0	0	6	4.1
Fecal coliforms (coliform 100mL^{-1})	20	43	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	21	0	0	0.3	<0.02
pH (units)	6.5-8.5	29	5	17	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	2017 Mean[1]
Sodium, undig., filt. (mg L^{-1})	20	9	9	100	15	36.5
Soluble reactive phosphorus (µg L^{-1})	15	21	1	5	na	na
Sulfate (mg L^{-1})	25	9	0	0	15	11.2
Total ammonia-N (mg L^{-1})	0.10	21	3	14	0.05	0.05
Total dissolved phosphorus (µg L^{-1})	15	21	3	14	na	na
Total dissolved solids (mg L^{-1})[3]	175	21	21	100	150	270
Total phosphorus (µg L^{-1})	15	21	21	100	na	na
Total phytoplankton (ASU mL^{-1})	2000	8	1	13	na	na
Primary genus (ASU mL^{-1})	1000	8	1	13	na	na
Secondary genus (ASU mL^{-1})	1000	8	1	13	na	na
Total suspended solids (mg L^{-1})	8.0	9	0	0	5	2
Turbidity (NTU)	5	21	1	5	na	na
Boyd's Corners Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	7	na	na	>40	35
Chloride (mg L^{-1})	40	7	7	100	30	44.1
Chlorophyll a (µg L^{-1})	15	8	0	0	10	6.1
Color (Pt-Co units)	15	20	20	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	20	0	0	6	3.9
Fecal coliforms (coliform $100mL^{-1}$)	20	53	3	6	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	20	0	0	0.3	0.06
pH (units)	6.5-8.5	25	0	0	na	na
Sodium, undig., filt. (mg L^{-1})	20	7	7	100	15	26.5
Soluble reactive phosphorus (µg L^{-1})	15	20	0	0	na	na
Sulfate (mg L^{-1})	25	7	1	14	15	29.1
Total ammonia-N (mg L^{-1})	0.10	20	0	0	0.05	0.02
Total dissolved phosphorus (µg L^{-1})	15	20	0	0	na	na
Total dissolved solids (mg L^{-1})[3]	175	20	0	0	150	152
Total phosphorus (µg L^{-1})	15	20	13	65	na	na
Total phytoplankton (ASU mL^{-1})	2000	8	1	13	na	na
Primary genus (ASU mL^{-1})	1000	8	1	13	na	na
Secondary genus (ASU mL^{-1})	1000	8	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	7	0	0	5	1.5
Turbidity (NTU)	5	20	0	0	na	na
Cross River Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	48

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	2017 Mean[1]
Chloride (mg L^{-1})	40	9	9	100	30	49
Chlorophyll a (µg L^{-1})	15	16	0	0	10	7.4
Color (Pt-Co units)	15	48	47	98	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	48	0	0	6	3.6
Fecal coliforms (coliform 100mL^{-1})	20	48	5	10	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	48	0	0	0.3	0.02
pH (units)	6.5-8.5	48	1	2	na	na
Sodium, undig., filt. (mg L^{-1})	20	9	9	100	15	24.4
Soluble reactive phosphorus (µg L^{-1})	15	48	0	0	na	na
Sulfate (mg L^{-1})	25	9	0	0	15	9
Total ammonia-N (mg L^{-1})	0.10	48	11	23	0.05	0.06
Total dissolved phosphorus (µg L^{-1})	15	48	6	13	na	na
Total dissolved solids (mg L^{-1})[3]	175	48	48	100	150	187
Total phosphorus (µg L^{-1})	15	48	45	94	na	na
Total phytoplankton (ASU mL^{-1})	2000	16	3	19	na	na
Primary genus (ASU mL^{-1})	1000	16	3	19	na	na
Secondary genus (ASU mL^{-1})	1000	16	1	6	na	na
Total suspended solids (mg L^{-1})	8.0	9	0	0	5	2
Turbidity (NTU)	5	48	3	6	na	na
Croton Falls Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	18	na	na	>40	69
Chloride (mg L^{-1})	40	18	18	100	30	93.1
Chlorophyll a (µg L^{-1})	15	24	7	29	10	12.1
Color (Pt-Co units)	15	64	60	94	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	64	0	0	6	3.7
Fecal coliforms (coliform 100mL^{-1})	20	64	2	3	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	64	7	11	0.3	0.19
pH (units)	6.5-8.5	64	10	16	na	na
Sodium, undig., filt. (mg L^{-1})	20	18	18	100	15	51.4
Soluble reactive phosphorus (µg L^{-1})	15	64	2	3	na	na
Sulfate (mg L^{-1})	25	18	0	0	15	11.9
Total ammonia-N (mg L^{-1})	0.10	64	17	27	0.05	0.09
Total dissolved phosphorus (µg L^{-1})	15	64	6	9	na	na
Total dissolved solids (mg L^{-1})[3]	175	64	64	100	150	344
Total phosphorus (µg L^{-1})	15	64	60	94	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	2017 Mean[1]
Total phytoplankton (ASU mL^{-1})	2000	24	7	29	na	na
Primary genus (ASU mL^{-1})	1000	24	3	13	na	na
Secondary genus (ASU mL^{-1})	1000	24	1	4	na	na
Total suspended solids (mg L^{-1})	8.0	9	0	0	5	2.4
Turbidity (NTU)	5	64	9	14	na	na
Diverting Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	6	na	na	>40	84
Chloride (mg L^{-1})	40	0			30	
Chlorophyll a (µg L^{-1})	15	15	9	60	10	16.9
Color (Pt-Co units)	15	34	34	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	0			6	
Fecal coliforms (coliform 100mL^{-1})	20	35	2	6	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	0			0.3	
pH (units)	6.5-8.5	33	1	3	na	na
Sodium, undig., filt. (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})[3]	175	34	34	100	150	283
Total phosphorus (µg L^{-1})	15	34	34	100	na	na
Total phytoplankton (ASU mL^{-1})	2000	16	5	31	na	na
Primary genus (ASU mL^{-1})	1000	16	4	25	na	na
Secondary genus (ASU mL^{-1})	1000	16	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	6	0	0	5	3
Turbidity (NTU)	5	34	6	18	na	na
East Branch Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	85
Chloride (mg L^{-1})	40	9	9	100	30	60.4
Chlorophyll a (µg L^{-1})	15	8	0	0	10	8.2
Color (Pt-Co units)	15	24	24	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	24	0	0	6	4.7
Fecal coliforms (coliform 100mL^{-1})	20	43	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	24	0	0	0.3	0.05
pH (units)	6.5-8.5	30	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	2017 Mean[1]
Sodium, undig., filt. (mg L^{-1})	20	9	9	100	15	30.5
Soluble reactive phosphorus (µg L^{-1})	15	24	0	0	na	na
Sulfate (mg L^{-1})	25	9	0	0	15	9
Total ammonia-N (mg L^{-1})	0.10	24	3	13	0.05	0.05
Total dissolved phosphorus (µg L^{-1})	15	24	7	29	na	na
Total dissolved solids (mg L^{-1})[3]	175	24	24	100	150	253
Total phosphorus (µg L^{-1})	15	24	23	96	na	na
Total phytoplankton (ASU mL^{-1})	2000	8	1	13	na	na
Primary genus (ASU mL^{-1})	1000	8	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	8	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	9	0	0	5	2.2
Turbidity (NTU)	5	24	1	4	na	na
Kirk Lake						
Alkalinity (mg $CaCO_3$ L^{-1})	na	3	na	na	>40	61
Chloride (mg L^{-1})	40	3	3	100	30	104.3
Chlorophyll a (µg L^{-1})	15	3	2	67	10	14.3
Color (Pt-Co units)	15	3	3	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	3	0	0	6	4.5
Fecal coliforms (coliform $100mL^{-1}$)	20	15	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	3	0	0	0.3	<0.02
pH (units)	6.5-8.5	15	3	20	na	na
Sodium, undig., filt. (mg L^{-1})	20	3	3	100	15	52.4
Soluble reactive phosphorus (µg L^{-1})	15	3	0	0	na	na
Sulfate (mg L^{-1})	25	3	0	0	15	9.5
Total ammonia-N (mg L^{-1})	0.10	3	0	0	0.05	0.04
Total dissolved phosphorus (µg L^{-1})	15	3	0	0	na	na
Total dissolved solids (mg L^{-1})[3]	175	3	3	100	150	322
Total phosphorus (µg L^{-1})	15	3	3	100	na	na
Total phytoplankton (ASU mL^{-1})	2000	3	1	33	na	na
Primary genus (ASU mL^{-1})	1000	3	1	33	na	na
Secondary genus (ASU mL^{-1})	1000	3	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	3	0	0	5	3.2
Turbidity (NTU)	5	3	1	33	na	na
Lake Gilead						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	46

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	2017 Mean[1]
Chloride (mg L^{-1})	40	9	9	100	30	59.2
Chlorophyll a (µg L^{-1})	15	3	0	0	10	4.3
Color (Pt-Co units)	15	9	4	44	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	9	0	0	6	3.3
Fecal coliforms (coliform $100mL^{-1}$)	20	15	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	9	0	0	0.3	<0.02
pH (units)	6.5-8.5	15	1	7	na	na
Sodium, undig., filt. (mg L^{-1})	20	9	9	100	15	31.9
Soluble reactive phosphorus (µg L^{-1})	15	9	2	22	na	na
Sulfate (mg L^{-1})	25	9	0	0	15	7.8
Total ammonia-N (mg L^{-1})	0.10	9	3	33	0.05	<u>0.15</u>
Total dissolved phosphorus (µg L^{-1})	15	9	2	22	na	na
Total dissolved solids (mg L^{-1})[3]	175	9	9	100	150	202
Total phosphorus (µg L^{-1})	15	9	8	89	na	na
Total phytoplankton (ASU mL^{-1})	2000	3	0	0	na	na
Primary genus (ASU mL^{-1})	1000	3	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	2	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	9	0	0	5	1.4
Turbidity (NTU)	5	9	0	0	na	na
Lake Gleneida						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	66
Chloride (mg L^{-1})	40	9	9	100	30	106.6
Chlorophyll a (µg L^{-1})	15	3	0	0	10	2.9
Color (Pt-Co units)	15	9	1	11	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	9	0	0	6	3
Fecal coliforms (coliform $100mL^{-1}$)	20	45	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	9	0	0	0.3	<0.02
pH (units)	6.5-8.5	20	1	5	na	na
Sodium, undig., filt. (mg L^{-1})	20	9	9	100	15	62.8
Soluble reactive phosphorus (µg L^{-1})	15	9	1	11	na	na
Sulfate (mg L^{-1})	25	9	0	0	15	6.5
Total ammonia-N (mg L^{-1})	0.10	9	3	33	0.05	0.12
Total dissolved phosphorus (µg L^{-1})	15	9	2	22	na	na
Total dissolved solids (mg L^{-1})[3]	175	9	9	100	150	337
Total phosphorus (µg L^{-1})	15	9	7	78	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	2017 Mean[1]
Total phytoplankton (ASU mL^{-1})	2000	3	0	0	na	na
Primary genus (ASU mL^{-1})	1000	3	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	3	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	9	0	0	5	1.9
Turbidity (NTU)	5	9	0	0	na	na
Middle Branch Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	67
Chloride (mg L^{-1})	40	0			30	
Chlorophyll a (µg L^{-1})	15	16	2	13	10	10.8
Color (Pt-Co units)	15	40	39	98	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	0			6	
Fecal coliforms (coliform $100mL^{-1}$)	20	40	2	5	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	0			0.3	
pH (units)	6.5-8.5	35	6	17	na	na
Sodium, undig., filt. (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})[3]	175	40	40	100	150	370
Total phosphorus (µg L^{-1})	15	40	38	95	na	na
Total phytoplankton (ASU mL^{-1})	2000	16	3	19	na	na
Primary genus (ASU mL^{-1})	1000	16	3	19	na	na
Secondary genus (ASU mL^{-1})	1000	16	1	6	na	na
Total suspended solids (mg L^{-1})	8.0	9	0	0	5	2.2
Turbidity (NTU)	5	40	4	10	na	na
Muscoot Reservoir		9	na	na	>40	67
Alkalinity (mg $CaCO_3$ L^{-1})	na	6	na	na	>40	83
Chloride (mg L^{-1})	40	6	6	100	30	103.9
Chlorophyll a (µg L^{-1})	15	32	12	38	10	22.1
Color (Pt-Co units)	15	54	54	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	54	1	2	6	4.3
Fecal coliforms (coliform $100mL^{-1}$)	20	54	7	13	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	54	4	7	0.3	0.2
pH (units)	6.5-8.5	54	2	4	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	2017 Mean[1]
Sodium, undig., filt. (mg L^{-1})	20	6	6	100	15	53.9
Soluble reactive phosphorus (µg L^{-1})	15	54	5	9	na	na
Sulfate (mg L^{-1})	25	6	0	0	15	9.5
Total ammonia-N (mg L^{-1})	0.10	54	16	30	0.05	0.21
Total dissolved phosphorus (µg L^{-1})	15	54	10	19	na	na
Total dissolved solids (mg L^{-1})[3]	175	54	54	100	150	333
Total phosphorus (µg L^{-1})	15	54	54	100	na	na
Total phytoplankton (ASU mL^{-1})	2000	32	6	19	na	na
Primary genus (ASU mL^{-1})	1000	32	6	19	na	na
Secondary genus (ASU mL^{-1})	1000	32	1	3	na	na
Total suspended solids (mg L^{-1})	8.0	6	1	17	5	4.4
Turbidity (NTU)	5	54	10	19	na	na
New Croton Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	30	na	na	>40	70
Chloride (mg L^{-1})	40	30	30	100	30	96.8
Chlorophyll a (µg L^{-1})	15	56	3	5	10	9.5
Color (Pt-Co units)	15	168	155	92	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	168	0	0	6	3.5
Fecal coliforms (coliform $100mL^{-1}$)	20	155	7	5	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	168	10	6	0.3	0.19
pH (units)	6.5-8.5	160	14	9	na	na
Sodium, undig., filt. (mg L^{-1})	20	30	30	100	15	50
Soluble reactive phosphorus (µg L^{-1})	15	168	9	5	na	na
Sulfate (mg L^{-1})	25	30	0	0	15	11.7
Total ammonia-N (mg L^{-1})	0.10	168	54	32	0.05	0.14
Total dissolved phosphorus (µg L^{-1})	15	168	19	11	na	na
Total dissolved solids (mg L^{-1})[3]	175	168	168	100	150	317
Total phosphorus (µg L^{-1})	15	168	139	83	na	na
Total phytoplankton (ASU mL^{-1})	2000	69	6	9	na	na
Primary genus (ASU mL^{-1})	1000	69	6	9	na	na
Secondary genus (ASU mL^{-1})	1000	69	1	1	na	na
Total suspended solids (mg L^{-1})	8.0	56	0	0	5	1.6
Turbidity (NTU)	5	168	11	7	na	na
Titicus Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	72

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	2017 Mean[1]
Chloride (mg L^{-1})	40	0			30	
Chlorophyll a (µg L^{-1})	15	16	0	0	10	8.2
Color (Pt-Co units)	15	36	32	89	na	na
Dissolved organic carbon (mg L^{-1})[2]	7.0	0			6	
Fecal coliforms (coliform 100mL^{-1})	20	40	2	5	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	0			0.3	
pH (units)	6.5-8.5	39	9	23	na	na
Sodium, undig., filt. (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})[3]	175	36	36	100	150	223
Total phosphorus (µg L^{-1})	15	36	35	97	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	2.3
Turbidity (NTU)	5	36	4	11	na	na
Catskill System						
Ashokan East Basin Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>10	14
Chloride (mg L^{-1})	12	9	0	0	8	9.9
Chlorophyll a (µg L^{-1})	12	24	0	0	7	2.6
Color (Pt-Co units)	15	64	2	3	na	na
Dissolved organic carbon (mg L^{-1})[2]	4.0	64	0	0	3	1.6
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	63	15	24	na	na
Sodium, undig., filt. (mg L^{-1})	16	9	9	100	3	5.8
Soluble reactive phosphorus (µg L^{-1})	15	64	0	0	na	na
Sulfate (mg L^{-1})	15	9	0	0	10	3.6
Total ammonia-N (mg L^{-1})	0.10	64	0	0	0.05	0.02
Total dissolved phosphorus (µg L^{-1})	15	64	0	0	na	na
Total dissolved solids (mg L^{-1})[3]	50	64	6	9	40	47

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	2017 Mean[1]
Total phosphorus (µg L^{-1})	15	64	1	2	na	na
Total phytoplankton (ASU mL^{-1})	2000	40	0	0	na	na
Primary genus (ASU mL^{-1})	1000	40	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	40	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	64	0	0	5	1.6
Turbidity (NTU)	5	64	2	3	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	8.3
Chlorophyll a (µg L^{-1})	12	23	0	0	7	3.6
Color (Pt-Co units)	15	71	12	17	na	na
Dissolved organic carbon (mg L^{-1})[2]	4.0	71	0	0	3	1.6
Fecal coliforms (coliform $100mL^{-1}$)	20	71	1	1	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	71	0	0	0.3	0.11
pH (units)	6.5-8.5	69	12	17	na	na
Sodium, undig., filt. (mg L^{-1})	16	11	11	100	3	5
Soluble reactive phosphorus (µg L^{-1})	15	71	0	0	na	na
Sulfate (mg L^{-1})	15	11	0	0	10	3.3
Total ammonia-N (mg L^{-1})	0.10	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})[3]	50	71	0	0	40	41
Total phosphorus (µg L^{-1})	15	71	10	14	na	na
Total phytoplankton (ASU mL^{-1})	2000	40	0	0	na	na
Primary genus (ASU mL^{-1})	1000	40	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	40	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	71	4	6	5	3.1
Turbidity (NTU)	5	71	17	24	na	na
Schoharie Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>10	15
Chloride (mg L^{-1})	12	9	0	0	8	8.7
Chlorophyll a (µg L^{-1})	12	28	0	0	7	2.4
Color (Pt-Co units)	15	58	44	76	na	na
Dissolved organic carbon (mg L^{-1})[2]	4.0	78	0	0	3	2.6
Fecal coliforms (coliform $100mL^{-1}$)	20	78	12	15	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	57	0	0	0.3	0.13

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	2017 Mean[1]
pH (units)	6.5-8.5	66	3	5	na	na
Sodium, undig., filt. (mg L^{-1})	16	9	9	100	3	5.6
Soluble reactive phosphorus (µg L^{-1})	15	57	1	2	na	na
Sulfate (mg L^{-1})	15	9	0	0	10	3.3
Total ammonia-N (mg L^{-1})	0.10	57	1	2	0.05	0.02
Total dissolved phosphorus (µg L^{-1})	15	57	0	0	na	na
Total dissolved solids (mg L^{-1})[3]	50	78	22	28	40	48
Total phosphorus (µg L^{-1})	15	77	35	45	na	na
Total phytoplankton (ASU mL^{-1})	2000	41	0	0	na	na
Primary genus (ASU mL^{-1})	1000	53	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	53	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	78	20	26	5	6.6
Turbidity (NTU)	5	78	51	65	na	na
Delaware System						
Cannonsville Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	17	na	na	>10	17
Chloride (mg L^{-1})	12	17	7	41	8	11.6
Chlorophyll a (µg L^{-1})	12	40	7	18	7	8.5
Color (Pt-Co units)	15	110	58	53	na	na
Dissolved organic carbon (mg L^{-1})[2]	4.0	89	1	1	3	2
Fecal coliforms (coliform 100mL^{-1})	20	110	9	8	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	110	4	4	0.3	0.27
pH (units)	6.5-8.5	110	7	6	na	na
Sodium, undig., filt. (mg L^{-1})	16	16	16	100	3	7.4
Soluble reactive phosphorus (µg L^{-1})	15	110	1	1	na	na
Sulfate (mg L^{-1})	15	17	0	0	10	4.3
Total ammonia-N (mg L^{-1})	0.10	110	0	0	0.05	0.03
Total dissolved phosphorus (µg L^{-1})	15	110	12	11	na	na
Total dissolved solids (mg L^{-1})[3]	50	89	85	96	40	58
Total phosphorus (µg L^{-1})	15	110	69	63	na	na
Total phytoplankton (ASU mL^{-1})	2000	49	0	0	na	na
Primary genus (ASU mL^{-1})	1000	56	1	2	na	na
Secondary genus (ASU mL^{-1})	1000	56	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	48	1	2	5	2
Turbidity (NTU)	5	89	17	19	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	2017 Mean[1]
Neversink Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	12	na	na	>10	3
Chloride (mg L^{-1})	12	12	0	0	8	4.7
Chlorophyll a (µg L^{-1})	12	24	0	0	7	2
Color (Pt-Co units)	15	99	1	1	na	na
Dissolved organic carbon (mg L^{-1})[2]	4.0	75	0	0	3	1.8
Fecal coliforms (coliform $100mL^{-1}$)	20	99	1	1	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	75	0	0	0.3	0.11
pH (units)	6.5-8.5	99	69	70	na	na
Sodium, undig., filt. (mg L^{-1})	16	12	0	0	3	2.6
Soluble reactive phosphorus (µg L^{-1})	15	75	0	0	na	na
Sulfate (mg L^{-1})	15	12	0	0	10	2.8
Total ammonia-N (mg L^{-1})	0.10	75	0	0	0.05	0.02
Total dissolved phosphorus (µg L^{-1})	15	75	0	0	na	na
Total dissolved solids (mg L^{-1})[3]	50	99	0	0	40	22
Total phosphorus (µg L^{-1})	15	75	1	1	na	na
Total phytoplankton (ASU mL^{-1})	2000	48	0	0	na	na
Primary genus (ASU mL^{-1})	1000	48	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	48	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	24	0	0	5	0.9
Turbidity (NTU)	5	99	0	0	na	na
Pepacton Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	21	na	na	>10	13
Chloride (mg L^{-1})	12	21	0	0	8	8.7
Chlorophyll a (µg L^{-1})	12	40	2	5	7	5.4
Color (Pt-Co units)	15	123	21	17	na	na
Dissolved organic carbon (mg L^{-1})[2]	4.0	124	0	0	3	1.5
Fecal coliforms (coliform $100mL^{-1}$)	20	124	2	2	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	124	0	0	0.3	0.13
pH (units)	6.5-8.5	124	1	1	na	na
Sodium, undig., filt. (mg L^{-1})	16	21	21	100	3	5.1
Soluble reactive phosphorus (µg L^{-1})	15	124	0	0	na	na
Sulfate (mg L^{-1})	15	21	0	0	10	3.6
Total ammonia-N (mg L^{-1})	0.10	124	0	0	0.05	0.01
Total dissolved phosphorus (µg L^{-1})	15	124	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	2017 Mean[1]
Total dissolved solids (mg L^{-1})[3]	50	123	15	12	40	47
Total phosphorus (µg L^{-1})	15	124	29	23	na	na
Total phytoplankton (ASU mL^{-1})	2000	62	0	0	na	na
Primary genus (ASU mL^{-1})	1000	62	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	62	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	62	0	0	5	1.2
Turbidity (NTU)	5	123	5	4	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	9.3
Chlorophyll a (µg L^{-1})	12	24	0	0	7	4.5
Color (Pt-Co units)	15	80	15	19	na	na
Dissolved organic carbon (mg L^{-1})[2]	4.0	56	1	2	3	1.6
Fecal coliforms (coliform 100mL^{-1})	20	80	2	3	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	56	0	0	0.3	0.15
pH (units)	6.5-8.5	80	11	14	na	na
Sodium, undig., filt. (mg L^{-1})	16	12	12	100	3	5.4
Soluble reactive phosphorus (µg L^{-1})	15	56	0	0	na	na
Sulfate (mg L^{-1})	15	12	0	0	10	3.8
Total ammonia-N (mg L^{-1})	0.10	56	0	0	0.05	0.02
Total dissolved phosphorus (µg L^{-1})	15	56	0	0	na	na
Total dissolved solids (mg L^{-1})[3]	50	80	0	0	40	45
Total phosphorus (µg L^{-1})	15	80	4	5	na	na
Total phytoplankton (ASU mL^{-1})	2000	48	0	0	na	na
Primary genus (ASU mL^{-1})	1000	48	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	48	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	32	0	0	5	0.9
Turbidity (NTU)	5	80	0	0	na	na
West Branch Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	15	na	na	>10	28
Chloride (mg L^{-1})	12	16	16	100	8	35.1
Chlorophyll a (µg L^{-1})	12	32	1	3	7	4.6
Color (Pt-Co units)	15	72	45	63	na	na
Dissolved organic carbon (mg L^{-1})[2]	4.0	73	1	1	3	2.7
Fecal coliforms (coliform 100mL^{-1})	20	72	3	4	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	2017 Mean[1]
Nitrate+Nitrite-N (mg L^{-1})	0.5	73	0	0	0.3	0.03
pH (units)	6.5-8.5	64	2	3	na	na
Sodium, undig., filt. (mg L^{-1})	16	15	15	100	3	19.5
Soluble reactive phosphorus (µg L^{-1})	15	73	0	0	na	na
Sulfate (mg L^{-1})	15	16	0	0	10	6.4
Total ammonia-N (mg L^{-1})	0.10	72	5	7	0.05	0.03
Total dissolved phosphorus (µg L^{-1})	15	73	2	3	na	na
Total dissolved solids (mg L^{-1})[3]	50	72	72	100	40	123
Total phosphorus (µg L^{-1})	15	72	27	38	na	na
Total phytoplankton (ASU mL^{-1})	2000	43	1	2	na	na
Primary genus (ASU mL^{-1})	1000	43	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	43	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	9	0	0	5	1.8
Turbidity (NTU)	5	72	1	1	na	na
Terminal Reservoir for Catskill/Delaware System						
Kensico Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	23	na	na	>10	13
Chloride (mg L^{-1})	12	24	19	79	8	12.8
Chlorophyll a (µg L^{-1})	12	64	0	0	7	3
Color (Pt-Co units)	15	200	16	8	na	na
Dissolved organic carbon (mg L^{-1})[2]	4.0	200	0	0	3	1.7
Fecal coliforms (coliform $100mL^{-1}$)	20	200	2	1	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	200	0	0	0.3	0.13
pH (units)	6.5-8.5	200	18	9	na	na
Sodium, undig., filt. (mg L^{-1})	16	24	24	100	3	7.5
Soluble reactive phosphorus (µg L^{-1})	15	200	0	0	na	na
Sulfate (mg L^{-1})	15	24	1	4	10	5
Total ammonia-N (mg L^{-1})	0.10	200	1	1	0.05	<0.02
Total dissolved phosphorus (µg L^{-1})	15	200	1	1	na	na
Total dissolved solids (mg L^{-1})[3]	50	200	145	73	40	54
Total phosphorus (µg L^{-1})	15	200	4	2	na	na
Total phytoplankton (ASU mL^{-1})	2000	96	1	1	na	na
Primary genus (ASU mL^{-1})	1000	90	1	1	na	na
Secondary genus (ASU mL^{-1})	1000	90	0	0	na	na
Total suspended solids (mg L^{-1})	8.0	80	0	0	5	1.2

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	2017 Mean[1]
Turbidity (NTU)	5	200	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 using two lines. In cases where >80% of data is censored the mean cannot be estimated and here we report the detection limit preceded by <.

[2]Dissolved organic carbon replaced total organic carbon in 2000. In New York City Reservoirs the dissolved portion comprises the majority of the total organic carbon.

[3]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	2017 Mean[1]
Ashokan Watershed						
E10I (Bushkill at West Shokan)						
Alkalinity (mg L^{-1})	≥10.0	12	9	75	na	7.8
Chloride (mg L^{-1})	50	12	0	0	10	4.0
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	<u>0.7</u>
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	<u>0.07</u>
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	0	0	40	26
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.5
E16i (Esopus Brook at Coldbrook)						
Alkalinity (mg L^{-1})	≥10.0	14	3	21	na	14.7
Chloride (mg L^{-1})	50	14	0	0	10	9.1
Dissolved organic carbon (mg L^{-1})	25	14	0	0	9	1.4
Nitrate+Nitrite-N (mg L^{-1})	1.5	14	0	0	0.40	<u>0.12</u>
Sulfate (mg L^{-1})	15	4	0	0	10	3.5
Total ammonia-N (mg L^{-1})	0.25	14	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	14	4	29	40	48
Dissolved sodium (mg L^{-1})	10	4	0	0	5	5.5
E5 (Esopus Creek at Allaben)						
Alkalinity (mg L^{-1})	≥10.0	12	5	42	na	12.0
Chloride (mg L^{-1})	50	12	0	0	10	7.0
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	0.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	<u>0.09</u>
Sulfate (mg L^{-1})	15	4	0	0	10	3.2
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	13	3	23	40	39
Dissolved sodium (mg L^{-1})	10	4	0	0	5	3.7

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	2017 Mean[1]
Schoharie Watershed						
S5I (Schoharie Creek at Prattsville)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	21.0
Chloride (mg L^{-1})	50	12	0	0	10	12.7
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.8
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	<u>0.15</u>
Sulfate (mg L^{-1})	15	4	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	13	10	77	40	64
Dissolved sodium (mg L^{-1})	10	4	0	0	5	7.6
S6I (Bear Kill at Hardenburgh Falls)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	30.3
Chloride (mg L^{-1})	50	12	0	0	10	21.8
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.8
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.43
Sulfate (mg L^{-1})	15	4	0	0	10	5.5
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	12	100	40	100
Dissolved sodium (mg L^{-1})	10	4	3	75	5	13.4
S7I (Manor Kill)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	29.6
Chloride (mg L^{-1})	50	12	0	0	10	12.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.4
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	<u>0.10</u>
Sulfate (mg L^{-1})	15	4	0	0	10	4.4
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	10	83	40	74
Dissolved sodium (mg L^{-1})	10	4	0	0	5	6.8

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	2017 Mean[1]
SRR2CM (Schoharie Reservoir Diversion) [3]						
Alkalinity (mg L^{-1})	≥10.0	12	2	17	na	17.1
Chloride (mg L^{-1})	50	11	0	0	10	10.7
Dissolved organic carbon (mg L^{-1})	25	51	0	0	9	2.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	<u>0.19</u>
Sulfate (mg L^{-1})	15	4	0	0	10	4.0
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	242	132	55	40	53
Dissolved sodium (mg L^{-1})	10	4	1	25	5	8.7
Cannonsville Watershed						
C-7 (Trout Creek above Cannonsville Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	1	8	na	17.8
Chloride (mg L^{-1})	50	12	0	0	10	15.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.27
Sulfate (mg L^{-1})	15	4	0	0	10	4.9
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	11	92	40	70
Dissolved sodium (mg L^{-1})	10	4	2	50	5	9.4
C-8 (Loomis Brook above Cannonsville Reservoir						
Alkalinity (mg L^{-1})	≥10.0	12	1	8	na	16.9
Chloride (mg L^{-1})	50	12	0	0	10	12.7
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.22
Sulfate (mg L^{-1})	15	4	0	0	10	5.0
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	63
Dissolved sodium (mg L^{-1})	10	4	0	0	5	8.3

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	2017 Mean[1]
CBS (formerly WDBN, West Branch Delaware River at Beerston Bridge)						
Alkalinity (mg L^{-1})	≥10.0	12	1	8	na	20.9
Chloride (mg L^{-1})	50	12	0	0	10	13.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.46
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	13	11	85	40	72
Dissolved sodium (mg L^{-1})	10	4	1	25	5	7.7
Neversink Watershed						
NCG (Neversink River near Claryville)						
Alkalinity (mg L^{-1})	≥10.0	12	12	100	na	3.7
Chloride (mg L^{-1})	50	12	0	0	10	4.1
Dissolved organic carbon (mg L^{-1})	25	13	0	0	9	1.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.13
Sulfate (mg L^{-1})	15	4	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	14	0	0	40	22
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.3
NK4 (Aden Brook above Neversink Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	11	92	na	5.9
Chloride (mg L^{-1})	50	12	0	0	10	4.7
Dissolved organic carbon (mg L^{-1})	25	13	0	0	9	1.2
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	<u>0.12</u>
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	13	0	0	40	27
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.5

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	2017 Mean[1]
NK6 (Kramer Brook above Neversink Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	9	75	na	9.4
Chloride (mg L^{-1})	50	13	4	31	10	45.7
Dissolved organic carbon (mg L^{-1})	25	13	0	0	9	2.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.57
Sulfate (mg L^{-1})	15	4	0	0	10	4.7
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	13	13	100	40	131
Dissolved sodium (mg L^{-1})	10	4	4	100	5	24.4
Pepacton Watershed						
P-13 (Tremper Kill above Pepacton Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	17.2
Chloride (mg L^{-1})	50	11	0	0	10	11.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.2
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.27
Sulfate (mg L^{-1})	15	4	0	0	10	4.0
Total ammonia-N (mg L^{-1})	0.25	11	0	0	0.05	<u>0.02</u>
Total dissolved solids (mg L^{-1})[2]	50	12	9	75	40	58
Dissolved sodium (mg L^{-1})	10	4	0	0	5	6.9
P-21 (Platte Kill at Dunraven)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	17.9
Chloride (mg L^{-1})	50	11	0	0	10	8.3
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	<u>0.18</u>
Sulfate (mg L^{-1})	15	4	0	0	10	3.8
Total Ammonia-N (mg L^{-1})	0.25	11	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	6	50	40	51
Dissolved sodium (mg L^{-1})	10	4	0	0	5	5.4

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	2017 Mean[1]
P-60 (Mill Brook near Dunraven)						
Alkalinity (mg L^{-1})	≥10.0	12	6	50	na	10.8
Chloride (mg L^{-1})	50	11	0	0	10	2.0
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.17
Sulfate (mg L^{-1})	15	4	0	0	10	3.5
Total ammonia-N (mg L^{-1})	0.25	11	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	28
Dissolved sodium (mg L^{-1})	10	4	0	0	5	1.3
P-7 (Terry Clove above Pepacton Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	3	25	na	14.3
Chloride (mg L^{-1})	50	11	0	0	10	1.0
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.26
Sulfate (mg L^{-1})	15	4	0	0	10	3.8
Total ammonia-N (mg L^{-1})	0.25	11	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	1.2
P-8 (Fall Clove above Pepacton Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	4	33	na	13.7
Chloride (mg L^{-1})	50	11	0	0	10	2.7
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.31
Sulfate (mg L^{-1})	15	4	0	0	10	4.1
Total ammonia-N (mg L^{-1})	0.25	11	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	2.1

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	2017 Mean[1]
PMSB (East Branch Delaware River near Margaretville)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	18.9
Chloride (mg L^{-1})	50	11	0	0	10	12.8
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.32
Sulfate (mg L^{-1})	15	4	0	0	10	3.8
Total ammonia-N (mg L^{-1})	0.25	11	0	0	0.05	0.03
Total dissolved solids (mg L^{-1})[2]	50	13	11	85	40	65
Dissolved sodium (mg L^{-1})	10	4	1	25	5	7.2
Rondout Reservoir						
RD1 (Sugarloaf Brook near Lowes Corners)						
Alkalinity (mg L^{-1})	≥10.0	12	12	100	na	4.9
Chloride (mg L^{-1})	50	12	0	0	10	8.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.09
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	0	0	40	33
Dissolved sodium (mg L^{-1})	10	4	0	0	5	4.0
RD4 (Sawkill Brook near Yagerville)						
Alkalinity (mg L^{-1})	≥10.0	12	12	100	na	5.7
Chloride (mg L^{-1})	50	12	0	0	10	6.7
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.7
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.06
Sulfate (mg L^{-1})	15	4	0	0	10	4.4
Total ammonia-N (mg L^{-1})	0.25	11	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	1	25	5	6.0

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	2017 Mean[1]
RDOA (Rondout Creek near Lowes Corners)						
Alkalinity (mg L^{-1})	≥10.0	12	12	100	na	4.0
Chloride (mg L^{-1})	50	12	0	0	10	4.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	0.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.10
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	24	0	0	40	23
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.8
RGB (Chestnut Creek below Grahamsville STP)						
Alkalinity (mg L^{-1})	≥10.0	12	8	67	na	8.3
Chloride (mg L^{-1})	50	12	0	0	10	18.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.28
Sulfate (mg L^{-1})	15	4	0	0	10	4.1
Total ammonia-N (mg L^{-1})	0.25	13	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	12	100	40	65
Dissolved sodium (mg L^{-1})	10	4	2	50	5	10.7

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	2017 Mean[1]
East of Hudson						
AMAWALKR (Amawalk Reservoir Release)						
Alkalinity (mg L^{-1})	≥40.0	11	0	0	na	76.8
Chloride (mg L^{-1})	100	11	11	100	35	136.0
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	4.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	11	0	0	0.35	<u>0.14</u>
Sulfate (mg L^{-1})	25	4	0	0	15	11.4
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	<u>0.09</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	412
Dissolved sodium (mg L^{-1})	20	4	4	100	15	70.1
BOGEASTBRR (Combined release for Bog Brook and East Branch Reservoirs)						
Alkalinity (mg L^{-1})	≥40.0	11	0	0	na	79.9
Chloride (mg L^{-1})	100	11	1	9	35	76.3
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	11	0	0	0.35	0.13
Sulfate (mg L^{-1})	25	4	0	0	15	11.0
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	<u>0.04</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	287
Dissolved sodium (mg L^{-1})	20	4	4	100	15	34.9
BOYDR (Boyd's Corners Release) [3]						
Alkalinity (mg L^{-1})	≥40.0	11	9	82	na	34.5
Chloride (mg L^{-1})	100	11	0	0	35	44.7
Dissolved organic carbon (mg L^{-1})	25	50	0	0	9	4.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	10	0	0	0.35	<u>0.06</u>
Sulfate (mg L^{-1})	25	4	0	0	15	6.7
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	<u>0.04</u>
Total dissolved solids (mg L^{-1})[2]	175	52	0	0	150	153
Dissolved sodium (mg L^{-1})	20	4	4	100	15	25.2

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	2017 Mean[1]
CROFALLSVC (Croton Falls Reservoir Release)						
Alkalinity (mg L^{-1})	≥40.0	9	0	0	na	69.3
Chloride (mg L^{-1})	100	9	6	67	35	101.2
Dissolved organic carbon (mg L^{-1})	25	42	0	0	9	3.4
Nitrate+Nitrite-N (mg L^{-1})	1.5	8	0	0	0.35	<u>0.24</u>
Sulfate (mg L^{-1})	25	3	0	0	15	12.4
Total ammonia-N (mg L^{-1})	0.20	10	4	40	0.10	<u>0.18</u>
Total dissolved solids (mg L^{-1})[2]	175	65	65	100	150	325
Dissolved sodium (mg L^{-1})	20	3	3	100	15	43.3
CROSS2 (Cross River above Cross River Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	11	0	0	na	61.4
Chloride (mg L^{-1})	100	11	0	0	35	52.8
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	4.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	11	0	0	0.35	<u>0.13</u>
Sulfate (mg L^{-1})	25	4	0	0	15	8.8
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	<0.02
Total dissolved solids (mg L^{-1})[2]	175	13	12	92	150	209
Dissolved sodium (mg L^{-1})	20	4	4	100	15	25.3
CROSSRVVC (Cross River Reservoir Release)						
Alkalinity (mg L^{-1})	≥40.0	11	0	0	na	49.0
Chloride (mg L^{-1})	100	11	0	0	35	48.5
Dissolved organic carbon (mg L^{-1})	25	50	0	0	9	3.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	10	0	0	0.35	<u>0.07</u>
Sulfate (mg L^{-1})	25	4	0	0	15	8.5
Total ammonia-N (mg L^{-1})	0.20	12	2	17	0.10	<u>0.14</u>
Total dissolved solids (mg L^{-1})[2]	175	52	51	98	150	189
Dissolved sodium (mg L^{-1})	20	4	3	75	15	29.8

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	2017 Mean[1]
DIVERTR (Diverting Reservoir Release)						
Alkalinity (mg L^{-1})	≥40.0	11	0	0	na	79.5
Chloride (mg L^{-1})	100	11	1	9	35	80.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	11	0	0	0.35	0.20
Sulfate (mg L^{-1})	25	4	0	0	15	11.7
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	<u>0.04</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	295
Dissolved sodium (mg L^{-1})	20	4	4	100	15	40.9
EASTBR (East Branch Croton River above East Branch River)						
Alkalinity (mg L^{-1})	≥40.0	11	0	0	na	94.9
Chloride (mg L^{-1})	100	11	0	0	35	61.0
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	5.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	11	0	0	0.35	<u>0.08</u>
Sulfate (mg L^{-1})	25	4	0	0	15	9.9
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	<u>0.02</u>
Total dissolved solids (mg L^{-1})[2]	175	13	13	100	150	270
Dissolved sodium (mg L^{-1})	20	4	4	100	15	29.7
GYPSYTRL1 (Gypsy Trail Brook above West Branch Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	8	67	na	35.9
Chloride (mg L^{-1})	100	12	0	0	35	46.1
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	5.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	<u>0.03</u>
Sulfate (mg L^{-1})	25	4	0	0	15	5.9
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	<0.02
Total dissolved solids (mg L^{-1})[2]	175	12	3	25	150	158
Dissolved sodium (mg L^{-1})	20	4	3	75	15	25.7

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	2017 Mean[1]
HORSEPD12 (Horse Pound Brook above West Branch Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	5	42	na	46.8
Chloride (mg L^{-1})	100	12	0	0	35	59.9
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	3.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.25
Sulfate (mg L^{-1})	25	4	0	0	15	8.1
Total Ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	<0.02
Total dissolved solids (mg L^{-1})[2]	175	13	12	92	150	205
Dissolved sodium (mg L^{-1})	20	4	4	100	15	31.3
KISCO3 (Kisco River above New Croton Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	11	0	0	na	87.3
Chloride (mg L^{-1})	100	11	9	82	35	134.1
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	3.8
Nitrate+Nitrite-N (mg L^{-1})	1.5	11	0	0	0.35	0.58
Sulfate (mg L^{-1})	25	4	0	0	15	15.8
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	0.02
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	432
Dissolved sodium (mg L^{-1})	20	4	4	100	15	64.3
LONGPD1 (Long Pond outflow above West Branch Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	60.0
Chloride (mg L^{-1})	100	12	6	50	35	100.3
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	5.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.16
Sulfate (mg L^{-1})	25	4	0	0	15	8.8
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	<0.02
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	312
Dissolved sodium (mg L^{-1})	20	4	4	100	15	46.2

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	2017 Mean[1]
MIKE2 (Michael Brook above Croton Falls Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	84.1
Chloride (mg L^{-1})	100	12	12	100	35	216.3
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	4.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	10	83	0.35	3.81
Sulfate (mg L^{-1})	25	4	1	25	15	22.0
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	0.02
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	620
Dissolved sodium (mg L^{-1})	20	4	4	100	15	106.8
MUSCOOT10 (Muscoot River above Amawalk Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	85.5
Chloride (mg L^{-1})	100	12	12	100	35	169.6
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	5.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.34
Sulfate (mg L^{-1})	25	4	0	0	15	10.1
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	0.03
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	494
Dissolved sodium (mg L^{-1})	20	4	4	100	15	74.9
TITICUSR (Titicus Reservoir Release)						
Alkalinity (mg L^{-1})	≥40.0	11	0	0	na	71.7
Chloride (mg L^{-1})	100	11	0	0	35	55.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	11	0	0	0.35	0.14
Sulfate (mg L^{-1})	25	4	0	0	15	9.8
Total ammonia-N (mg L^{-1})	0.20	12	1	8	0.10	0.08
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	231
Dissolved sodium (mg L^{-1})	20	4	4	100	15	26.9

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	2017 Mean[1]
WESTBR7 (West Branch Croton River above Boyd's Corners Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	6	50	na	40.4
Chloride (mg L^{-1})	100	12	0	0	35	39.9
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	5.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.03
Sulfate (mg L^{-1})	25	4	0	0	15	5.3
Total ammonia-N (mg L^{-1})	0.20	12	0	0	0.10	0.02
Total dissolved solids (mg L^{-1})[2]	175	12	1	8	150	144
Dissolved sodium (mg L^{-1})	20	4	4	100	15	24.6
WESTBRR (West Branch Reservoir Release)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	27.1
Chloride (mg L^{-1})	50	12	0	0	10	31.8
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	2.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.40	0.03
Sulfate (mg L^{-1})	15	4	0	0	10	6.0
Total ammonia-N (mg L^{-1})	0.20	12	1	8	0.05	0.07
Total dissolved solids (mg L^{-1})[2]	50	12	12	100	40	120
Dissolved sodium (mg L^{-1})	10	4	4	100	5	17.7

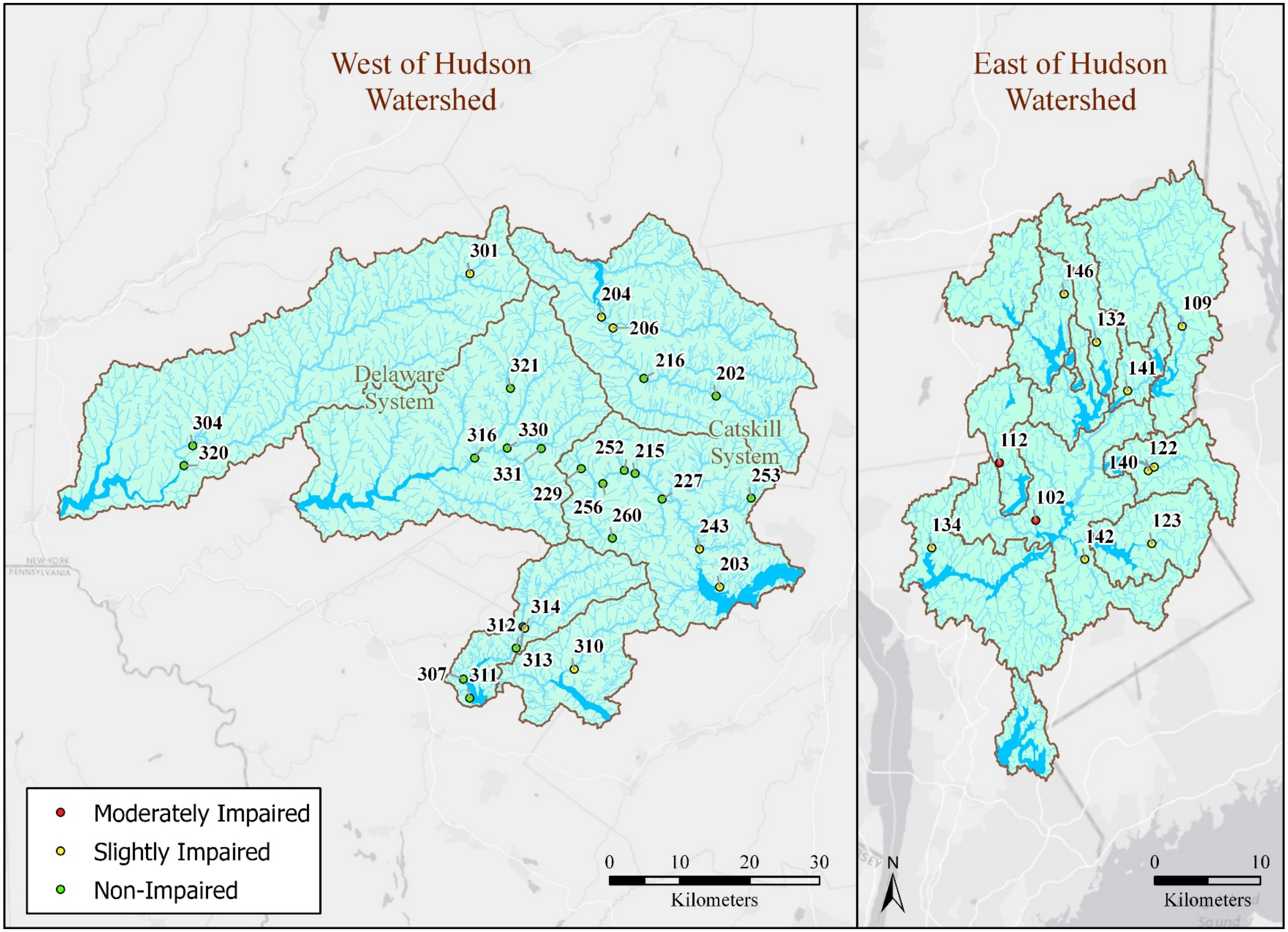
na = not applicable.

[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. In cases where >80% of data is censored the mean cannot be estimated and here we 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).

[3]Note: In 2017, CROFALLSVC, CROSSRVVC, SRR2CM and BOYDR were sampled weekly for dissolved organic carbon and total dissolved solids.

Appendix H. Biomonitoring Sampling Sites



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, Pentachlorophenol, 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