NYC Department of Environmental Protection

2018 Watershed Water Quality Annual Report

July 2019

Environmental Protection

Vincent Sapienza, P.E., Commissioner

Paul V. Rush, P.E., Deputy Commissioner

Bureau of Water Supply

The cover photo of the Neversink Intake Chamber was taken by Tina L. Johnstone, P.E. Tina began her career at DEP in 1992 as a Civil Engineer Intern in the Environmental Programs group in Ashokan and since then has held several positions of increasing responsibility. In 2016 Tina was appointed Director of Source Water Operations, where she has been responsible for source water reservoir operations, infrastructure maintenance and operations north of New York City, maintaining a robust dam safety program for all New York City owned and operated dams, and the operations of seven wastewater treatment plants in upstate New York. Tina will leave DEP in August 2019 to begin the next phase of her life and we thank her for her 27 years of service at DEP.

Table of Contents

List of Figures

List of Tables

List of Acronyms

BAP	Biological Assessment Profile
BEPA	Bureau of Environmental Planning and Analysis
BMP	Best Management Practice
BWS	Bureau of Water Supply
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
DOC	Dissolved Organic Carbon
DRO	Diesel Range Organics
EOH	East of Hudson
EWRM	Early Warning Remote Monitoring
FAD	Filtration Avoidance Determination
fDOM	Fluorescent Dissolved Organic Matter
GLEON	Global Lake Ecological Observatory Network
GWLF	Generalized Watershed Loading Function
HEV	Human Enteric Virus
IAR	Inactivation Ratio
LT2	Long Term 2 Enhanced Surface Water Treatment Rule
$\mu g\ L^{-1}$	microgram per liter
$\mu mhos\ cm^{-1}$	micromhos per centimeter
$mg\ L^{-1}$	milligram per liter
^oC	degree Celsius
MPN	Most Probable Number
MST	Microbial Source Tracking
NASEM	National Academies of Sciences, Engineering, and Medicine
ND	Non-detect
nm	Nanometers
NRT	Near real-time
NTU	Nephelometric Turbidity Units
NYC	New York City
NYSDEC	New York State Department of Environmental Conservation
NYSDOH	New York State Department of Health
Obs	Observations
OGP	Operational Guidance Plan
OST	Operational Support Tool
RHESSys	Regional Hydro-Ecologic Simulation System

ROS	Regression on order statistics
SPDES	State Pollutant Discharge Elimination System
SSM	single sample maximum
STRP	Sediment and Turbidity Reduction Project
SVOC	Semivolatile Organic Compound
SWAT	Soil Water Assessment Tool
SWTR	Surface Water Treatment Rule
TMDL	Total Maximum Daily Load
TNTC	too numerous to count
TP	Total Phosphorus
TSI	Trophic State Index
USEPA	United States Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	United States Geological Survey
UV	ultraviolet
VOC	Volatile Organic Compound
WISKI	Water Information Systems KISTERS
WMP	Waterfowl Management Program
WOH	West of Hudson
WPP	Watershed Protection Programs
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 2018 to manage the water quality of the New York City water supply and to provide information for regulatory agencies and the general public. Department of Environmental Protection (DEP) Commissioner Vincent Sapienza, P.E., provided oversight of the Department throughout 2018. 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. Mr. Andrew Bader, Chief of Watershed Water Quality Operations (WWQO), provided oversight of Watershed Field Operations, Watershed Laboratory Operations, Wildlife Studies, and Systems Support. Water Quality's Data Management section 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. Kurt Gabel, Deputy Chief for West of Hudson Field Operations; Mr. John Canning, Section Chief, Early Warning Remote Monitoring (EWRM),and Mr. David Robinson, Deputy Chief, East of Hudson Laboratory Operations. Mr. Gabel provided the information on Robotic Monitoring and Reservoir Operations, Mr. Canning described EWRM, and Mr. Robinson provided the text on operations to control water quality. Chapter 2 on Water Quantity was written by Mr. James Mayfield, Mr. Rich Van Dreason, and Mr. Matthew Giannetta, Chief of Regulatory & Engineering Programs, provided the text on use of rainfall data in the design of stormwater pollution prevention plans, and Mr. Ken DeRose, Section Chief for Data Management in Water System Operations provided 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. Kurt Gabel, and Ms. Allison Dewan. Chapter 4 on Kensico Reservoir was written by Mr. Dave Van Valkenburg, Mr. Chris Nadareski, Mr. Kurt Gabel, Mr. Christian Pace, Mr. David Quentin, and Ms. Kerri Alderisio, Section Chief of Watershed Impacts and Pathogen Assessment. Chapter 5 on Pathogens was co-authored by Ms. Kerri Alderisio, and Mr. Christian Pace. Chapter 6 Water Quality Modeling was written by Mr. Emmet Owens, P.E., Section Chief of Water Quality Modeling, Dr. Rakesh Gelda, Dr. Rajith Mukundan, Mr. Jordan Gass, Dr. Theo Kpodonu, and Dr. Myeong-Ho (Chris) Yeo. This chapter describes ongoing model development and applications conducted by the Modeling Section. 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, Mr. 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 Dr. Karen Moore 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.

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 8.6 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 2018, and compliance with regulatory standards. Field sampling, along with early warning and robotic monitoring equipment, are employed at over 550 sites throughout the watershed to measure an array of water quality analytes at various frequencies. DEP in 2018 performed approximately 240,000 analyses on 15,700 samples from these sites. In addition, DEP's Robotic Monitoring (RoboMon) network, which provides near real-time (NRT) data, made over 1.3 million measurements on over 550 sites throughout the watershed. These data provide scientific information to guide system operations, for use in water quality models, and for watershed protection policies. In 2018, the main water quality components driving operational changes were turbidity or disinfection by-product formation potential (DBPfp) surrogates, which were relatively low throughout the year. 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 2018 was 14.4 inches (365.76 mm) above the historical annual average (1988-2017) of 45.44 inches (1154 mm). The July-December 2018 period was the second wettest on record for New York. The annual runoff in 2018 was high (greater than the 85th percentile) for all sites. The United States Geological Survey (USGS) reported that New York State had above normal annual runoff (33rd highest out of the last 118 years) for the USGS 2018 water year (October 1, 2017-September 30, 2018), which does not include the high runoff from the latter part of calendar year 2018.

Storage capacity was well below normal levels at the start of the year, but above average rainfall in January and February allowed capacity to exceed 95 percent in late February. Drier conditions in March lowered capacity to average historical values (1991-2017 average), but rain events in April and May increased capacity back above historic levels until early June when capacity approached the historic average where it remained until mid-July. Numerous rainstorms caused the capacity to reach nearly 100 percent by mid-August and capacity remained well above the historical values for the remainder of the year.

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

Despite higher than normal rainfall in 2018, turbidity levels in most of the Catskill/Delaware and Croton system streams and reservoirs were generally close to or below their historic median levels. However, a small number of streams, often sampled soon after rain events, had elevated turbidity in 2018.

Fecal coliform counts were higher than historic levels in most Croton System reservoirs and some streams in 2018. Higher levels were occasionally observed in the Catskill/Delaware System as well. Elevated counts in most cases were associated with rain events. However, coliform-restricted assessments indicated that all terminal reservoir basins remained “non-restricted” in 2018.

The phosphorus-restricted basin assessment for 2018 concluded that no Delaware or Catskill reservoir basin was phosphorus-restricted. With the exception of Boyd’s Corners, all Croton System reservoir basins continued to have phosphorus-restricted status. The 2018 geometric mean total phosphorus (TP) concentrations increased from the previous year in five reservoirs, with the largest increases in New Croton Reservoir (3.7 µg L^{-1} increase).

Total phosphorus (TP) levels in most Catskill/Delaware System reservoirs were within 1 µg L^{-1} of their historic median TP concentrations. TP in Rondout Reservoir was slightly elevated, and one tributary stream, Rondout Creek, showed its highest TP concentration in the last 10 years. Ten-year highs were also observed at the primary inputs to Pepacton and Cannonsville reservoirs but the reservoirs themselves did not exhibit elevated TP. Seven out of 11 Croton System reservoirs, as well as three of six Croton streams had high median TP concentrations compared to historic medians. Higher concentrations in both systems were typically associated with rain events.

Trophic state indices (TSI) are used to describe algal productivity of lakes and reservoirs. In 2018, TSI was within historic levels for all Catskill System reservoirs. In contrast, headwater Delaware System reservoirs, Cannonsville, Pepacton and Neversink, were slightly above their historic medians by 2-4 TSI units. Elevated phosphorus associated with numerous rain events preceding sample collection coincided with the highest monthly TSI observed at these reservoirs. TSI was higher than historic levels in nine of 11 reservoirs of the Croton System. Rain-associated TP inputs as well as unusually warm water temperatures in New Croton likely contributed the observed elevated TSI.

Evaluation of additional reservoir and stream analytes in 2018 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. Ashokan East, Schoharie, Pepacton, and Rondout Reservoirs had no exceedances of the single sample maximum and their annual means were slightly above the mean benchmark value of 8 mg L^{-1}. Ashokan West and Neversink had no exceedances, while Cannonsville was the only WOH reservoir that exceeded both the single sample and mean chloride benchmarks. 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 2018. Assessments followed protocols developed by the New York State Stream Biomonitoring Unit. Of the 11 Croton System sites assessed in 2018, only two were considered moderately impaired, while the other nine sites were slightly impaired based on Biological Assessment Profile (BAP) scores. Of the 11 sites assessed in the Catskill System, five were considered slightly impaired and six sites ranked as non-impaired. Of the 13 assessed in the Delaware System, three were slightly impaired and 10 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 2018.

In 2018, there were 15 water quality special studies conducted throughout the system. Four of these occurred in the Kensico basin and are reported in Chapter 4. In the first study, Foamstream, an alternative to the herbicide glyphosate was evaluated. It was found to be less effective than glyphosate and prone to equipment failure. The second study involved sampling to determine potential water quality impacts from the use of goats to clear unwanted vegetation from reservoir dikes. Baseline samples for total phosphorus, fecal coliform bacteria, and turbidity were collected at several locations from one dike in July. After the goats are introduced in 2019, samples for these analytes will be collected each month and compared to the baseline results. In the third study, a synoptic field survey was performed to assess spatial variability of fluorescent dissolved organic matter (fDOM) levels at sites in the Neversink and Cannonsville watersheds, including wetland sites. Variability in fDOM, a possible surrogate for disinfection byproducts (DBP) precursors, helped to identify source areas for these precursors. The fourth study was a one-time sampling event of a cloudy discharge from the Boyd's Corners Reservoir release. A number of parameters were analyzed, including metals and phytoplankton. All results were in a typical range for summer release water quality and no additional samples were collected. In a fifth study, additional sites were sampled for zebra mussels within Amawalk Reservoir in response to zebra mussels and veligers being observed upstream of the reservoir. Zebra mussels were not detected at any of these sites nor were they detected in a shoreline survey of the reservoir. In a sixth study, ultrasonic buoys were deployed as part of a pilot study to determine the effectiveness of ultrasonic treatment in preventing and reducing algal blooms. Two areas in East of Hudson reservoirs that historically have experienced high concentrations of blue-green algae during the summer months were selected for the study. A sonic platform was activated in June in Croton Falls Reservoir to with the aim of preventing an algae bloom. A second sonic platform was activated in August in New Croton Reservoir with the aim of reducing the algal bloom that occurred. A seventh study focused on sampling visible algal blooms for algal toxins. Sample collection supported the ultrasonic algal control pilot project and included all reservoirs where blooms were observed and sampled. Microcystin was detected in surface blooms at three reservoirs and anatoxin-a was detected in one reservoir. No algal toxins were detected in the reservoir keypoints. An eighth study for evaluating best management practices in stream restoration took place upstream and downstream from a project site on the Batavia Kill (Schoharie watershed). Monitoring continued in 2018 with collection of pre-construction turbidity data. A ninth and separate ongoing sampling effort for program assessment to evaluate septic-to-sewer conversion sites in the Schoharie and Pepacton basins continued in 2018. Monthly samples collected at four sites (one upstream and one downstream site for each project area) resulted in 542 analyses. A tenth special study focused on *Giardia* in the Rondout basin. The study was initiated due to unusually high *Giardia* cysts at the Delaware inflow to Kensico Reservoir. The high counts were traced back to the Rondout Reservoir outflow and sampling was performed to evaluate sources. Samples positive for *Giardia* were sent to the Center for Disease Control and Prevention (CDC) in Atlanta, Georgia, and results from the typing were helpful in identifying potential sources of the cysts. This investigation is continuing in 2019. An eleventh study was initiated in response to an increase in the number of taste and odor complaints that began in early October and were mostly for "musty" water. Special sampling was undertaken to try to identify the cause. This included reviewing the algal genera present and testing for geosmin and 2-methylisoborneol (MIB), which are known to cause taste and odor issues. Ultimately, it was concluded that the withdrawal of anoxic water from the bottom inlets was the main cause of the problem, but other factors may have also contributed. Operationally the intake level of withdrawal was changed to a higher elevation and the Croton Water Filtration Plant was restarted on October 16. Water from the Catskill Aqueduct was blended with the Croton water via the Catskill connection for the first 12 days to minimize the potential for the reoccurrence of taste and odor complaints.

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 keypoint 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. There was above average precipitation during 2018 with DEL18DT having turbidity values less than 5 NTU and most of the fecal coliform values were less than 20 fecal coliforms $100mL^{-1}$, which meant DEP continued to meet the SWTR turbidity and fecal coliform limits. The Waterfowl Management Program continues to be instrumental in keeping coliform bacteria concentrations well below the limits set by the SWTR. Routine inspections of the turbidity curtains near the Catskill Upper Effluent Chamber cove continued to show they were intact. Overall, water quality from Kensico continued to be excellent during 2018.

In addition to DEP's routine monitoring, there were four special investigations conducted in the Kensico watershed plus 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 and contained trace to low-level detections for human markers. The other two special investigations were in response to observed visual clues that were deemed not to have impacted water quality. The 2018 Bryozoan inspections were performed, but technical issues prevented observations during the middle part of the summer. After the video equipment was repaired, an early October video showed several colonies missing pieces and it was suspected that the pictures captured colonies beginning to slough off.

Chapter 5 Pathogen Monitoring and Research

DEP collected 581 samples for protozoan analysis, 53 for *Cryptosporidium* infectivity testing, and 40 samples for human enteric virus (HEV) monitoring in 2018. Most samples were collected at watershed streams (32.4%) and source water keypoint locations (30.5%). Additional samples were collected at Hillview Reservoir, the CAT/DEL UV plant, 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 improve the ability to genotype samples after slide processing. In many cases, this method change appeared coincident with a possible shift in data that suggested a potential increased detection of *Cryptosporidium* oocysts and, at times, a decreased detection of *Giardia* cysts. Moreover, an additional method variation - replacing acid dissociation with heat dissociation - was implemented by DEP in August 2017. This alteration has improved matrix spike recoveries for *Giardia*. Therefore, fluctuations in the sample data may be a result of the method changes and not a variation of prevalence in the environment. Additional data gathered using the new methods are needed to confirm the method changes as a cause of the potential shift in the data.

For the two-year period from January 1, 2017, to December 31, 2018, 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 0.0014 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 0.0010 oocysts L^{-1}.

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. An exception was *Giardia* levels at Rondout Reservoir, particularly in mid-November when cyst concentrations at the outflow were in the double digits. Several actions were taken to investigate this increase, which lasted into 2019. There were three samples positive for *Giardia* cysts at WWTPs this year, and one of those positive for *Giardia* was also positive for *Cryptosporidium*. As per the Hillview Administrative Order, DEP continued weekly protozoan monitoring at the Hillview Reservoir outflow (Site 3) through 2018, with 53 routine samples collected. Of the 53, there were nine samples positive for *Giardia* and five samples positive for *Cryptosporidium*.

Chapter 6 Water Quality Modeling

The staff of the Water Quality Science and Research Water Quality Modeling section undertakes the development, testing and application of climate, watershed/terrestrial, reservoir, and system operations models. To support this modeling work, the staff compiles, analyzes, and organizes data from various sources. Following testing and validation, models are used 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 precursors of disinfection byproduct precursors.

In the area of climate modeling, an analysis of historical precipitation data from stations in and around the West of Hudson watersheds was conducted in order to identify regions within the watersheds where statistics of precipitation are similar. Based on these regions, a stochastic weather model was developed to predict the spatial variation of precipitation over the entire watershed for historic periods. Also in climate modeling, procedures were developed and tested to utilize meteorological forecasts that have been downscaled from global climate models for use as inputs to watershed and reservoir models to evaluate climate change impacts. Final testing of the Regional Hydro-Ecologic Simulation System (RHESSys) watershed model for two small watersheds draining to Neversink Reservoir is described, and RHESSys simulations of streamflow are compared to predictions by the Soil and Water Assessment Tool (SWAT) model. Software that has been developed to automate the preparation of input data and the execution of model simulations for the Generalized Watershed Loading Function (GWLF) model is also described.

In addition to the comparison to RHESSys, SWAT was also used to evaluate the impacts of climate change on streamflow and stream turbidity in the Esopus Creek watersheds, and to evaluate the impact of agricultural management practices (a component of DEP's watershed protection program) in the Cannonsville Reservoir watershed. Predictions resulting from the integration of the turbidity model for Rondout Reservoir into DEP's Operations Support Tool (OST) are presented. Contributions and follow-up work by the Water Quality Modeling section related to reviews by two expert panels from the National Academies of Sciences, Engineering and Medicine are described.

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). DEP has found this an efficient way to bring specialized expertise into the work of the Directorate and to remain at the forefront of developments in the water supply industry.

In 2018, the WQD managed nine water quality-related contracts to enhance its ability to monitor and model the watershed. These included several contracts for specialized laboratory analyses, hydrological monitoring by United States Geological Survey (USGS), modeling support through CUNY-RF, waterfowl management, zebra mussel monitoring, bathymetric surveys by the USGS, and Water Information Systems KISTERS (WISKI) software support.

DEP participated in six Water Research Foundation (WRF) projects as both project advisory committee members and as participating utilities. Topics of research included a watershed project on the impact of wildfires, emerging contaminants, workforce skills, customer communications, and two projects on reducing lead in distribution systems.

WQSR and the Bureau of Environmental Planning and Analysis (BEPA) staff participate with the other members of the Water Utility Climate Alliance (WUCA), a consortium of 10 water utilities across the nation with interest in planning for climate change. DEP shared expertise on turbidity modeling with scientific staff from Portland, Oregon and the use of weather generators for evaluating climate change impacts with staff from Austin, Texas.

In addition, DEP participated in the international Global Lake Ecological Observatory Network (GLEON). GLEON20 was held on December 3-7, 2018 on Rottnest Island, Australia and provided an opportunity to follow up on existing projects and discuss potential future collaborations. DEP co-chaired a project formed at GLEON19, "*Before the Pipe: Monitoring and Modeling DBP Precursors in Drinking Water Sources*", to identify important questions on disinfection byproduct precursors. The project group made progress in refining the scope of a systematic review of the state of knowledge on DBP precursors. DEP also contributed data for the "*Long-term Dissolved Oxygen (DO) Concentrations in Lakes and Reservoirs*" study. This project focuses on using long-term dissolved oxygen profiles from 400 lakes around the globe to identify trends in dissolved oxygen. These projects allow DEP to see water quality in a global context and provide insight 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 2018, 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 2018 Drinking Water Supply and Quality Report (https://www1.nyc.gov/site/dep/about/drinking-water-supply-quality-report.page), which is distributed to consumers annually to provide information about the quality of the City's tap water. Thus, the two reports together document water quality from its source to the tap.

The New York City Water Supply System (Figure 1.1) provides drinking water to almost half the state's population, which includes over 8.6 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 develop the information needed to meet these goals, there is an ongoing process of water quality data collection, data analysis, report generation, and modeling runs that

Figure 1.1 The New York City Water Supply System.

guide operational responses to changing conditions. The data for these activities is provided by the field and laboratory crews of Watershed Water Quality Operations based at three upstate locations in Grahamsville, Kingston, and Hawthorne, NY. Water Quality Science and Research is the division responsible for data analysis. This report provides an overview of watershed water quality in 2018 and describes how high quality source water is reliably maintained through constant vigilance and operational changes. The work of the Water Quality Directorate is also supplemented 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 to meet several objectives. 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 2018a). 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 specific objectives of DEP.

A summary of the number of grab samples and analyses that were processed in 2018 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 2018 WWQMP (DEP 2018a). Samples taken as the result of special investigations (SIs) are included. The sample numbers for the City's distribution system are also listed for completeness. (However, this report focuses on results from watershed samples.) Analyses of samples from the free residential lead test kits were performed at the DEP Kingston Laboratory. These are included in the number of analyses conducted by DEP's watershed laboratories. (The number of free residential lead kits returned to DEP and analyzed increased slightly from 2017 (with 3,535 analyzed of 7,947 requested) to 2018 (with 3,892 analyzed of 8,972 requested).

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

Table 1.1 Summary of grab samples collected, water quality analyses performed, and sites visited by WQD in 2018.

System	Number of Samples	Number of Analyses	Number of Sites
Watershed	15,700	240,000	553
Distribution	37,500	414,700	~1,000
Total	**53,200**	**654,700**	**~1,553**

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 invaluable for protection of the water supply, particularly during storm events; for special investigations; and for construction of water supply infrastructure projects that potentially affect water quality.

The RoboMon network began in 2012 with four reservoir sites (three at Ashokan and one at Kensico). The network has continued to grow to its current configuration of 19 sites located in both reservoirs and streams (Figure 1.2), and also includes under-ice buoys during the winter at two sites (4.2EAE and 3.1EAW). There has also been enhancement of the sites with additional sensors to obtain data essential for model development.

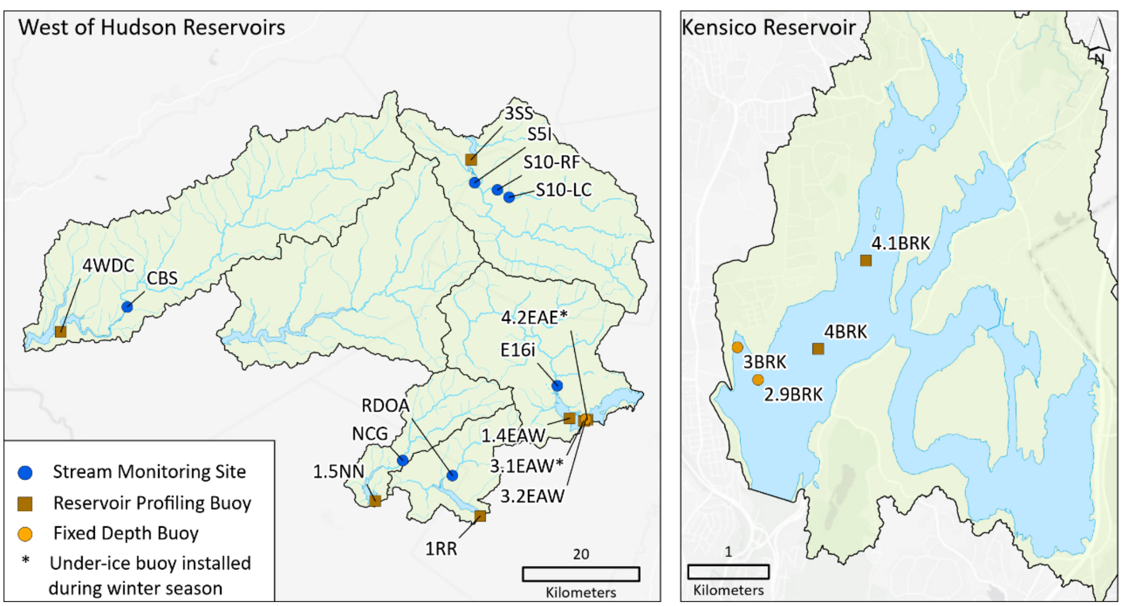


Figure 1.2 Robotic monitoring sites and types in the Catskill and Delaware Systems in 2018.

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. The profiling buoys deployed at Kensico (4.1BRK and 4BRK) both had issues that required frequent troubleshooting, indicating that routine replacement is essential as a consequence of age. 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 2BRK and 2.9BRK. 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 2018. These buoys have been successfully set up and operated for four years. 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).

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.

Each robotic monitoring location contains datalogging 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 1.3 million measurements in 2018 at 19 sites (Table 1.2).

Table 1.2 Summary of Robotic Monitoring measurements in 2018.

System/Field Section	Number of Measurements	Number of Sites
Catskill/Kingston	520,000	9
Delaware/Grahamsville	517,000	6
EOH/Hawthorne	286,000	4
Total	**1,323,000**	**19**

1.1.3 Early Warning Remote Monitoring (EWRM)

Early Warning Remote Monitoring (EWRM) of selected keypoint (aqueduct) sites 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 EWRM sites includes the use of daily or weekly grab samples and continuously-recording automated monitoring equipment. The automated equipment at these keypoint sites is operated and maintained by the EWRM group. 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 Water 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 dramatic water quality changes or possible contamination. The purchase of a new fish biological monitoring system called the ToxProtect 64 progressed in 2018 for delivery and installation in 2019. The new system is anticipated to reduce both false alarms and maintenance expenditures.

In 2018, enhancements to EWRM included instrumentation data for the Rondout elevation taps made available in the Supervisory Control and Data Acquisition (SCADA) system and a temporary panel was installed at the Schoharie Tunnel Intake Chamber (STIC).

1.2 Operations in 2018 to Manage Water Quality

In 2018, the potential formation of disinfection by-products (DBPfp) was formally added to the list of key parameters driving selective withdrawal in order to deliver the highest quality water to the distribution system. As surrogates for DBPfp, absorbance at 254 nm (UV254), an indicator of aromatic organic compounds found in natural organic matter and dissolved organic carbon (DOC) were monitored weekly at the reservoir effluents and elevation taps, and the data helped guide decision making when selecting which reservoirs to utilize. This proved most useful in the Delaware District where there can be significant differences between the three headwater reservoirs. Utilizing reservoirs with lower UV254 and DOC may have helped minimize DBP formation in the distribution system.

In the Catskill System, the elevation and location (East and/or West Basin) of withdrawal at Ashokan Reservoir was adjusted throughout the year to draw the best quality water (e.g., low turbidity, coliforms, UV254, and DOC) from the reservoir. Also, several changes were made to meet operational needs (e.g., lowering the West Basin to create a void to accept more runoff during large storm events). In 2018, the main water quality component driving operational changes was turbidity or the DBPfp surrogates which were relatively low throughout the year.

In 2018, the Catskill system diverted water from middle elevations from the East and West Basins. In the beginning of the year, the water was diverted from the West Basin. This configuration continued only until mid-January when the diversion was switched to the East Basin to take advantage of lower turbidity. The dividing weir was opened as needed to equalize the two basin elevations, and closed at times to reduce the spill from East Basin when reservoir storage was high. In June, the diversion was changed to the West Basin to begin developing a storage void to protect the East Basin from future storm event impacts. This configuration persisted until the end of July when lower turbidity in the East Basin warranted a change to that basin. The diversion remained on East Basin for the remainder of the year, and the dividing weir was opened as necessary to equalize the basin elevations.

In the Delaware System, intake chambers at the four reservoirs were configured for diversion through the mid- or lower-level intakes, and no elevation changes were needed at any of the reservoirs in 2018. As mentioned above, UV254 and DOC data did help guide decisions on how much water was diverted into Rondout from the three upstream reservoirs and out of Rondout to the Delaware Aqueduct`.

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. This proactive change is made due to the potential for wave action to resuspend adjacent shoreline sediments. Float mode operation brings water from the Delaware Aqueduct directly to the downtake at Delaware Aqueduct Shaft 18, supplemented by water drawn from Kensico Reservoir. This operational change minimizes turbidity that could otherwise enter the distribution system. Float operation in anticipation of strong winds occurred six times (for all or part of 16 days) in 2018. The reservoir was also placed in float mode two times (for all or part of 9 days) to control for further turbidity issues and one additional time for all or part of 4 days, to minimize fecal coliform bacteria.

The Croton Water Filtration Plant was in operation from May 17 to August 15, when it was shut down for maintenance. The plant was restarted on October 1. Taste and odor complaints began to rise on October 5, as a result the plant was shut down on October 15. The plant was restarted on October 16 using only Catskill Aqueduct water. Croton and Catskill waters were then blended with the proportion of Croton water gradually increasing until October 28, when Catskill water was no longer being used. For additional information on the water quality investigation related to the taste and odor issue, see section 3.13.11.

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

2.2 2018 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 2018 monthly precipitation total for each watershed is plotted along with the historical monthly average (1988-2017) (Figure 2.1).

The total monthly precipitation figures show that precipitation was generally near normal for the first four months of 2018. However, in February all watersheds were above average with four of them more than 2 inches above normal, and in April, Ashokan and Schoharie were more than two inches above normal. From May through June, all watersheds had below average monthly precipitation values, with Ashokan having the largest deficit, 1.86 inches in May and 3.39 inches in June. From July through November, the monthly rainfall totals were above the historic average except for Ashokan and New Croton in October. All of the watersheds were near normal in December, except for Ashokan and New Croton (1.75 and 3.56 inches above normal, respectively). In 2018 the NYC water supply watershed received 14.4 inches (366 mm) of precipitation above the historical annual average (1988-2017) of 45.44 inches (1154 mm).

The National Climatic Data Center's (NCDC) climatological rankings (https://www.ncdc.noaa.gov/cag/) were queried to determine the 2018 rankings for New York. Overall total precipitation for New York State in 2018 was 48.63 inches (1,235 mm), which was 8.34 inches (212 mm) above the 20th-century mean (1901-2000) and the eighth wettest in the last 124 years (1895-2018). It should be noted that the July-December 2018 period was the second wettest on record for New York. In New York's Climate Division 2, which includes the WOH reservoirs, the 2018 precipitation total was 14.94 inches (379.5 mm) above the 20th-century mean and the second wettest since 1895 and the July-December period was the wettest July-December on record for the division. In New York's Climate Division 5, which includes the EOH reservoirs, precipitation was 11.96 inches (303.8 mm) above the 20th-century mean (1901-2000) and the fourth wettest on record, and the July-December period was second only to 2011 as the wettest July-December period on record for this division. Also, the average temperature for New York State in 2018 was 46.2°F (7.9°C), which was 1.7°F (1.0°C) above normal (1901-2000) and the eighteenth warmest in the last 124 (1895-2018) years for New York.

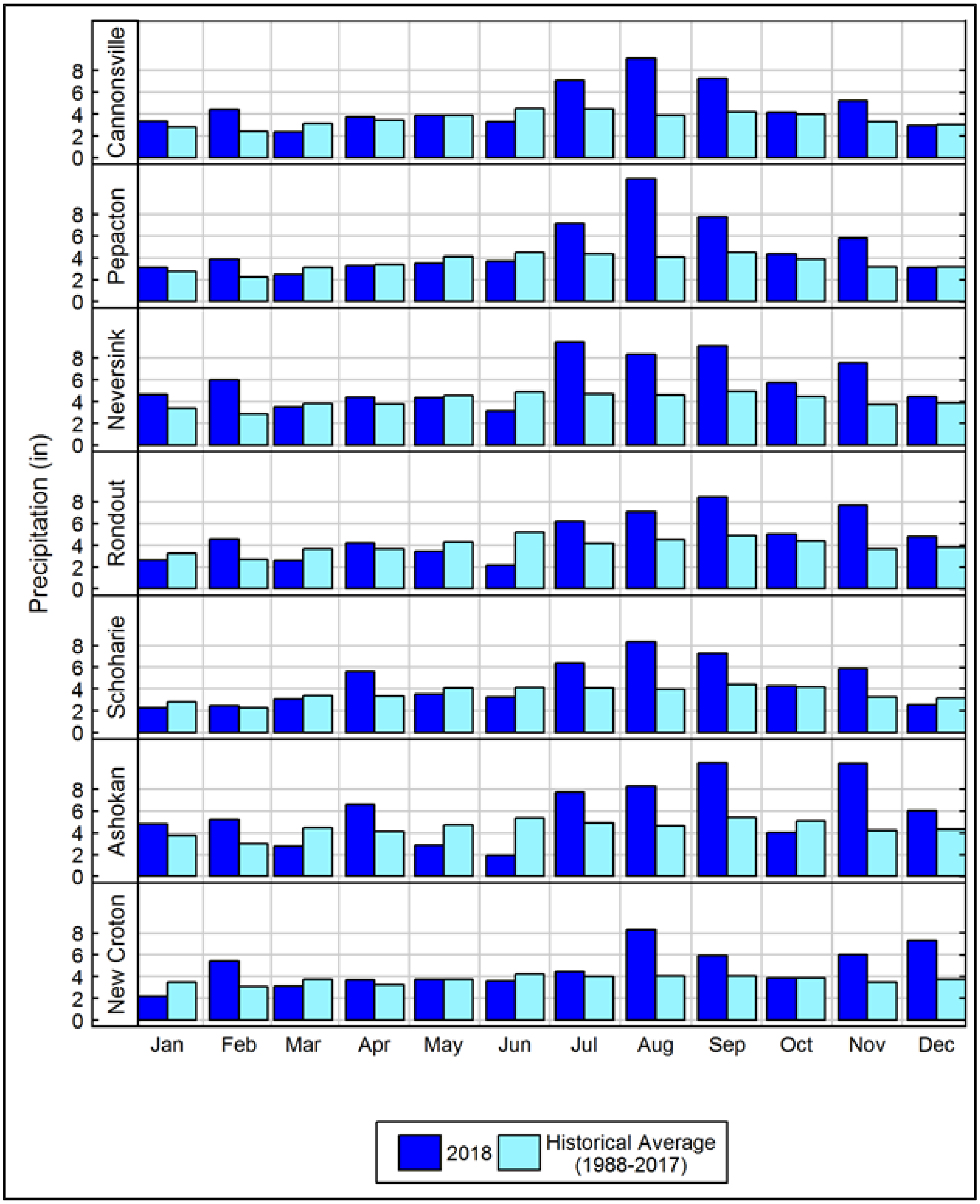


Figure 2.1 Monthly precipitation totals for New York City watersheds, 2018 and historical values (1988-2017).

2.3 2018 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, drainage network pattern, and occurrence and area of ponds, lakes, reservoirs, sinks, and other features of the basin which store or alter runoff. The annual runoff is a useful statistic to compare the runoff between watersheds. It is calculated by dividing the annual flow volume by the drainage basin area, yielding a depth that would cover the drainage area if all the runoff for the year were uniformly distributed over the basin. This statistic allows comparisons of the hydrologic conditions in watersheds of varying sizes.

Selected USGS stations (Figure 3.8) were used to characterize annual runoff in the different NYC watersheds (Figure 2.2). The time period with a complete record to calculate annual statistics for the WOH USGS stations ranges from 55 years at the Esopus Creek Allaben station to 112 years at the Schoharie Creek Prattsville gage. The EOH USGS stations have a 23-year period of record, except for the Wappinger Creek site (90-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 calendar year 2018 was high (greater than the 85th percentile) for all sites, with the Neversink at Claryville having its highest annual runoff value for its period of record. Overall, New York State had above normal runoff (33rd highest (72.27nd percentile) out of the last 118 years) for the 2018 water year (October 1, 2017-September 30, 2018), 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 calculation for water year 2018 results does not include the impacts from the latter part of 2018, in particular November when each watershed exceeded its historical rainfall average, ranging from an increase of 1.94 at Cannonsville to 6.14 inches at Ashokan.)

Figure 2.3 shows the 2018 mean daily discharge, along with the minimum, maximum, and median daily discharge for the period of record, for the same USGS stations used to characterize annual runoff. The stream discharge reflects patterns that were near normal for the first six months of the year with occasional spikes from storms. From late June until December stream discharge was above the historic median at all sites.

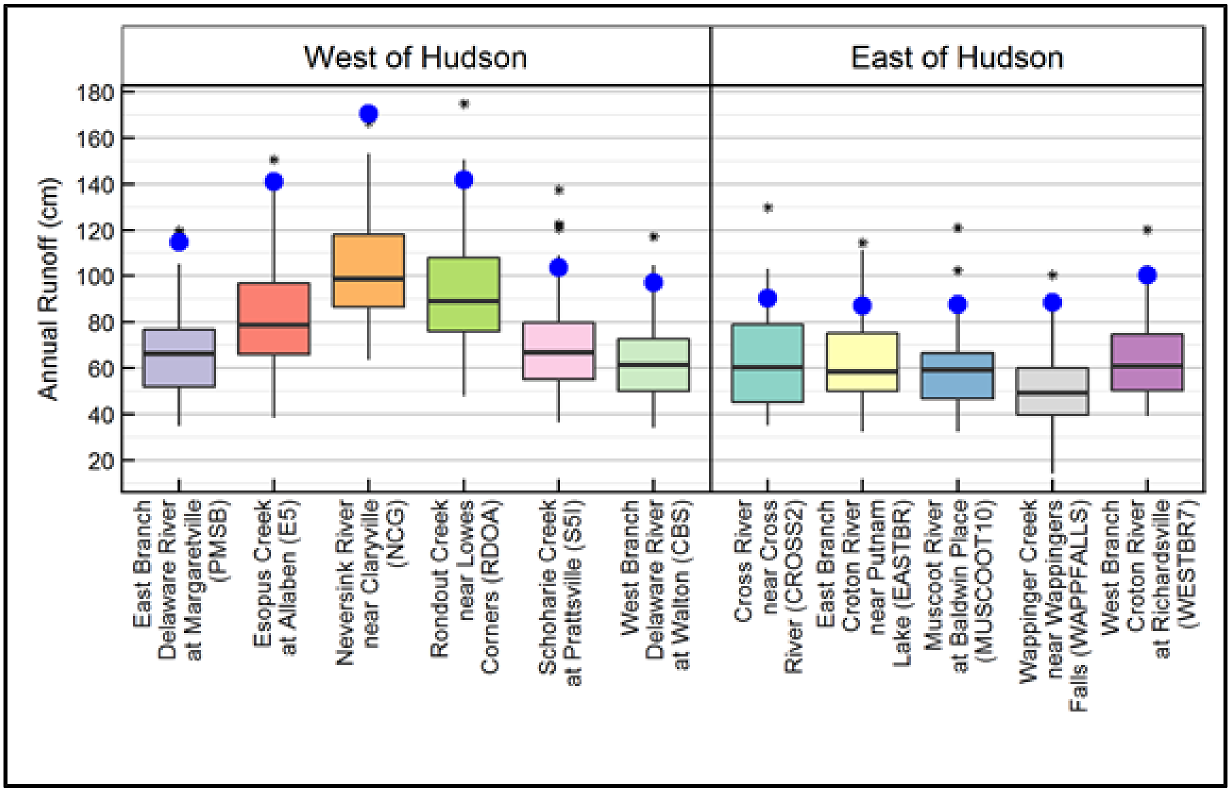


Figure 2.2 Historical annual runoff as boxplots for the WOH and EOH watersheds, with the values for 2018 displayed as a solid blue dot. The asterisks indicate outliers (see Appendix C for a key to the boxplot).

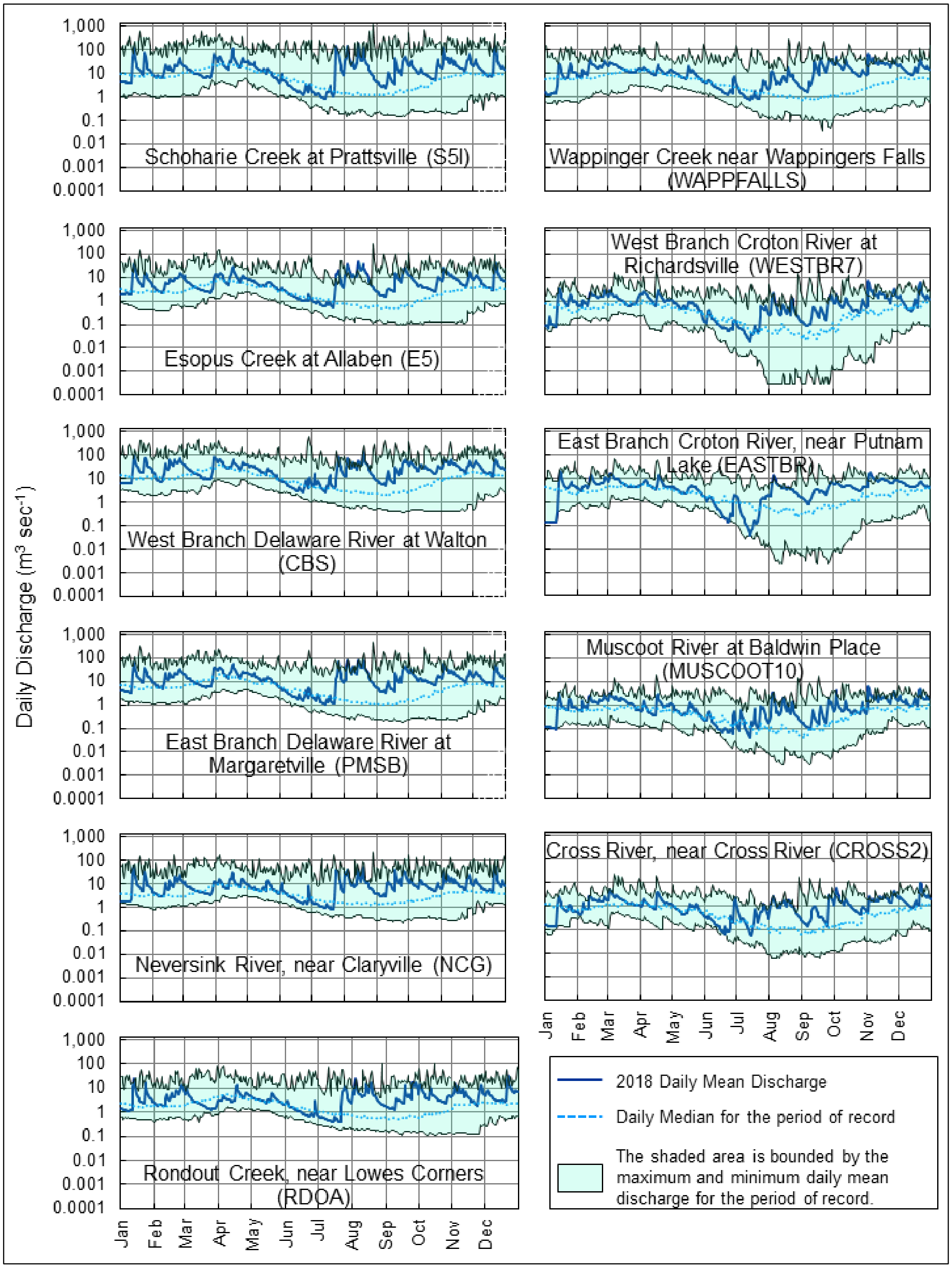


Figure 2.3 Daily mean discharge for 2018 at selected USGS stations. Daily data from October 1-December 31, 2018 are provisional and subject to revision until they have received final approval from the USGS.

2.4 Rainfall Data for the Design of Stormwater Pollution Prevention Plans

DEP is responsible for regulatory oversight of land development activities in the watershed through 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 90th percentile 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 90th percentile storm indicates the rainfall depth that is equaled or exceeded during 90% of all events of 24-hour duration. Figure 2.4 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.

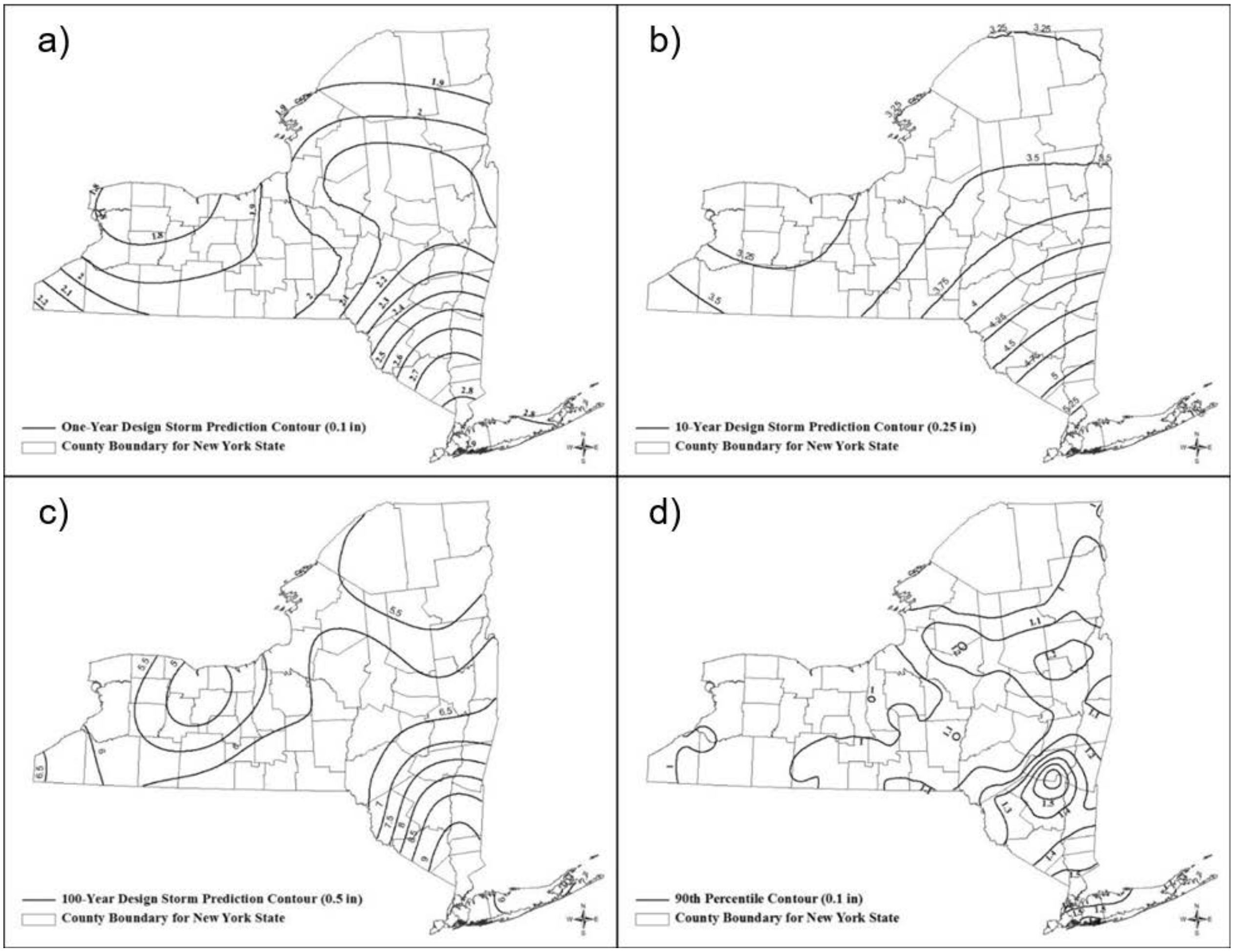


Figure 2.4 Design storm maps for New York State from the NYSDEC 2015 Stormwater Management Design Manual: a) One-year, 24-hour design storm; b) The 10-year, 24-hour design storm; c) The 100-year, 24-hour storm; d) 90th percentile, 24-hour rainfall.

2.5 Reservoir Usable Storage Capacity in 2018

Ongoing daily monitoring of reservoir storage allows DEP to compare the system-wide storage in 2018 (including Kensico Reservoir) against average historical values for 1991-2017 for any given day of the year (Figure 2.8). Storage capacity started well below normal levels at the start of the year due to limited precipitation in December 2018. Above average rainfall in January and February allowed capacity to exceed 95 percent in late February, providing about a 10 percent surplus compared to historic levels. Drier conditions in March lowered capacity to historic levels later in that month. Frequent rain events in April and May increased capacity above historic levels until early June. Closely mimicking historic patterns, capacity then declined through early summer. However, nearly constant rain starting in mid-July caused capacity to reach nearly 100 percent by mid-August. Conditions remained unusually wet with capacity fluctuating between 90 and 95 percent for the remainder of the year.

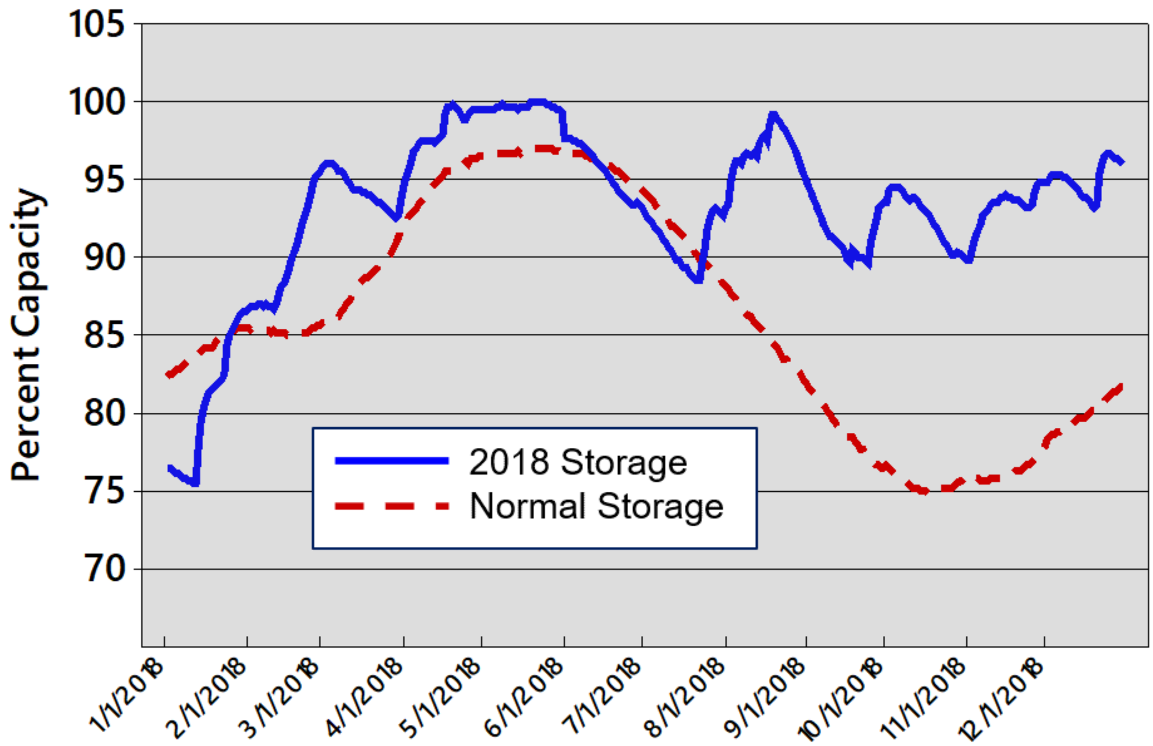


Figure 2.5 Systemwide usable storage in 2018 compared to the average historical value (1991-2017). Storage greater than 100% occurs when the water surface elevation is greater than the spillway elevation and reservoirs are spilling.

3. Water Quality

3.1 Monitoring Overview

Water quality samples are collected from designated sites (Appendix B, Figures 1-7) at streams, reservoirs, and aqueduct locations throughout the NYC water supply. Routine stream samples used in this report are collected on a fixed frequency, typically monthly schedule. Unless otherwise indicated, reservoir samples are obtained from multiple sites and multiple depths with routine sampling frequencies of once per month from April through November. Aqueduct keypoint samples are collected year round at frequencies that vary from daily to weekly. Note that although Kensico Reservoir is usually operated as a source water, the reservoir can be bypassed so that any or all of the following reservoirs can be operated as source waters: Rondout, Ashokan East Basin, Ashokan West Basin, and West Branch. When operating as a source, water from these reservoirs is regulated by the Surface Water Treatment Rule (SWTR).

3.2 Reservoir Turbidity Patterns in 2018

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

Despite relatively high rainfall totals in 2018 (Figure 2.1), turbidity levels throughout the Catskill/Delaware System reservoirs were close to their median historic levels or well below in the cases of Ashokan East and West, and Cannonsville (Figure 3.1). (A key to boxplots is provided in Appendix C).

Past turbidity and suspended-sediment monitoring in the Ashokan basin found that the Stony Clove sub-basin was the highest yielding suspended-sediment contributor in the Ashokan basin prior to 2013 (McHale and Siemion, 2014). Since 2012, DEP and the U.S. Department of Agriculture Natural Resource Conservation Service have sponsored eight stream sediment and turbidity reduction projects (STRPs) - totaling approximately 2 kilometers in length - in the Stony Clove sub-basin to help reduce turbidity at the sub-basin scale within the Ashokan basin. DEP and USGS began a 10-year suspended-sediment and turbidity monitoring study in 2016 to (1) track sub-basin trends in suspended-sediment yield and turbidity-discharge relationships in the upper Esopus Creek basin, and (2) evaluate the turbidity reduction efficacy of STRPs in the Stony Clove sub-basin. The most recent findings of this research are presented in a biennial

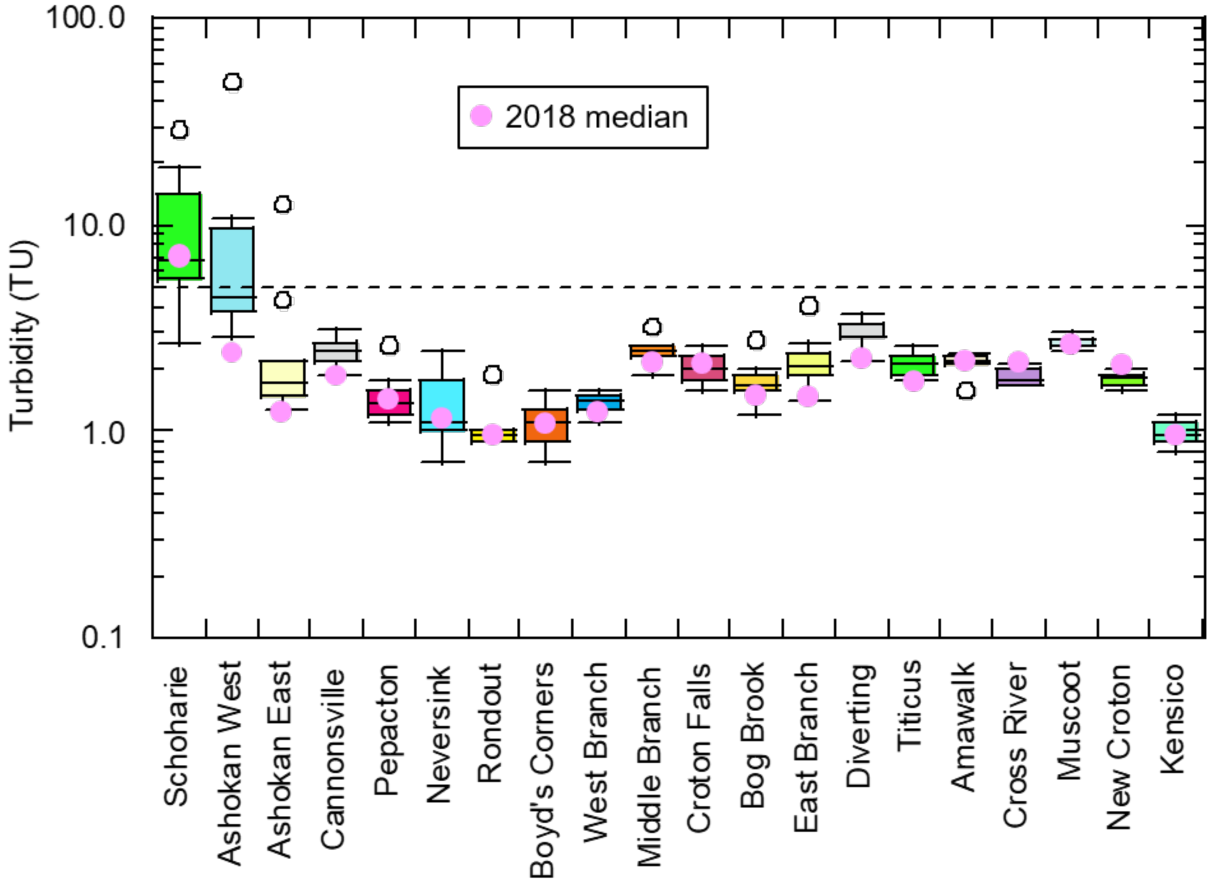


Figure 3.1 Annual median turbidity in NYC water supply reservoirs (2018 vs. 2008-2017) with the 2018 values displayed as a solid dot. The dashed line represents the SWTR standard for source water as a reference.

status report submitted as a FAD deliverable in March 2019 (DEP, 2019a). The current monitoring results show that Woodland Creek is ranked the highest yielding suspended-sediment and turbidity source in the Ashokan basin, followed by Broadstreet Hollow, Birch Creek, Beaver Kill and Stony Clove Creek. Figure 3.2 presents provisional turbidity-discharge regression relationships before and after STRP construction periods that clearly show a sustained reduction in Stony Clove Creek turbidity for monitored streamflow below 1,000 cfs. For reference, bankfull discharge is approximately 2,500-3,000 cfs at the monitoring station. Though it is early in the 10-year study, it appears that concentrating STRP implementation in a high suspended-sediment yielding sub-basin has reduced turbidity at low to moderately high flows and has an impact at the basin scale in modifying sub-basin source contributions.

West Branch Reservoir, which receives inputs from both the Delaware and Croton Systems, also had low turbidity levels in 2018. 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 1.2 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/Delaware System, turbidity was low corresponding to the high clarity of water received from both systems in 2018.

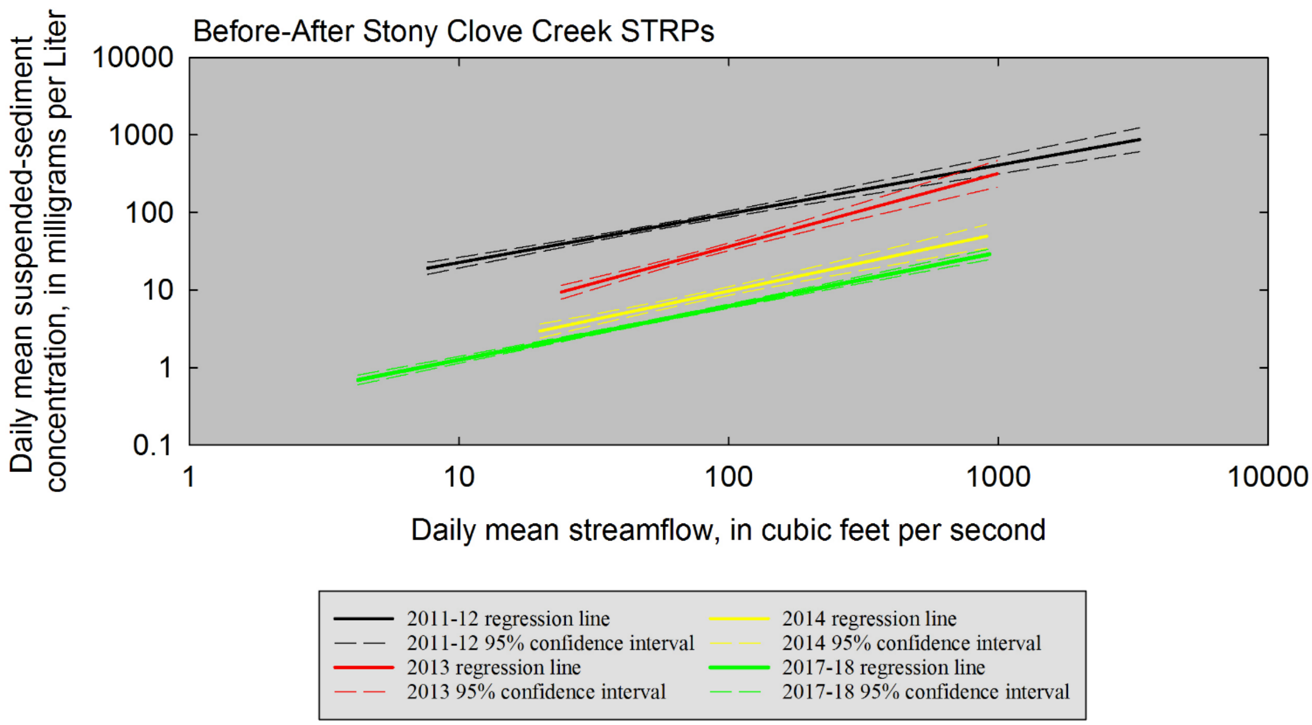


Figure 3.2 Daily mean suspended-sediment concentration versus daily mean streamflow for Stony Clove Creek before and after STRP construction periods.

Similar to the Catskill/Delaware System, turbidity in the Croton System was generally normal to well below normal in 2018 (reservoirs shown in Figure 3.1, controlled lakes in Table 3.1). Annual rainfall in the region was 13.8 inches more (32% above average) than the average rainfall from the previous 26-year period, with August, September, November, and December being particularly wet.

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

Lake	**Median Turbidity (2008-17)**	**Median Turbidity (2018)**
Gilead	1.4	1.0
Gleneida	1.5	1.1
Kirk	4.3	3.4

3.3 Coliform-Restricted Basin Assessments in 2018

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 water bodies classified as restricted. These regulations require the City to perform an annual review of its reservoir basins to make "coliform-restricted" determinations.

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

There were two method changes made during 2017 that are important to mention as it has bearing on comparing results for subsequent years with data from 2017 and prior. 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 August 28, 2017 Clean Water Act Methods Update Rule, and from NYS DOH laboratory accreditation on April 1, 2017. 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 " >" or ">=" when colonies on the plate exceed 200 coliforms 100mL^{-1}, "E" when target organisms are not in the ideal range, or a combination of those codes. A second change made in September 2017 required that the two DEP WOH laboratories add an additional plate with a different dilution to increase the likelihood of obtaining a valid coliform result and potentially reducing the number of data codes.

3.3.1 Terminal Basin Assessments

Table 3.2 provides coliform-restricted assessments for the five terminal reservoir basins. The results are based on 2018 fecal coliform data from a minimum of five samples each week over two consecutive six-month periods. If 10% or more of the coliform samples measured have values >20 fecal coliforms 100mL^{-1} and the source of the coliforms is determined to be anthropogenic (Section 18-48(d)(2)), the basin is classified as a "coliform-restricted" basin. All terminal reservoirs had fecal coliform counts below the 10% threshold and met the criteria for non-restricted basins for both six-month assessment periods in 2018.

Table 3.2 Coliform-restricted basin status as per Section18-48(c)(1) for terminal reservoirs in 2018.

Reservoir basin	Effluent keypoint	2018 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 2018 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 2018, there was an increase in exceedances of the Part 703 standard for total coliform as compared to the previous year for eight reservoirs. The highest number of exceedances occurred in Diverting Reservoir for all eight months sampled in 2018. Three reservoirs and three controlled lakes had no exceedances, while there was a reduction in exceedances from the previous year for three reservoirs.

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 2018.

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	3/8
Boyd's Corners	AA	50/240	5/8
Croton Falls	A/AA	50/240	4/8
Cross River	A/AA	50/240	0/8
Diverting	AA	50/240	8/8
East Branch	AA	50/240	2/8
Lake Gilead	A	2400/5000	0/8
Lake Gleneida	AA	50/240	0/8
Kirk Lake	B	2400/5000	0/8
Muscoot	A	2400/5000	1/8
Middle Branch	A	2400/5000	0/8
Titicus	AA	50/240	1/8
Cannonsville	A/AA	50/240	3/8
Pepacton	A/AA	50/240	3/8
Neversink	AA	50/240	1/8
Schoharie	AA	50/240	6/8

3.4 Reservoir Fecal and Total Coliform Patterns in 2018

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 3.3 and reservoir total coliform results in Figure 3.4. Coliform results for the controlled lakes of the Croton System are summarized in Table 3.4. 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. If a calculated annual 75th

percentile results in a censored value or zero it was estimated using the robust regression on statistics method (ROS) of Helsel and Cohn (1988).

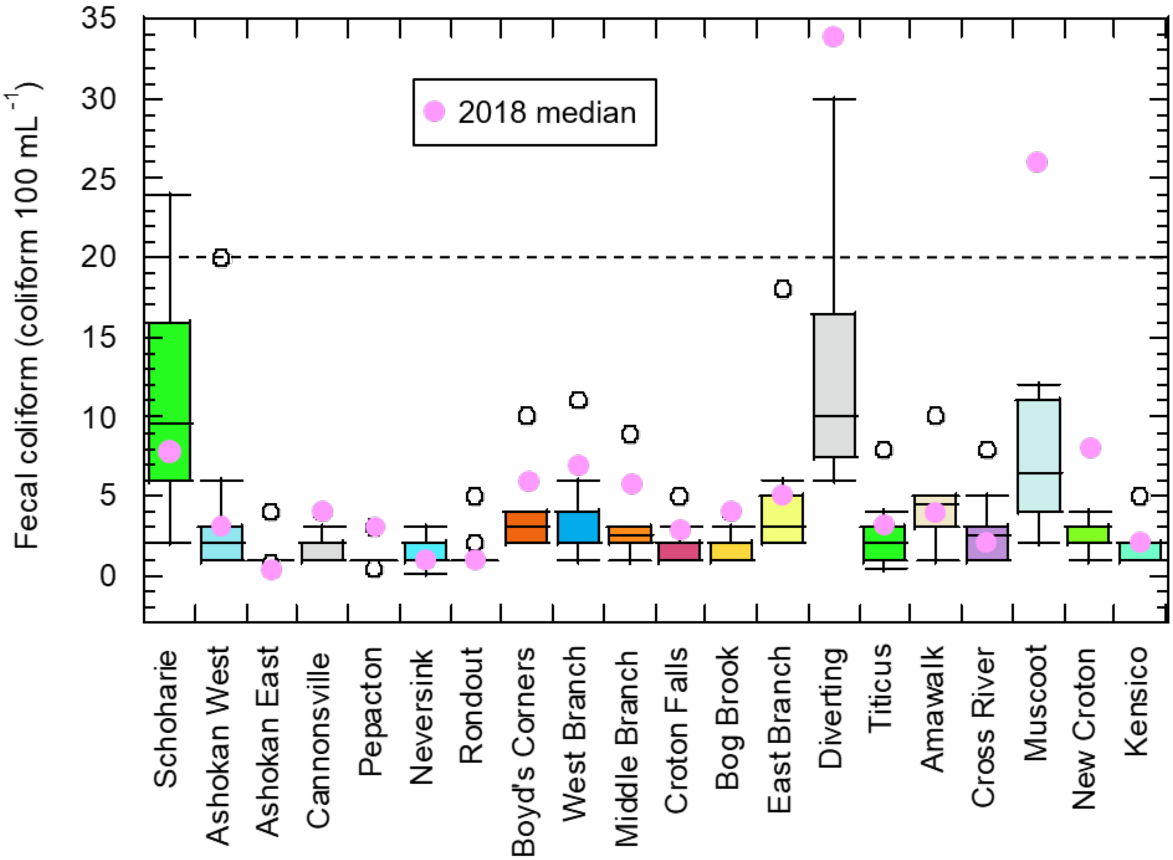


Figure 3.3 Annual 75th percentile of fecal coliforms in NYC water supply reservoirs (2018 vs. 2008-2017) with the 2018 values displayed as a solid dot. The dashed line represents the SWTR standard for source water as a reference. Values below zero indicate that the annual 75th percentile was below the detection limit.

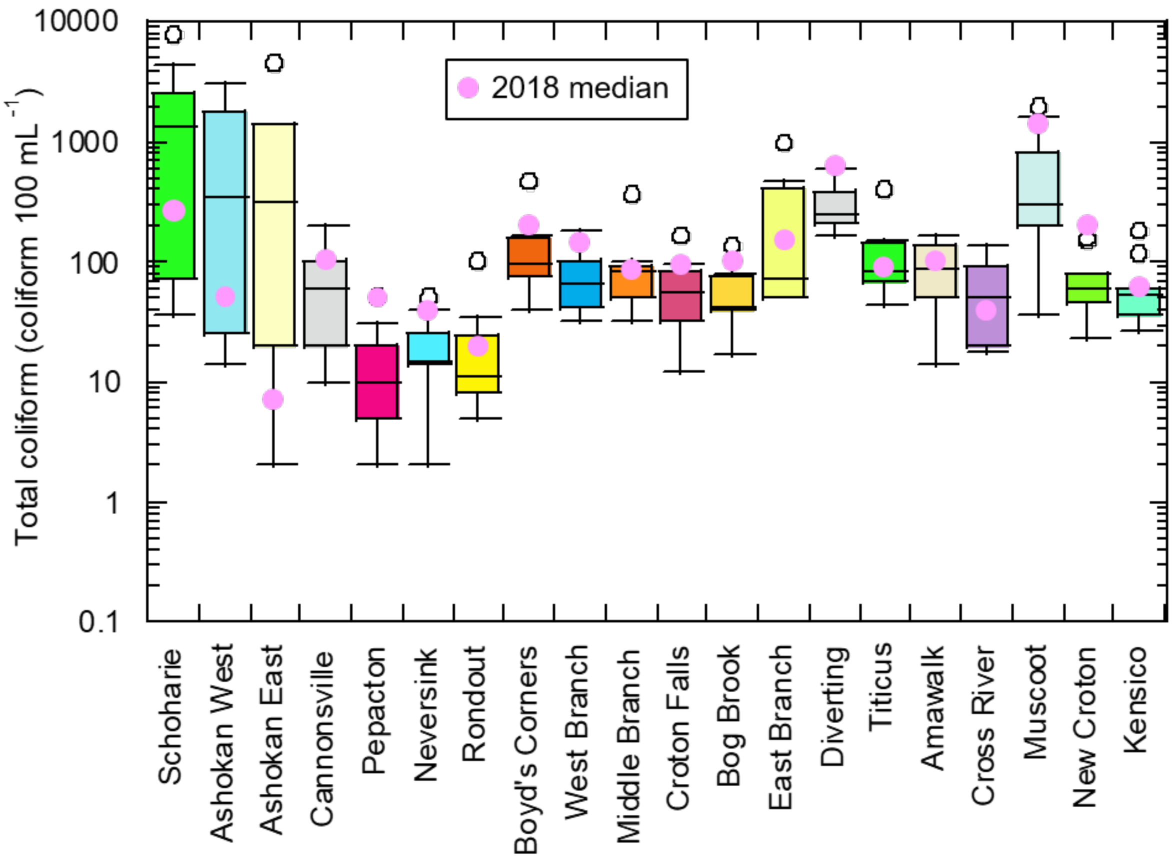


Figure 3.4 Annual 75th percentile of total coliforms in NYC water supply reservoirs (2018 vs. 2008-2017) with the 2018 75th percentile values displayed as a solid dot.

Fecal coliform counts were generally within normal levels in most of the Catskill/Delaware reservoirs in 2018 (Figure 3.3). However, higher than normal fecal counts were observed at Cannonsville, Pepacton, West Branch and most Croton reservoirs, particularly Diverting and Muscoot, during the summer and fall. Elevated counts were associated with numerous rain events that occurred within the week prior to sampling each reservoir.

Total coliform counts were lower than normal in the Catskill System reservoirs but were generally higher than normal in the Delaware and Croton Systems (Figure 3.4). The numerous summer and fall rain events were likely responsible for the higher counts observed in these systems. 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 2018, Catskill total coliform counts were 5 to 45 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.

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

Lake	Historical total coliforms (75th percentile 2008-17)	Current total coliforms (75th percentile 2018)	Historical fecal coliforms (75th percentile 2008-17)	Current fecal coliforms (75th percentile 2018)
Gilead	15	15	1	1
Gleneida	10	5	1	1
Kirk	97	130	3	5

3.5 Phosphorus-Restricted Basin Assessments in 2018

The phosphorus-restricted basin status determination for 2018 is presented in Table 3.5. Basin status is determined from two consecutive assessments (2013-2017 and 2014-2018) using the methodology described in Appendix E. Reservoirs and lakes with a geometric mean total phosphorus (TP) concentration that exceeds the benchmarks in the WR&R for both assessments are classified as restricted.

In 2018, there were no changes in phosphorus-restricted status from the previous assessment period. 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 2018, there were slight to moderate declines in annual geometric mean TP concentration in 18 reservoirs and lakes, with the largest declines from the previous year in Bog Brook (8.4 µg L^{-1} decrease), Muscoot (5.9 µg L^{-1} decrease), and Lake Gleneida (4.0 µg L^{-1} decrease) (Appendix E). The 2018 geometric mean TP concentrations increased from the previous year in five reservoirs, with the largest increases in New Croton Reservoir (3.7 µg L^{-1} increase) (Appendix E). As in the previous assessment, none of the Delaware or Catskill reservoirs 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 source water (i.e., terminal) reservoirs, New Croton, Cross River, and Croton Falls reservoirs were classified as phosphorus-restricted. West Branch Reservoir was non-restricted, reflecting the influence of Delaware System water on its water quality status.

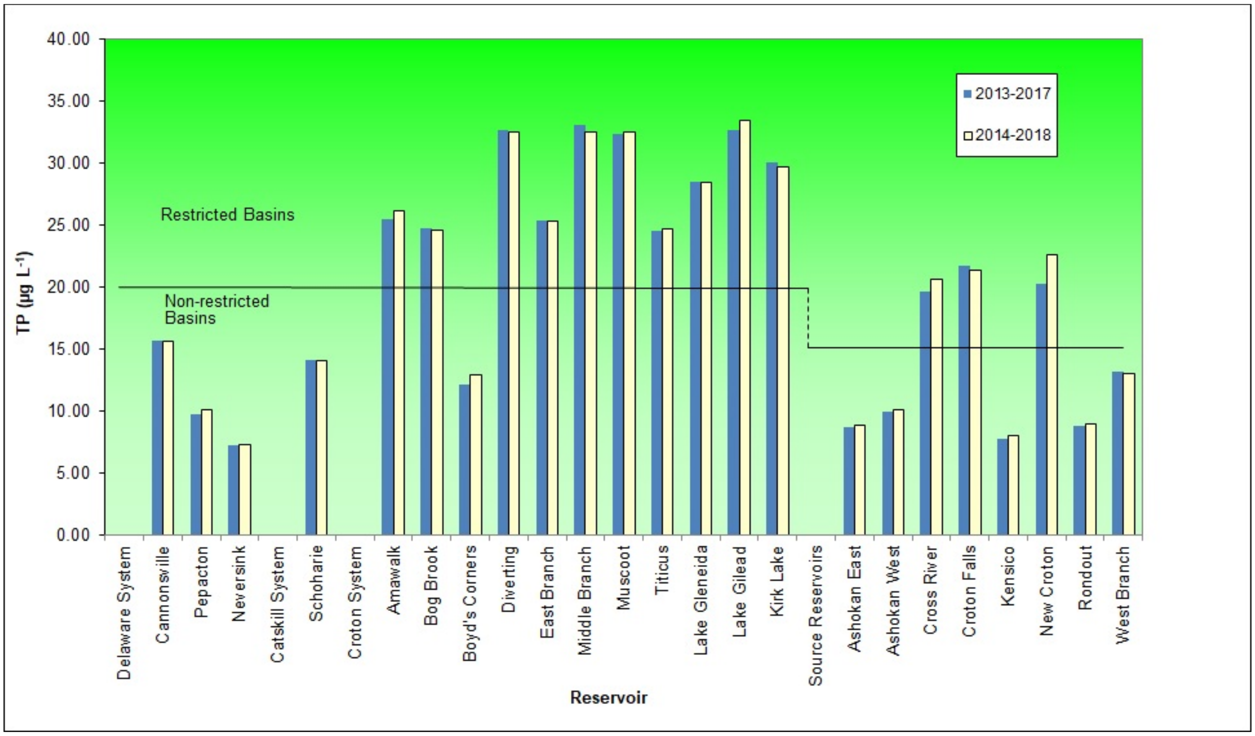


Figure 3.5 Phosphorus-restricted basin assessments.The horizontal solid lines at 20 µg L^{-1} and 15 µg L^{-1} represent the trophic guidance value for non-source and source waters, respectively.

Table 3.5 Phosphorus-restricted basin status for 2018.

Reservoir basin	2013-2017 Assessment[1] (μg L^{-1})	2014-2018 Assessment[1] (μg L^{-1})	Phosphorus restricted status[2]
Non-Source Waters (Delaware System)			
Cannonsville	15.7	15.6	Non-restricted
Pepacton	9.7	10.1	Non-restricted
Neversink	7.2	7.2	Non-restricted
Non-Source Waters (Catskill System)			
Schoharie	14.1	14.1	Non-restricted
Non-Source Waters (Croton System)			
Amawalk	25.5	26.1	Restricted
Bog Brook	24.7	24.6	Restricted
Boyd's Corners	12.1	12.9	Non-restricted
Diverting	32.6	32.5	Restricted
East Branch	25.3	25.3	Restricted
Middle Branch	33.1	32.5	Restricted
Muscoot	32.3	32.4	Restricted
Titicus	24.5	24,7	Restricted
Lake Gleneida	28.5	28.4	Restricted
Lake Gilead	32.6	33.5	Restricted
Kirk Lake	30.0	29.7	Restricted
Source Waters (all systems)			
Ashokan East	8.7	8.8	Non-restricted
Ashokan West	9.9	10.1	Non-restricted
Cross River	19.6	20.6	Restricted
Croton Falls	21.7	21.3	Restricted
Kensico	7.7	8.0	Non-restricted
New Croton	20.3	22.6	Restricted
Rondout	8.8	8.9	Non-restricted
West Branch	13.1	13.0	Non-restricted

[1]Arithmetic mean of annual geometric mean total phosphorus concentration for 5-year period with S.E. (standard error of the mean) added to account for interannual variability.
[2]The guidance value for non-source waters is 20 μg L^{-1} and for source waters is 15 μg L^{-1}.

3.6 Reservoir Total Phosphorus Patterns in 2018

Total phosphorous (TP) levels in the Catskill/Delaware reservoirs in 2018, including West Branch and Kensico, were within their historic ranges (Figure 3.6). Seven of 11 Croton System reservoirs showed TP increases in 2018 (Figure 3.6, Table 3.6). The average increase for these reservoirs was 3.3 µg L^{-1} and ranged from 2 to 6 µg L^{-1} compared to historic (2008-2017) concentrations. TP was elevated much of the year and was mostly associated with wet conditions in the week prior to sampling.

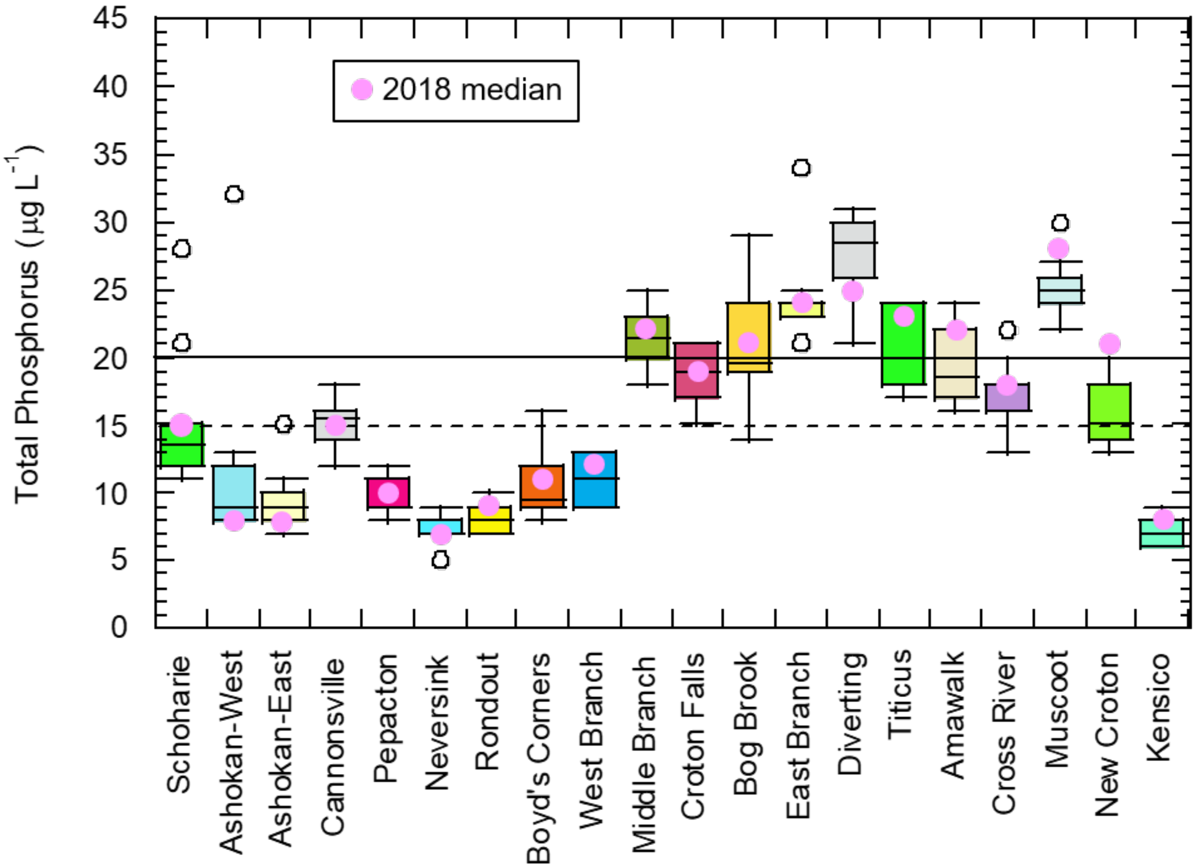


Figure 3.6 Annual median total phosphorus in NYC water supply reservoirs (2018 vs. 2008-2017) with the 2018 75th percentile values displayed as a solid dot. The horizontal dashed line at 15 µg L^{-1} refers to the NYC Total Maximum Daily Load (TMDL) guidance value for source waters. The horizontal solid 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 (2008-2017)	Median Total Phosphorus (2018)
Gilead	20	20
Gleneida	17	15
Kirk	30	19

3.7 Reservoir Comparisons to Benchmarks in 2018

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 2018 water quality sampling, including a variety of physical, biological, and chemical analytes for the terminal reservoirs, are evaluated by comparing the results to the water quality benchmarks listed in Table 3.7. These benchmarks are based on applicable federal, state, and DEP standards or guidelines. Note that the standards in this table are not necessarily applicable to all individual samples and medians described herein (e.g., SWTR limits for turbidity and fecal coliforms apply only to the source water point of entry to the system) and different values apply to Croton reservoirs than to Catskill/Delaware reservoirs. Placing the data in the context of these benchmarks assists in understanding the robustness of the water system and helps in identifying water quality issues.

Comparisons of 2018 reservoir sample results to benchmark values are provided in Appendix F. Data represent samples collected monthly from April to November for multiple reservoir and controlled lake sites and depths as part of the fixed-frequency water quality monitoring program. Highlights of the benchmark comparisons for terminal reservoirs from 2018 include the following:

pH

Reservoir samples were generally in the circumneutral pH range (6.5-8.5) in 2018. The majority of pH values outside the benchmark range for Kensico and West of Hudson reservoirs, with lower alkalinities than Croton System reservoirs, were below a pH of 6.5. The greatest number of pH values below 6.5 were in Neversink Reservoir, with 85% of all samples below this benchmark. A few exceptions occurred for WOH reservoirs where pH was above 8.5 when phytoplankton counts were high. Occurrences of pH exceeding 8.5 are frequently associated with algal blooms. There were few values greater than the benchmark range for pH in Kensico, West Branch, and Rondout reservoirs in 2018 with 11%, 5%, and 7% of samples, respectively, falling outside the range. In New Croton Reservoir, the number of high values of pH was relatively low (8% of samples collected). Croton Falls had the greatest number of high values in Croton System, with 19% exceeding the upper boundary of pH 8.5. Boyd's Corners Reservoir, Lake Gilead, and Kirk Lake had no pH values outside the circumneutral range.

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.

Phytoplankton

Phytoplankton counts exceeded the single sample maximum of 2000 ASU mL^{-1} for total phytoplankton for a total of 17 out of 537 samples evaluated across both EOH and WOH reservoirs and controlled lakes. These 17 exceedances occurred in five reservoirs, four EOH (Amawalk, Croton Falls, Diverting, and Muscoot) and one WOH (Cannonsville), but represented a low percentage of samples collected (12-19%). 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 2018 (see section 3.13.7). Four NYC reservoirs and one controlled lake were included on the NYSDEC Harmful Algal Blooms (HABs) Program notification page (NYSDEC 2018) (http://www.dec.ny.gov/docs/water_pdf/habsextentsummary.pdf). As in the preceding year, Kirk Lake was listed as having a confirmed bloom in 2018. 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, Diverting, and Cannonsville reservoirs were listed as having a "suspicious bloom" based on visual observation and/or digital photographs.

Chlorophyll a, Color, and Dissolved Organic Carbon

Chlorophyll *a* concentration is a surrogate measure of algal biomass. None of the Catskill System reservoirs exceeded the single sample maximum or the mean benchmark values in 2018. In the Delaware System, Cannonsville had three samples (8%) that exceeded the single sample maximum and also exceeded the annual mean standard. Pepacton had a single sample that exceeded the single sample maximum, while Neversink and Rondout had no chlorophyll sample exceedances. Ten reservoirs in the Croton System exceeded the single sample maximum and seven of these reservoirs exceeded the annual mean benchmark. Kirk Lake exceeded both the single sample maximum and annual mean benchmark for chlorophyll *a*. There were no chlorophyll *a* exceedances in Kensico, and West Branch Reservoir had only one exceedance of the single sample maximum.

Color is an indicator of organic matter both from reservoir and watershed sources. In 2018, all samples from Croton System reservoirs and West Branch exceeded the 15 Pt-Co unit color single sample maximum. Color was not monitored in the controlled lakes in 2018. By contrast, Kensico Reservoir had a single exceedance of the color benchmark, reflecting the characteristics of Catskill/Delaware water. For WOH reservoirs, Cannonsville had the highest number of color exceedances (100%), followed by Pepacton (38%), and Schoharie (25%). Neversink was not evaluated for color in 2018.

There were no exceedances of the annual mean standards for dissolved organic carbon (DOC) in 2018. Schoharie Reservoir had the highest number of exceedances of the single sample maximum (11%) in the entire system.

Chloride

In 2018, chloride in all Croton System reservoirs and controlled lakes exceeded the single sample maximum of 40 mg L^{-1} and annual mean benchmark of 30 mg L^{-1}. Four reservoirs were not sampled for chloride (Amawalk, Diverting, Middle Branch, and Titicus). This is consistent with previous years and reflects the population and road density for the region. Kensico Reservoir exceeded both the single sample maximum (20 of 24 samples or 83%) and mean annual benchmark values for chloride. Cannonsville was the only WOH reservoir to exceed the single sample maximum (33%) in 2018, although all WOH reservoirs except Ashokan West and

Neversink exceeded the annual mean benchmark value of 8 mg L^{-1}. All chloride samples were well below the health secondary standard of 250 mg L^{-1}.

Turbidity

Turbidity levels in Kensico, Rondout, and West Branch reservoirs did not exceed the single sample maximum of 5 NTU in 2018. For the entire system, the highest number of values exceeding the benchmark of 5 NTU were for Schoharie Reservoir (74%), but the number of exceedances was much lower in the receiving waters Ashokan West (16%) and Ashokan East (8%). There were some exceedances in six reservoirs in the Croton System, a filtered supply, with the highest numbers occurring in Croton Falls (14%) and Cross River (13%). New Croton Reservoir had few exceedances (7%).

Nutrients

If the 15 µg L^{-1} benchmark TP concentration is applied to the Croton System, exceedances range from 43% (Boyd's Corners) to 100% (Middle Branch). New Croton Reservoir exceeded the single sample benchmark for 86% of samples collected and analyzed for TP. By contrast, West Branch exceeded the TP benchmark for 18% of the samples, a decrease from 38% in the previous year, and a reflection of contributions of water from Rondout, with no exceedances of the TP benchmark value. In the Delaware System, Cannonsville had the highest number of single sample maximum exceedances (58%), Pepacton had few exceedances (17%), and Neversink had no exceedances. In the Catskill System, Schoharie had the highest number of exceedances (52%), and with few in Ashokan West (7%) and Ashokan East (6%). Kensico had only 3 samples out of 200 (2%) that exceed the TP benchmark value. For soluble reactive phosphorus (SRP), there were no exceedances of the single sample maximum benchmark of 15 µg L^{-1} for WOH reservoirs and Kensico. West Branch had one exceedance, while three additional reservoirs and two controlled lakes in the Croton System had a small number of exceedances (ranging from 8 to 22%).

In 2018, there were few exceedances for nitrate/nitrite throughout the system. In EOH, Croton Falls (16%), Muscoot (15%), and New Croton (4%) exceeded the single sample maximum. The only exceedances of the single sample maximum for the WOH reservoirs was in Cannonsville (5%). Cannonsville was the only reservoir in the system to slightly exceed the annual mean benchmark of 0.30 mg L^{-1} in 2018, with an annual mean of 0.31 mg L^{-1}.

Fecal Coliform Bacteria

Fecal coliform counts exceeded the single sample maximum of 20 fecal coliforms 100mL^{-1} for one sample in Kensico and two samples in Rondout, representing 1% and 3% of samples, respectively. West Branch had few high values (six samples or 8%), while New Croton Reservoir had 13% exceedances of the single sample maximum. The highest percentage of values greater than the benchmark were fecal coliform in the Catskill System is Schoharie (20%), with fewer high values for Ashokan West (8%) and Ashokan East (2%).

3.8 Reservoir Trophic Status in 2018

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

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

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

The Carlson TSI ranges from approximately 0 to 100 (there are no upper or lower bounds), and is scaled so that values under 40 indicate oligotrophic conditions, values between 40 and 50 indicate mesotrophic conditions, and values greater than 50 indicate eutrophic conditions. Trophic state indices are generally calculated from data collected in the photic zone of the reservoir during the growing season (May through October). A low trophic state is desirable because such reservoirs produce better water quality at the tap.

Historical (2008-2017) annual median TSI based on chlorophyll *a* concentration is presented in boxplots for all reservoirs in Figure 3.7. 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.

In 2018, TSI was within historic levels for all Catskill System reservoirs. In contrast, headwater Delaware System reservoirs, Cannonsville, Pepacton and Neversink, were slightly above their historic median by 2-4 TSI units. Elevated phosphorus associated with numerous rain events preceding sample collection coincided with the highest monthly TSI observed at these reservoirs. TSI in the terminal Delaware reservoir, Rondout, was not higher than usual suggesting that the relatively deep withdrawal depths from the headwater reservoirs helped to limit the transfer of algal cells into Rondout. Algal counts were especially low in water transferred from Pepacton from August through October, when Cannonsville and Neversink diversions were mostly shut down.

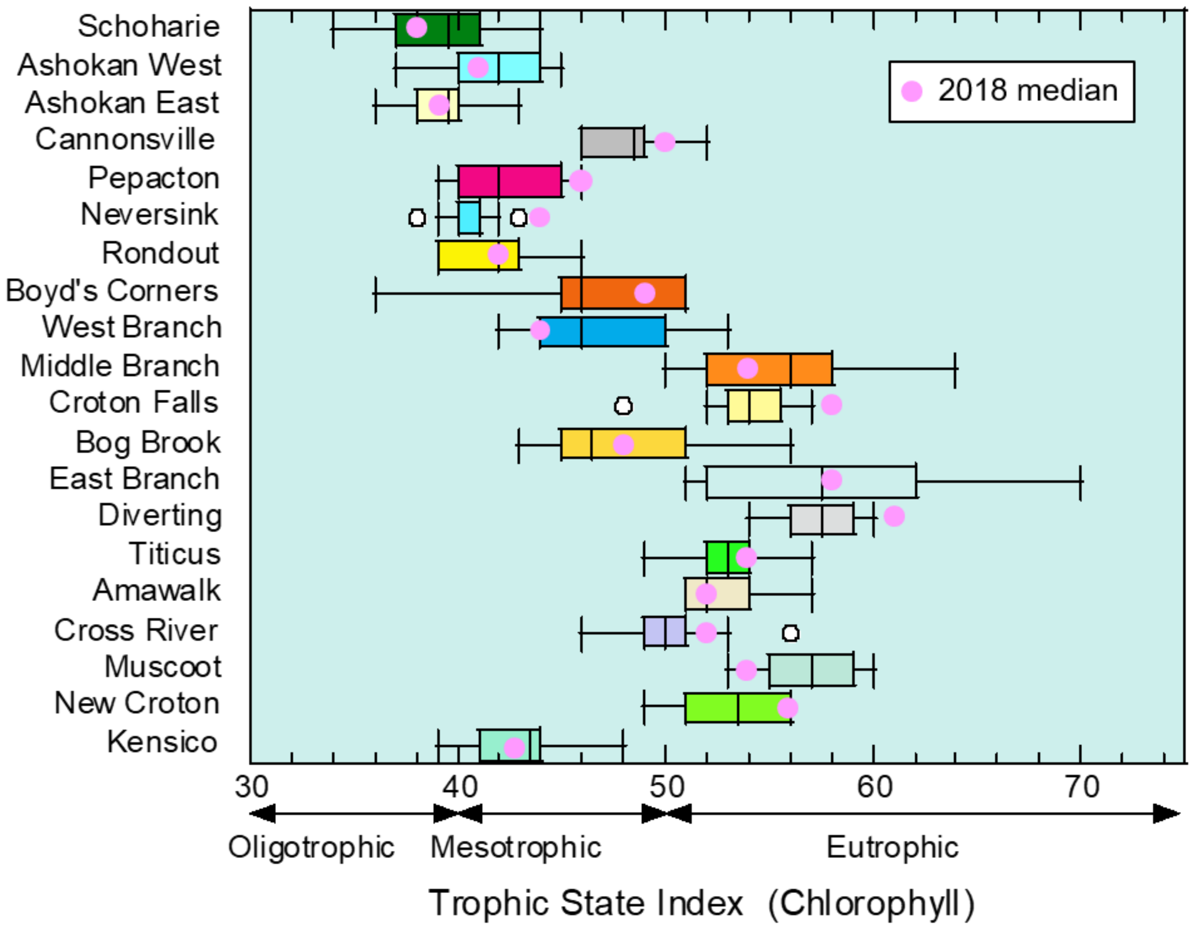


Figure 3.7 Annual median Trophic State Index (TSI) in NYC water supply reservoirs (2018 vs. 2008-2017). In general, data were obtained from epilimnetic depths at multiple sites, at routine sampling frequencies once per month from May through October. TSI is based on Chlorophyll *a* concentration.

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

Lake	**Median TSI (2008-2017)**	**Median TSI (2018)**
Gilead	47	43
Gleneida	43	41
Kirk	59	53

TSI was lower in reservoirs downstream from Rondout (West Branch and Kensico), reflecting the influence of Rondout on these reservoirs. Low Kensico TSI is also maintained by the low productivity water transfers from Ashokan.

TSI was higher than historic levels in nine of 11 reservoirs of the Croton System in 2018 although increases at Titicus and East Branch were very small (Figure 3.6, Table 3.8). High TP concentrations associated with rain events coincide with elevated TSI especially at Boyd's Corners and New Croton. New Croton was warmer than usual with surface temperatures 0.6 to 3.9° C higher than normal during the summer and fall coinciding with high productivity. The higher temperatures were presumably due to warmer flows from the spills of upstream reservoirs. The abundance of rain starting in late June periodically caused higher than normal spills in the summer and fall at Croton Falls, Cross River, East Branch and Titicus, which likely warmed the normally cold releases from these reservoirs. Such was the case at the Titicus and the combined Bog Brook-East Branch releases, and it may be assumed that the warm spill water at Cross River and Croton Falls also warmed those releases as well before they entered Muscoot.

3.9 Water Quality in the Major Inflow Streams in 2018

The stream sites discussed in this section are listed in Table 3.9, with locations shown in Figure 3.8. These stream sites were chosen because they are immediately upstream from the six Catskill/Delaware reservoirs and six of the Croton reservoirs. They represent the bulk of the water entering the reservoirs from their respective watershed. The exception is New Croton Reservoir, whose major inflow is from the Muscoot Reservoir release. Kisco River and Hunter Brook are tributaries to New Croton Reservoir and represent water quality conditions in the New Croton watershed.

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

The 2018 results presented in Figure 3.9 are based on routine grab samples generally collected once a month. Figure 3.9 compares the 2018 median values against historical median annual values for the previous 10 years (2008-2017). The higher values observed for these analytes were due to the high number of rainfall events and increased runoff observed in 2018 as discussed in Chapter 2.

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

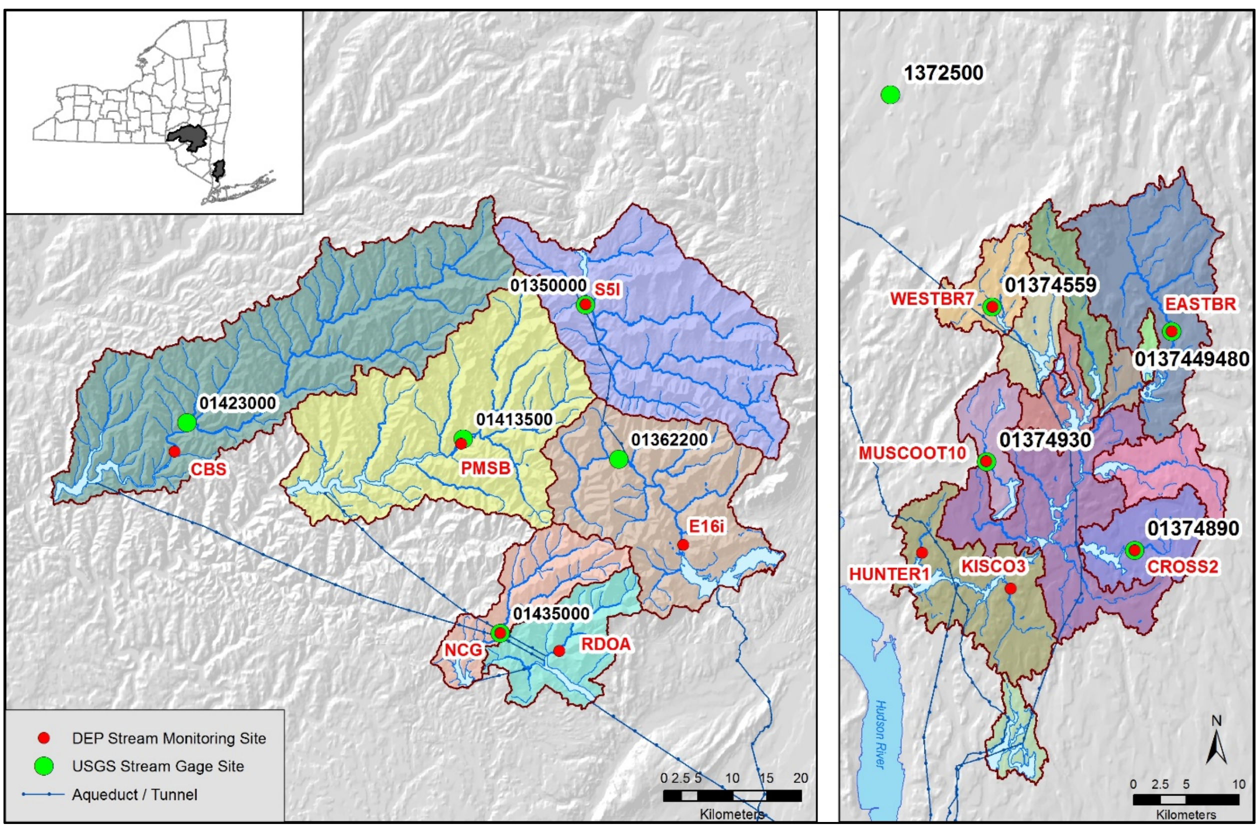


Figure 3.8 Locations of major inflow stream water quality sampling sites and USGS gage stations used to calculate runoff values (see Section 2.3).

Turbidity

The turbidity levels for 2018 were generally within the range of the annual medians observed over the previous 10 years (2008-2017) (Figure 3.9a), with the exception of West Branch Delaware River (CBS) and Rondout Creek (RDOA), which had the highest annual median turbidity values (3.9 and 1.0 NTU, respectively) compared to the last 10 years. The 2018 annual turbidity medians for East Branch Delaware River (PMSB), Cross River (CROSS2), and West Branch of the Croton River (WESTBR7) were the second highest annual medians for each of these sites since 2008, at 1.9, 1.8, and 1.3 NTU, respectively. The Amawalk River (MUSCOOT10) had the lowest annual median turbidity (1.1 NTU) compared to the last 10 years.

Total Phosphorus

The 2018 median TP concentrations (Figure 3.9b) exhibited mixed results among the major inflows. For example, six of the inflows (West Branch Delaware River (CBS), East Branch Delaware River (PMSB), Rondout Creek (RDOA), West Branch of the Croton River, above Boyd’s Corners (WESTBR7), Cross River (CROSS2), and Hunter Creek, a tributary to New Croton (HUNTER1), had their highest medians compared to the last 10 years, which was attributed to high runoff. The East Branch of the Croton River (EASTBR) had its lowest TP median, and the New Croton tributary Kisco River (KISCO3) and the Amawalk River (MUSCOOT10), had their third lowest annual median since 2008.

Fecal Coliform Bacteria

The fecal coliform bacteria levels for 2018 (Figure 3.9c) at several sites were elevated due to high runoff, while other sites were generally near their annual medians observed over the past 10 years (2008-2017). West Branch Delaware River (CBS), East Branch Delaware River (PMSB), and the New Croton tributaries Hunter Creek (HUNTER1) and Kisco River (KISCO3) had their highest annual median fecal coliform values (48, 44, 180, and 170 coliforms $100mL^{-1}$, respectively), and the Esopus Creek (E16i) had its second highest median (16 coliform $100mL^{-1}$), all compared to the last 10 years.

A fecal coliform benchmark of 200 coliforms $100mL^{-1}$ is shown as a solid line in Figure 3.9c. This benchmark relates to the NYSDEC water quality standard for fecal coliforms (which is a monthly geometric mean of five samples) (6NYCRR §703.4b). The 2018 median values for all streams shown here are below this benchmark value. There were 20 individual samples with a result greater than or equal to 200 coliforms $100mL^{-1}$ and all but one of those were at EOH sites. These elevated fecal coliform counts were mostly associated with rain events.

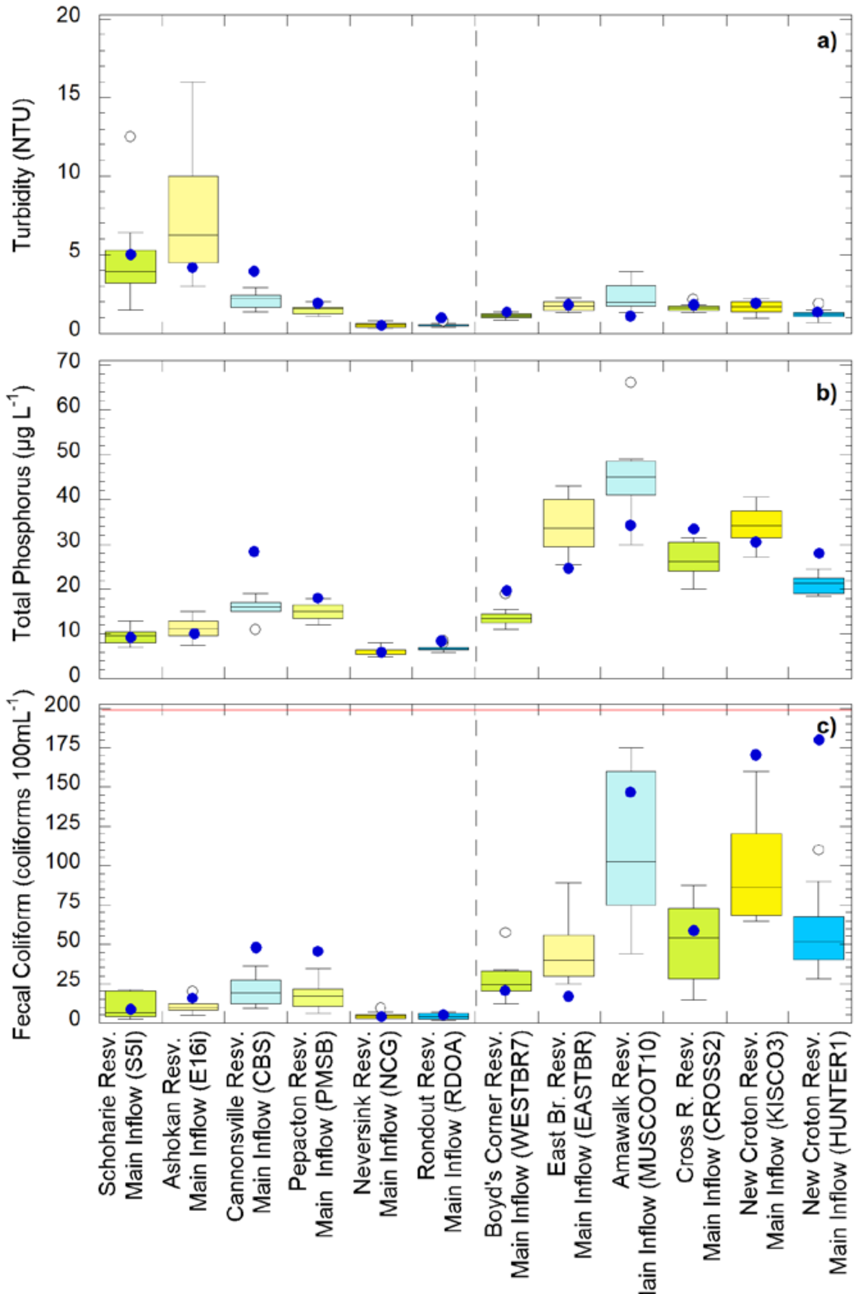


Figure 3.9 Boxplot of annual medians (2008-2017) for a) turbidity, b) total phosphorus, and c) fecal coliforms for selected stream (reservoir inflow) sites, with the 2018 values displayed as a solid dot. The dotted line separates WOH streams (left) from EOH streams (right). The solid red line indicates the fecal coliform benchmark of 200 coliforms $100mL^{-1}$.

3.10 Stream Comparisons to Benchmarks in 2018

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 2018 (DEP 2018a). 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 $CaCO_3L^{-1}$)	N/A	≥40.00	N/A	≥10.00
Ammonia-N (mg L^{-1})	0.1	0.2	0.05	0.25
Dissolved chloride (mg L^{-1})	35	100	10	50
Nitrite+Nitrate (mg L^{-1})	0.35	1.5	0.4	1.5
Organic Nitrogen [1]	0.5	1.5	0.5	1.5
Dissolved sodium (mg L^{-1})	15	20	5	10
Sulfate (mg L^{-1})	15	25	10	15
Total dissolved solids (mg L^{-1})[2]	150	175	40	50
Total organic carbon (mg L^{-1})[3]	9	25	9	25
Total suspended solids	5	8	5	8

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

Comparison of stream results to these benchmarks is presented in Appendix G along with site descriptions, which appear next to the site codes. Note that the Catskill/Delaware System criteria are applied to the release from West Branch Reservoir (WESTBRR) since that release usually is affected by Delaware System water. Below is a discussion of selected sites and analytes.

Alkalinity

Alkalinity is a measure of water's ability to neutralize acids and is largely controlled by the abundance of carbonate rocks/surficial materials in a watershed. Sufficient alkalinity ensures a stable pH in the 6.5 to 8.5 range, generally considered a necessary condition for a healthy ecosystem. Monitoring of alkalinity is also considered important to facilitate water treatment processes such as chemical coagulation, water softening, and corrosion control.

Watersheds of the Catskill/Delaware System vary in their capacity to neutralize acids. Low buffering capacity is typical of the surficial materials in the Ashokan, Rondout, and Neversink watersheds and excursions below the alkalinity single sample benchmark of 10 mg L^{-1} were common much of the year in most streams from these watersheds. In contrast, only occasional excursions below 10 mg L^{-1} were observed in streams of the Cannonsville and Pepacton basins. These excursions occurred mostly in the winter-spring period and were likely caused by rain and melting snow, which are naturally acidic, moving over frozen or semi-frozen ground into the streams. Streams of the Schoharie basin did not go below 10 mg L^{-1} in 2018. 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 32.5 to 42.1 mg L^{-1} in 2018.

Chloride

The Catskill/Delaware System annual mean benchmark of 10 mg L^{-1} was exceeded in 10 of the 24 streams monitored in the Catskill/Delaware System with the highest mean, 46.6 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 only exceeded at one stream, Kramer Brook in 2018. 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 4.5 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 contribute to the relatively high chloride levels.

Other Catskill/Delaware System streams with high annual mean chloride included Bear Kill at S6I (21.2 mg L^{-1}), Schoharie Creek at S5I (12.3 mg L^{-1}) and the Manor Kill at S7I (10.7 mg L^{-1}) all located within the Schoharie watershed; Trout Creek at C-7 (13.0 mg L^{-1}), Loomis Brook at C-8 (13.0 mg L^{-1}), and the West Branch of the Delaware River at CBS (12.6 mg L^{-1}), all tributaries to Cannonsville Reservoir; and Chestnut Creek at RGB (17.2 mg L^{-1}), a tributary to Rondout Reservoir. Two Pepacton streams: Tremper Kill at P-13 (11.9 mg L^{-1}) and the East Branch of the Delaware River at PMSB (13.5 mg L^{-1}) exceeded the average benchmark in 2018. 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 (32.9 mg L^{-1}) at the outflow from West Branch Reservoir release (WESTBRR). In 2018, less Rondout water – with its lower levels of chloride – was diverted to West Branch than in 2016. This combined with inputs from local West Branch streams, which ranged from 33.5 to 83.1 mg L^{-1} chloride, caused chloride to increase from 20.7 mg L^{-1} in 2016 to 32.9 mg L^{-1} in 2018.

The Croton System annual mean benchmark of 35 mg L^{-1} was exceeded in 15 of 16 monitored Croton streams with Gypsy Trail Brook, a tributary of West Branch Reservoir, being the lone exception with a mean concentration of 33.5 mg L^{-1}. Annual means exceeding the benchmark ranged from 38.7 mg L^{-1} in the West Branch of the Croton River at WESTBR7 to 172.8 mg L^{-1} in Michael's Brook at MIKE2. The mean 2018 chloride concentration for all 16 Croton streams was 82.0 mg L^{-1}, substantially higher than the streams of the Catskill/Delaware System, which together averaged 11.4 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 2018, 15 of 24 Catskill/Delaware streams had at least one value greater than the TDS single sample maximum of 50 mg L^{-1}. With the exception of the Schoharie Creek diversion at SRR2CM, these same streams also exceeded the TDS annual mean benchmark of 40 mg L^{-1}. All excursions of the single sample maximum were associated with chloride concentrations that exceeded 7.1 mg L^{-1} (Figure 3.10).

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 (7 mg L^{-1}) consistently met both TDS benchmarks.

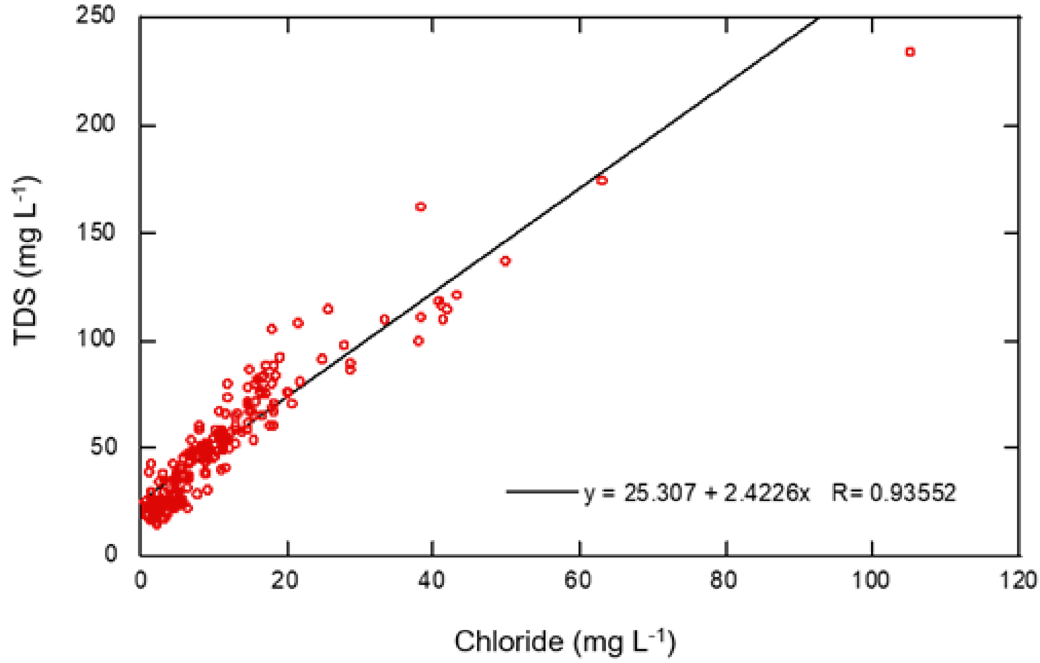


Figure 3.10 Total Dissolved Solids (TDS) versus chloride for Catskill/Delaware System streams in 2018.

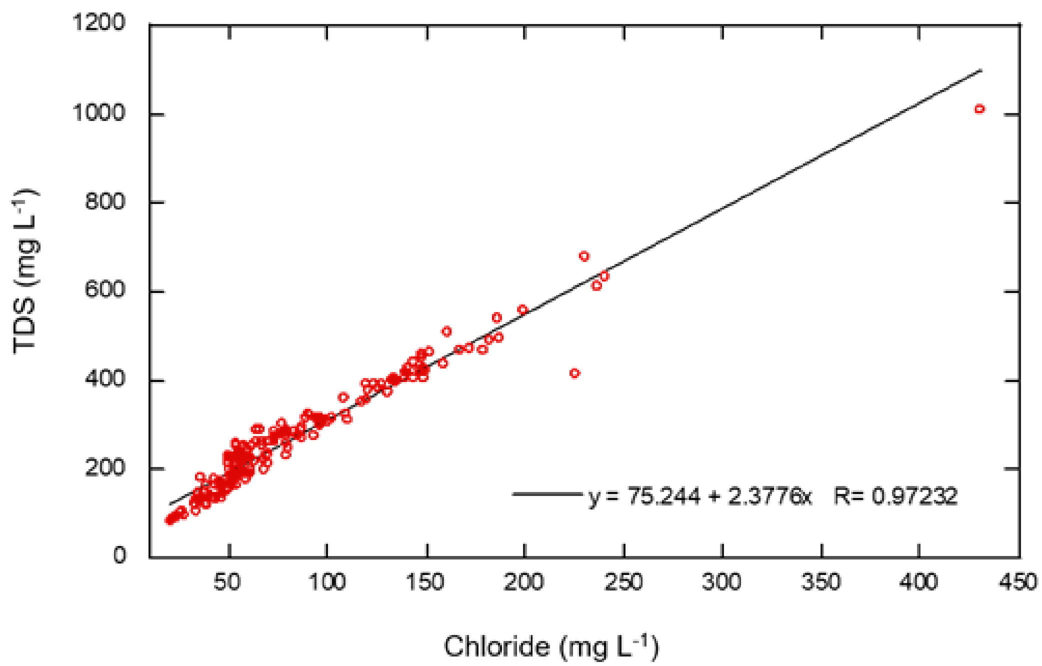


Figure 3.11 Total Dissolved Solids (TDS) versus chloride for Croton System streams in 2018.

TDS excursions in the Croton streams were also strongly associated with elevated chloride concentrations with chloride accounting for about 97 percent of the variation in TDS (Figure 3.11). In 2018, 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}.

Nitrogen

Nitrogen results were generally in compliance with benchmarks in the Catskill/Delaware System in 2018. No stream exceeded the single sample nitrate benchmark of 1.5 mg L^{-1}. The mean annual benchmark of 0.40 mg L^{-1} was exceeded in one stream, the West Branch of the Delaware River at CBS (0.50 mg L^{-1}). Likely sources for nitrate in the Cannonsville watershed are fertilizers associated with the relatively high agricultural activity in this basin, and wastewater treatment plants that discharge to these streams.

Three Croton streams exceeded the annual average benchmark of 0.35 mg L^{-1} for 2018: the Kisco River at KISCO3 (0.73 mg L^{-1}), the Muscoot River at MUSCOOT10 (0.36 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 nine of 12 monthly samples and was especially high in June (8.3 mg L^{-1}) and July (3.6 mg L^{-1}).

Ammonia results were generally in compliance with benchmarks in the Catskill/Delaware System in 2018. The single sample ammonia benchmark of 0.25 mg L^{-1} was exceeded at the West Branch Reservoir Release (WESTBRR) with a result of 0.34 mg L^{-1}. The mean ammonia annual benchmark of 0.05 mg L^{-1} was also exceeded at WESTBRR in 2017. Ammonia was detected in all 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 August and September.

Four Croton System streams reached or exceeded the ammonia single sample maximum of 0.20 mg L^{-1} in 2018. The Amawalk Reservoir Release (AMWALKR) exceeded it once, reaching 0.26 mg L^{-1} in October. The Cross River Release (CROSS2RVVC) exceeded the benchmark twice: 0.32 mg L^{-1} in October and 0.35 mg L^{-1} in November and the Croton Falls release (CROFALLSVC) exceeded it once reaching 0.35 mg L^{-1} in October. All high ammonia results from these sites were associated with the release of ammonia from upstream anoxic reservoir sediments in late summer/fall. Michael Brook (MIKE2) exceeded the benchmark in January with a result of 0.44 mg L^{-1}. The likely source is an upstream wastewater treatment plant where SPDES sampling indicated an elevated 30-day average outfall ammonia concentration of 2.28 mg L^{-1} for January.

Sulfate

Neither the single sample maximum (15 mg L^{-1}) nor the annual mean (10.0 mg L^{-1}) benchmarks for sulfate were exceeded in the Catskill/Delaware streams in 2018. The collective average for the Catskill/Delaware streams was 3.4 mg L^{-1}. All 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}. Only Michael Brook exceeded the annual mean benchmark of 15 mg L^{-1} with an average of 15.2 mg L^{-1}. Sulfate was consistently high in all four quarterly samples, ranging from 11.4-19.9 mg L^{-1} at MIKE2. The Michael Brook watershed has relatively high population density and sulfate is a common ingredient in personal care products (e.g., soaps, shampoos, and toothpaste) and mineral supplements. Note that USEPA does not consider sulfate to be a health risk and has only established a secondary maximum contaminant level of 250 mg L^{-1} as a benchmark for aesthetic consideration (i.e., salty taste).

Dissolved Organic Carbon

Dissolved organic carbon (DOC) was used in this analysis instead of total organic carbon since the latter is not routinely analyzed as part of DEP's monitoring program. Previous work has shown that DOC constitutes the majority of the organic carbon in stream and reservoir samples. The DOC single sample benchmarks of 25 mg L^{-1} and annual mean of 9.0 mg L^{-1} were not surpassed by any stream in the Catskill/Delaware and Croton Systems in 2018. In the Catskill/Delaware System, the highest single sample DOC result occurred at Kramer Brook at NK4 (5.9 mg L^{-1}) in the Neversink watershed while the annual mean DOC in the Catskill/Delaware System ranged from 1.5 to 2.8 mg L^{-1}; well below the annual mean benchmark. DOC is generally higher in the Croton System compared to the Catskill/Delaware System (although still well below benchmarks) due to a higher occurrence of wetlands in the Croton watersheds. Mean DOC in the Croton System ranged from 2.8 to 6.1 mg L^{-1} in 2018, and the highest single sample DOC, 9.7 mg L^{-1}, occurred at the West Branch of the Croton River, the main source of water to Boyd's Corners Reservoir.

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 to 10. The BAP 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: 1) total number of taxa (SPP or species richness); 2) total Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) taxa (EPT richness); 3) Hilsenhoff Biotic

Index for taxa tolerance to organic pollution (HBI), 4) Percent Model Affinity (PMA); and, since 2012, 5) Nutrient Biotic Index-Phosphorus (NBI-P).

In 2018, DEP collected samples from 35 stations in 29 streams throughout the City's watershed. Eleven sites were assessed on 11 streams in the Croton System, 11 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 results from previous years (see, e.g., DEP 2013a, 2013b, 2014, 2015, 2016, 2017, and 2018b).

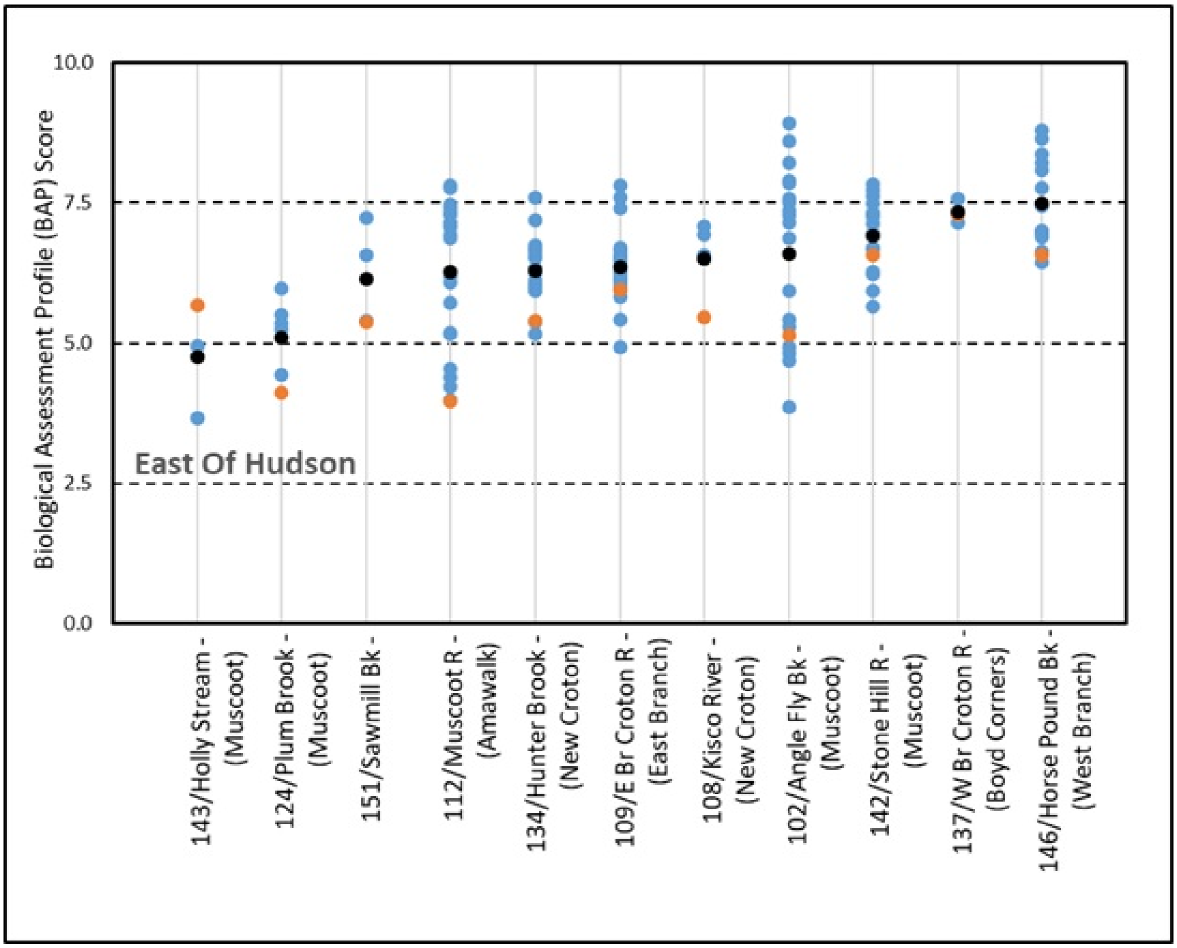


Figure 3.12 Biological Assessment Profile scores for East of Hudson biomonitoring sites sampled in 2018. Mean scores (black dots) are arranged from highest to lowest; 2018 score (orange dots), pre-2018 scores (blue dots). Watersheds are indicated in parentheses on the x-axis.

East of Hudson – Croton System

Of the 11 Croton System sites assessed in 2018, only two were considered moderately impaired (sites 112 and 124). However, both scored very close to the slightly impaired BAP threshold of 5.0. The remaining nine scored as slightly impaired (Figure 3.12). Ten of the sites had BAP scores lower than their respective period of record means, while one of the sites (143) scored higher than its period of record mean, and site 137 had a BAP score only slightly lower than its period of record average. While two sites (102 and 143) had BAP scores higher than the previous sampling year, the remaining nine sites showed declines of less than 1.5.

Site 109 on the East Branch of the Croton River saw a relatively unchanged BAP score. After the drop in 2015 to within the moderately impaired range, it rebounded back into slightly impaired (Figure 3.13). While the increased BAP score is encouraging, the DEP will monitor this East Branch Reservoir watershed stream again in 2019.

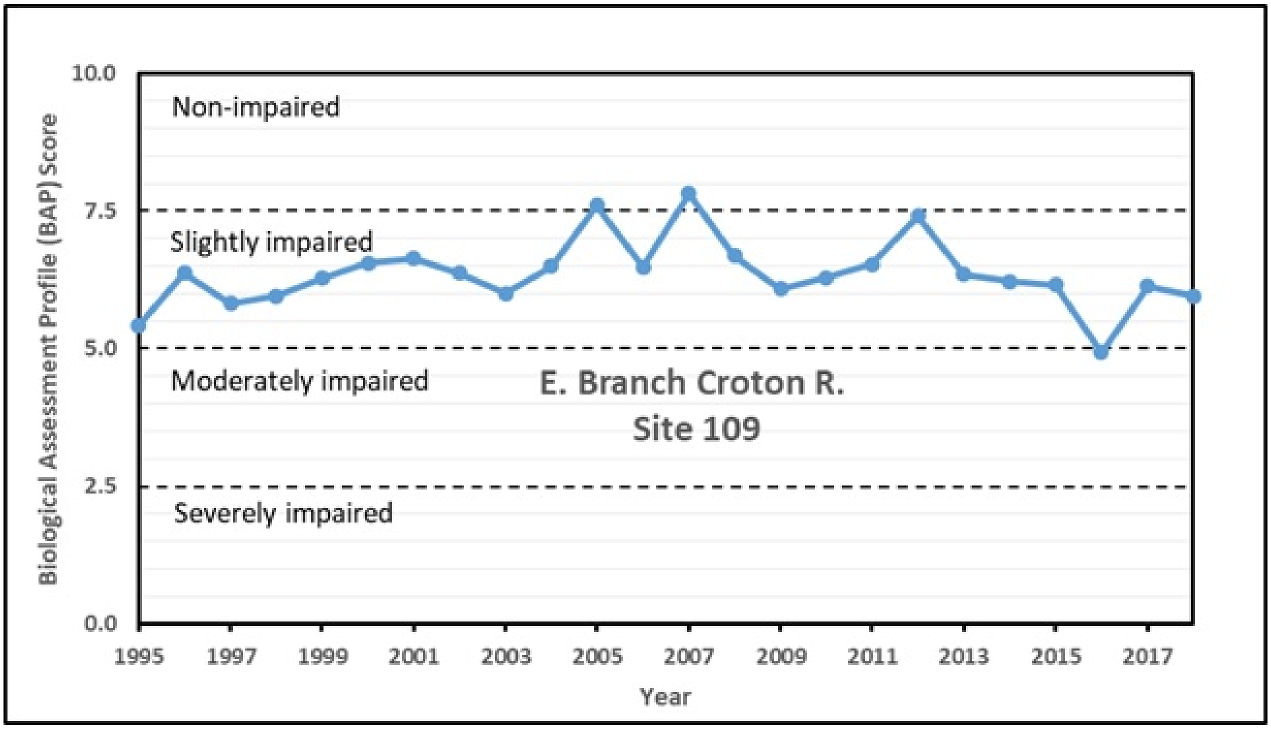


Figure 3.13 1995- 2018 BAP scores for the East Branch Croton River Site 109.

The assessment at Angle Fly Brook (Site 102) showed a third year of increased BAP score which, after the 2015 decline to 3.96, the site is now back into the slightly impaired status (Figure 3.14). DEP will continue to monitor this site in 2019.

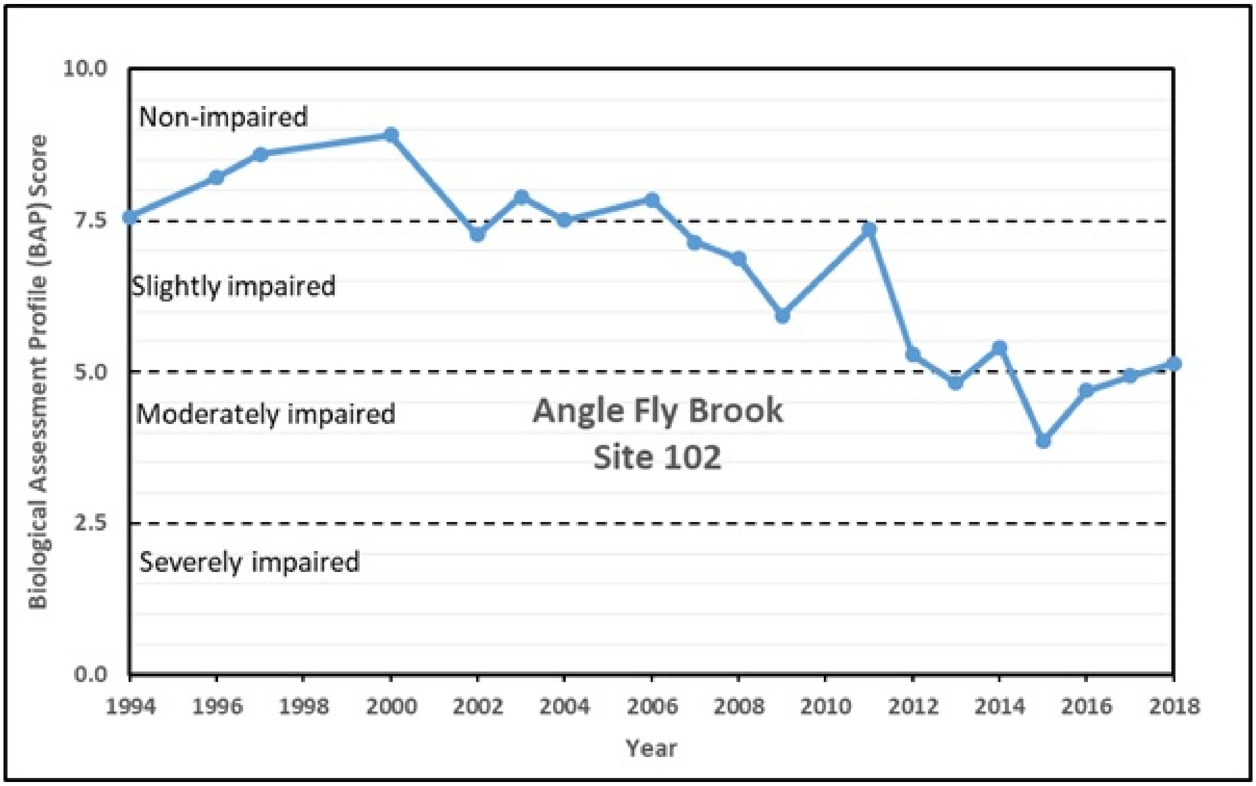


Figure 3.14 1994-2018 BAP scores for the Angle Fly Brook Site 102 showing a slightly improved rating in 2018.

West of Hudson - Catskill/Delaware System

Of the 11 Catskill System sites assessed in 2018, five were considered slightly impaired with the remaining six considered non-impaired (Figure 3.15). While eight of the 11 sites had BAP scores lower than or at about the same as their respective period of record means, three sites scored higher than their period of record means. Additionally, four of the sites scored higher than during the previous sampling year, and with the exception of sites 210 and 207, the remaining sites remained relatively unchanged.

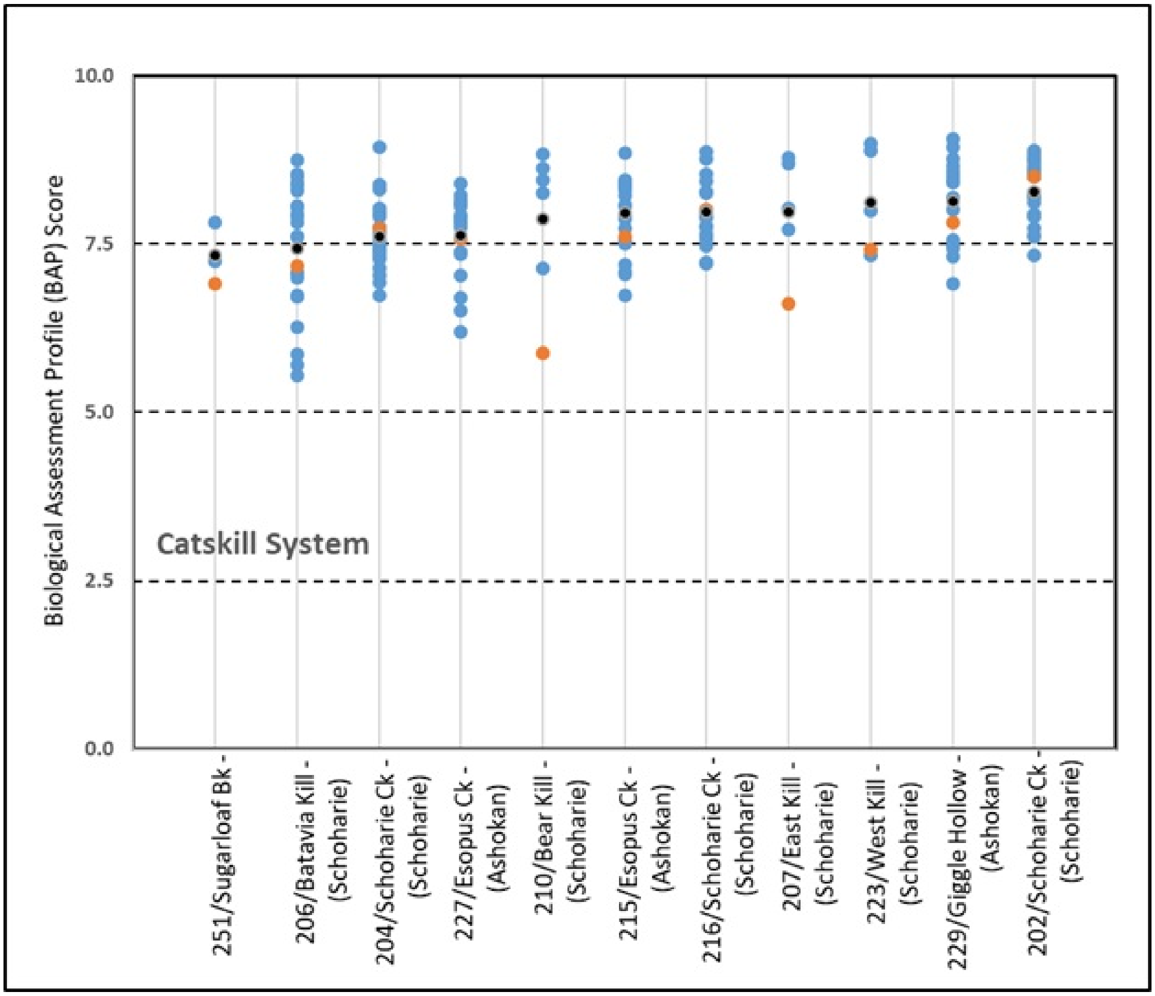


Figure 3.15 Biological Assessment Profile scores for Catskill System biomonitoring sites sampled in 2018. Mean scores (black dots) are arranged from highest to lowest; 2018 score (orange dots), pre-2018 scores (blue dots). Watersheds are indicated in parentheses on the x-axis.

Of the 13 Delaware System sites assessed in 2018, three were considered slightly impaired, with the remaining 10 considered non-impaired (Figure 3.16). While seven of the 13 sites had BAP scores lower than their respective period of record means, six of the sites scored higher than their period of record means. Additionally, seven of the sites scored higher than during the previous sampling year, and six sites stayed relatively unchanged.

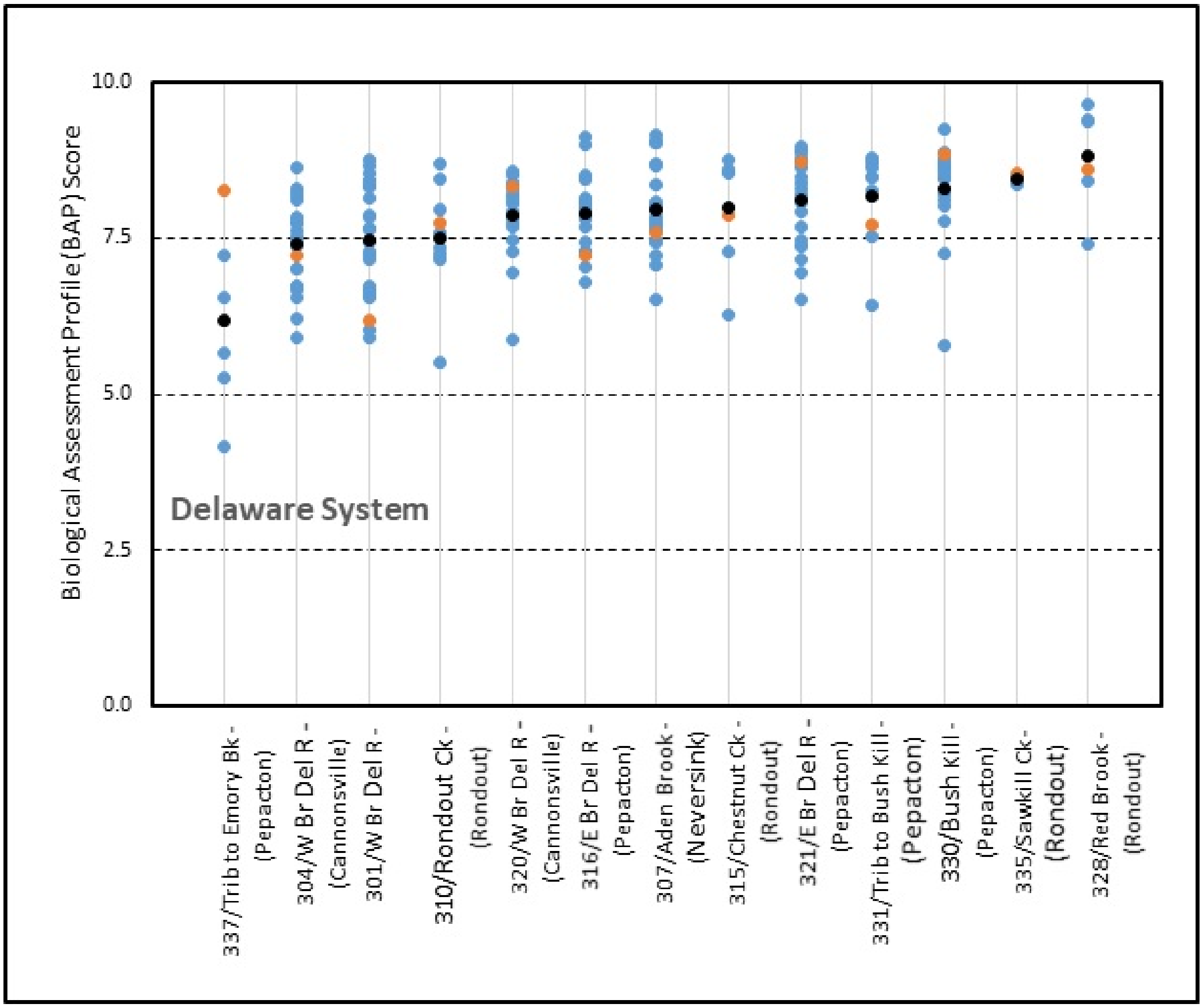


Figure 3.16 Biological Assessment Profile scores for Delaware System biomonitoring sites sampled in 2018. Mean scores (black dots) are arranged from highest to lowest; 2018 score (orange dots), pre-2018 scores (blue dots). Watersheds are indicated in parentheses on the x-axis.

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 3.11. In 2018, Delaware System VOC and SVOC samples were collected at sites NR2, PR2, CR2, and RDRRCM on October 15. Glyphosate samples were also collected on this date except for PR2, which was collected on October 1. Because Neversink, Pepacton and Cannonsville reservoirs were off-line at the time of sampling, reservoir elevation taps NR2, PR2 and CR2 were sampled instead of their respective intakes, NRR2CM, PRR2CM and WDTOCM. Catskill System SVOC and VOC samples were collected at sites EARCM and SRR2CM on October 22 with glyphosate collected on October 1. East of Hudson SVOC and VOC samples were collected on December 5 at CROGH, DEL10, and DEL18DT with glyphosate collected at these locations on December 4. All samples were shipped to a contract lab for analysis.

In 2018, no detections were observed in West of Hudson or East of Hudson samples for any of the compounds monitored.

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

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

In the event that one of these diversions is off-line at the collection time, the sample is drawn from the upstream reservoir elevation tap that corresponds to the tunnel intake depth as if that reservoir were on-line.

3.12.2 Metals Monitoring

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

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

Reservoir Basin	Site(s)
Catskill System	
Ashokan	EARCM[1]
Schoharie	SRR2CM[1]
Delaware System	
Cannonsville	WDTO[1]
Pepacton	PRR2CM[1]
Neversink	NRR2CM[1]
Rondout	RDRR2CM[1]
East of Hudson	
Kensico	CATALUM, DEL17, DEL18DT, DEL19LAB
Croton	CROGH, CROGH1CM[2], CROGHC, CRO9
West Branch	DEL9, DEL10, CWB1.5

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

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

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

Analyte	Primary Standard ($\mu g\ L^{-1}$)	Secondary Standard ($\mu g\ L^{-1}$)
Silver (Ag)		100
Aluminum (Al)		50-200
Arsenic (As)	10	
Barium (Ba)	2000	
Beryllium (Be)	4	
Cadmium (Cd)	5	
Chromium (Cr)	100	
Copper (Cu)	1300	1000
Iron (Fe)		300
Mercury (Hg)	2	
Manganese (Mn)		50
Nickel (Ni)		
Lead (Pb)	15	
Antimony (Sb)	6	
Selenium (Se)	50	
Thallium (Tl)	0.5	
Zinc (Zn)		5000

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

Analyte	Type	Standard ($\mu g\ L^{-1}$)
Silver (Ag)	H(WS)	50
Arsenic (As)	H(WS)	50
Barium (Ba)	H(WS)	1000
Cadmium (Cd)	H(WS)	5
Chromium (Cr)	H(WS)	50
Copper (Cu)	H(WS)	200
Mercury (Hg)	H(WS)	0.7
Manganese (Mn)	H(WS)	300
Nickel (Ni)	H(WS)	100
Lead (Pb)	H(WS)	50
Antimony (Sb)	H(WS)	3
Selenium (Se)	H(WS)	10

In 2018, most metal sample results were well below state and federal benchmarks. Arsenic, selenium, lead, antimony, beryllium, cadmium, silver, and thallium were not detected above the detection limit of 1.0 µg L^{-1} for any sample. No samples were detected for mercury at its detection limit of 0.10 µg L^{-1}.

Two samples were detected for zinc (13.4 and 12.1 µg L^{-1}) well below the USEPA secondary standard of 5000 µg L^{-1}. Nickel was detected seven times, twice at CRO1B and CROGH and once at NR2, RDRRCM, and PRR2CM. Detected concentrations ranged from 1.1 to 39.4 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 5.5 µg L^{-1} at SRR2CM to 40.4 µg L^{-1} at CROGH. Copper detections ranged from 1.0 to 33.7 µg L^{-1} with no detections in 25 of 51 samples. All detected barium and copper results were all well below their respective benchmarks.

Benchmarks for iron, aluminum, and manganese were occasionally exceeded in 2018. The iron benchmark of 300 µg L^{-1} was exceeded at SRR2CM in February (542 µg L^{-1}) and November (334 µg L^{-1}) and at RDRRCM in February (339 µg L^{-1}). The manganese benchmark of 50 µg L^{-1} was exceeded on four occasions, while the aluminum benchmark of 50 µg L^{-1} was exceeded in eight samples. Manganese exceedances occurred at CRO1B (70 µg L^{-1}), CROGH (71 µg L^{-1} and 89 µg L^{-1}), and PRR2CM (73 µg L^{-1}). Aluminum exceedances occurred in one sample each at NR2 (58.2 µg L^{-1}), CR2 (74.1 µg L^{-1}), in two samples at NRR2CM (60 and 111 µg L^{-1}) and in three samples at SRR2CM (127, 368 and 830 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, DEL19DT, were below the benchmarks, ranging from <10.0 to 23.8 µg L^{-1} for aluminum, <3.0 to 47.0 µg L^{-1} for iron, and 9.0 to 47.0 µg L^{-1} for manganese (the "<" designates the analytical detection limit). The Croton keypoint closest to the distribution system, CROGH (or CRO1B), was also below most benchmarks, ranging from <10.0 to 13.1 µg L^{-1} for aluminum and from 36.0 to 114.0 µg L^{-1} for iron. However, the benchmark for manganese was exceeded in three samples (70, 71, and 89 µg L^{-1}).

3.13 Special Studies

There were a total of 15 special studies conducted throughout the watershed during 2018. Among these, four of these investigations occurred in the Kensico basin and are reported in Chapter 4. Studies were initiated when a water quality concern was raised or were initiated to better understand monitoring and management alternatives.

3.13.1 Foamstream: An Alternative to Common Herbicides

The purpose of the Foamstream Study was to investigate whether there is a viable alternative to glyphosate, a commonly used herbicide in the NYC watershed system. Foamstream's mode of operation is to use super-heated water surrounded by a proprietary foam to scald plant tissue. Foamstream was compared in efficacy to glyphosate and another herbicide, Finale® (a non-synthetic herbicide). The study demonstrated that Foamstream was effective in scalding a variety of plant tissues. Regrowth occurred at all study sites after approximately one month, with rate of regrowth dependent upon the plant species at each plot and local environmental conditions. Glyphosate and Finale® were slower to act in eradicating plants, but were more effective at reducing regrowth at each plot over the long term.

Conclusions from this study were that Foamstream's effectiveness is short term (<1 month) and a consistent schedule of its use is necessary to achieve desired weed control. From a cost/benefit standpoint, Foamstream proved to have maintenance issues due to chronic equipment breakdowns making it, at present, an unreliable and questionable replacement for glyphosate use by DEP employees in the watershed.

3.13.2 Goats Grazing on the Glenford Dike of Ashokan Reservoir

Using goats is considered an environmentally friendly and cost effective way to clear unwanted vegetation. Goats are especially effective on steep slopes such as dikes that can be difficult and dangerous to mow. As a result of plans by Source Water Operations staff to use goats to maintain the Glenford Dike of the Ashokan East Basin, Watershed Water Quality Field staff were asked to monitor the water quality in the cove near the dike. The plan was to release the goats for grazing in early July and for Water Quality staff to take samples at two depths and analyze them for total phosphorous, fecal coliform bacteria, and turbidity once a month for the remainder of the goat deployment. Baseline samples were taken on July 2, 2018. The goats were not put on the dike, so no further sampling took place in 2018. There are plans to use the goats at this location in 2019.

3.13.3 A Short-term Synoptic Field Survey and Limited Lab Analysis for fDOM

Field surveys were conducted in the Neversink and Cannonsville watersheds to take a "snapshot" of fluorescent dissolved organic matter (fDOM) levels at sites above the Neversink Claryville gage (NCG) and Cannonsville Beerston stream (CBS) sites, and to measure levels of fDOM running off of wetland areas. The study used a YSI EXO2 sonde to collect field measurements of fDOM and other field analytes including temperature, pH, conductivity, and turbidity to compare with a Turner AquaFluor® fluorometer borrowed from the Hubbard Brook Ecosystem Study group in New Hampshire. Grab samples were collected along with the EXO2 sonde measurements. Samples were submitted to the DEP Kingston Laboratory and analyzed for total and dissolved organic carbon (TOC, DOC), total and dissolved nitrogen (TN, TDN), and absorbance at 254 nm (UV_{254}). This project served two purposes: to evaluate how well the YSI fDOM sensor compares with the Turner AquaFluor® CDOM/FDOM sensor and to look at a broader spatial distribution of sites to better understand how water moving through the system might change in character (as measured by fDOM concentration) along its route. These comparison data will be part of a larger effort to further understand the relationships among different sensor brands and gain insights into the spatial variability in fDOM in the Neversink and Cannonsville watersheds. This study was supplemental to ongoing monitoring for disinfection by-product precursors at the primary inflow, reservoir, and outflow of Cannonsville and Neversink reservoirs. The main objective of the ongoing study is to better understand and predict DBP precursors to inform water management through data and modeling.

3.13.4 Boyd's Corners Release – Cloudy Water Investigation

BWS Source Water Operations and Water Quality management staff requested samples at the Boyd's release due to the presence of a cloudy discharge. The impetus for taking the samples was the close proximity to the West Branch Reservoir and this reservoir's importance. Samples were taken on August 8, 2018 for the following analytes: dissolved oxygen, pH, phytoplankton, turbidity and two metals: iron (Fe) and manganese (Mn). Samples were taken at the following sites: CBC Plunge Pool, CBC Plunge Pool 1, CBC Plunge Pool Release and the CBC Release Pipe. All analytes investigated were within a normal range of detection for water quality during the summer. There was no further investigation.

3.13.5 Amawalk Reservoir Investigation – Zebra Mussels (*Dreissena polymorpha*)

Zebra mussels and veliger larvae have been observed in the Muscoot River downstream of Lake Mahopac. There is a concern that the mussels entered the Amawalk Reservoir as Lake Mahopac is in the Amawalk Reservoir watershed. The intent of this investigation was to add additional zebra mussel monitoring to discover if the mussels had entered the reservoir. Samples were taken for zebra mussels on August 22, 2018 at sites 3CA, 3.5 CA (new site added for this investigation) and 4CA. All aquatic samples were non-detects. Additionally, a shoreline survey was conducted to look for evidence of the mussels. There was no evidence of zebra mussels found during this survey. Further sampling will be based on continued detection in Lake Mahopac.

3.13.6 Ultrasonic Treatment for Algal Control Pilot Project

A pilot project using ultrasonic platforms was initiated to determine the effectiveness of ultrasonic treatment in preventing and reducing algal blooms. Two areas of the East of Hudson watershed that historically have experienced high concentrations of blue-green algae during the summer months were selected for the study. A sonic platform was activated in June in Croton Falls Reservoir in an attempt to prevent an algae bloom. A second sonic platform was activated in August in New Croton Reservoir in an attempt to diminish an algal bloom that occurred. Each unit has two sonic heads, which emit sound in four directions using two bandwidths for control of different algal groups. The units are designed to interrupt the gas vesicles within the cells of algae, which should then cause the algae to lose buoyancy and sink in the water column out of the photic zone. The system is designed to be effective on green algae and diatoms to a range of 150 meters radially from the platform, and blue-green algae to 400 meters. According to the manufacturer, the sonic signal will not disrupt the cells or have any impact on higher organisms.

The study design included an Operational Guidance Plan, which outlines the monitoring to be conducted throughout the study. Weekly monitoring of phytoplankton, chlorophyll *a*, total phosphorus and total dissolved phosphorus was done at depths of 1m below the reservoir surface and 1m off of the reservoir bottom. Dissolved oxygen profiles were made with measurements at 1-meter increments throughout the water column conducted weekly. Biweekly monitoring of zooplankton was performed using both fine and coarse mesh tow nets for vertical tows at each site. A total of 176 samples were collected and analyzed in the lab, as well as over 60,000 field measurements. Further details can be found in the summary report (DEP 2019b). The study results did not show differences in water quality at the control or treatment sites in terms of chemical or biological parameters. DEP plans on redeploying one of the sonic platforms at site 5 on Croton Falls in 2019 to provide additional data for comparison.

3.13.7 Algal Toxins

In May 2015, the U.S. Environmental Protection Agency (EPA) issued 10-Day Drinking Water Health Advisories (HAs) for the cyanobacterial toxins microcystins and cylindrospermopsin. EPA has also listed cyanotoxins on their Contaminant Candidate Lists (CCLs) and will be requiring monitoring within distribution systems under the fourth Unregulated Contaminant Monitoring Rule (UCMR4). As a result, DEP initiated baseline sampling of keypoint and routine reservoir sites in 2015 that is ongoing. In 2018, algal toxins were detected in three upstate watershed reservoirs. Samples were intentionally taken in search of toxins and were analyzed for total microcystins at DEP's Hawthorne Laboratory with an Abraxis® test kit, which utilizes the ELISA method. Selected samples were also sent to a contract laboratory and were processed through LC/MS/MS analysis for anatoxin-a, cylindrospermopsin, nodularian, and 6 variants of microcystin (*-LA*, *-LF*, *-LR*, *-LY*, *-RR*, *-YR*). Enhanced algal toxin sampling took place at site 5 in Croton Falls and the upper reaches of New Croton Reservoir in support of the ultrasonic algal control pilot project (see section 3.13.6). All sites with detections were distant from intakes. No algal toxins were detected in the reservoir keypoint (effluent) sites.

The three reservoirs that had detectable total microcystins in 2018 were Croton Falls (4.9 µg L^{-1} on September 18), New Croton (1.6 µg L^{-1} on October 10), and Diverting (1.2 µg L^{-1} on August 6). Further analysis by the contract lab revealed microcystin-*LR* at levels of 5.9 µg L^{-1} in Croton Falls on October 23; 0.18 µg L^{-1} in New Croton on September 11; and 0.32 µg L^{-1} in Diverting on August 6. Other microcystin variant values were observed in Croton Falls late in the growing season on October 23. Those values above detection limits were: -*RR* at 7.8 µg L^{-1}, and -*YR* at 1.2 µg L^{-1}. Additionally, -*LA* was detected at 0.44 µg L^{-1} in New Croton on September 11, and 0.47 µg L^{-1} in Diverting on August 6; both were sampled at observed surface blooms. All other samples analyzed for variants -*LF* and -*LY* were below detection limits.

New Croton Reservoir had anatoxin-a present at low levels (0.026 µg L^{-1} on October 12) just above the detection limit of 0.02 µg L^{-1}. All other contract lab sample results were below the detection limits or non-detect for anatoxin-a, cylindrospermopsin, and nodularian.

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

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

The objective of this sampling program is to assist in determining the effectiveness of best management practices (BMPs) used by DEP’s Stream Management Program to stabilize and reduce the natural turbidity and suspended sediment observed in Catskill Mountain streams. This study is attempting to quantify any change in turbidity which may occur due to the installation of BMPs on a project site on the Batavia Kill in the Schoharie watershed. To accomplish this, turbidity data are being collected at two sites: one located upstream (on Batavia Kill above Lewis Creek, site code S10-LC) and the other located downstream (Batavia Kill immediately upstream from Red Falls, site code S10-RF) of the BMP site. Data are being collected before and after BMP installation. Project construction is scheduled to begin in 2020. Turbidity sensors have been installed at each of the sites and will collect a turbidity reading every 15 minutes. Sensors will allow data to be collected over a wide range of flow and environmental conditions. The upstream site (S10-LC) began recording data on November 8, 2017, and the downstream site (S10-RF) began collecting data on October 21, 2016. In 2018 at S10-LC, 32,198 turbidity readings were made. At S10-LF, 39,716 readings were made. Upon completion of the sampling program, the data will be analyzed to determine if the BMP had a measurable impact on turbidity in the stream. The results of these analyses will be reported in the 2021 FAD Program Summary and Assessment Report.

3.13.9 Conversion of Septic to Sewer Evaluation

The objective of this sampling effort is to measure the potential water quality benefits of providing new or improved wastewater treatment to areas previously served by septic systems. Two areas were targeted for monitoring. The first area was in the Town of Hunter, which is in the Schoharie watershed. The new extension conveys sewage to the Tannersville WWTP. The second area was in the Town of Middletown in the Pepacton watershed with new construction sending the sewage from Bull Run Road residences to the Margaretville WWTP. Monitoring locations were established upstream and downstream of these areas.

For Tannersville, the sites were located on Sawmill Creek above (site code SSMA) and below (site code SSMB) the area to be connected to the wastewater treatment plant. Sawmill Creek is a tributary to Gooseberry Creek, which flows into Schoharie Creek.

In Pepacton, watershed sites were located on Bull Run above (site code PBRA and below (site code PBRB) the project area. Bull Run is a tributary to the East Branch of the Delaware River.

The monitoring plan calls for samples to be collected at these sites before the projects were installed and continue for at least two years after completion of the projects. Monthly sampling of these sites commenced in March 2009. The connections for the Sawmill Creek project were completed in June 2016 and those for the Bull Run Project were completed in May 2019.

During 2018 monthly samples collected at the four sites for this project resulted in 542 analyses. Upon completion of the monitoring for the projects, the data will be analyzed and documented in a report to determine if any effects from the conversion are apparent.

3.13.10 Investigation of *Giardia* in the Rondout Basin

In November of 2018, an increase in the number of *Giardia* cysts was observed at the Delaware inflow to Kensico Reservoir. The increase was traced to the upper end of the Delaware Aqueduct at the Rondout Reservoir outflow. Concentrations of cysts were several times higher than normal for this time of year at Rondout, with a maximum of 29 cysts $50L^{-1}$ in December, while historical data show concentrations only in the single digits. Several different areas of investigation were explored to identify the source(s) and transport of the *Giardia* cysts. Initial review of other water quality data included fecal coliforms, turbidity, and other physical parameters, as well as a review of precipitation, runoff, and stream flows. Supplemental water samples were collected at streams, at various depths in the reservoir, and at different aqueduct elevations to narrow down locations of the *Giardia*. With regard to sources, waterbird population counts, wildlife surveys and trapping were performed in order to test scat samples for the presence and types of *Giardia* in the animal populations around the reservoir. Samples positive for *Giardia* were sent to the Center for Disease Control and Prevention (CDC) in Atlanta, Georgia, to attempt to identify the species and subtypes of *Giardia* that were recovered from the water and the wildlife. Results from the typing were helpful in identifying potential sources of the cysts, and determining if the types recovered were types capable of causing disease in humans. This investigation has continued into 2019 and is currently ongoing. Pathogen results through 2018 are provided in section 5.3.

3.13.11 Taste and Odor Issues in the Croton System, Autumn 2018

The Croton Water Filtration Plant was restarted on October 1 after being shut down since August 15 for maintenance. Taste and odor complaints began to rise on October 5 and peaked on October 10, and as a result the plant was shut down on October 15. The complaints were mostly for “musty” water. Limnology reports from September for the New Croton Reservoir did not detect any of the six algal genera (*Anabaena*, *Chrysosphaerella*, *Fragilaria, Microcystis*, *Synura*, and *Uroglenopsis*) that are historically the greatest concern for taste and odor for NYC drinking water. However, the dominant algal genera observed in September was the blue-green algae, *Lyngbya*, which is also a potential taste and odor algae due to the production of geosmin and 2-methylisoborneol (MIB). Samples were collected from various monitoring sites and analyzed by Eurofins for geosmin and MIB. The intake level of withdrawal was changed to a higher elevation and the Croton Water Filtration Plant was restarted on October 16 using water from the Catskill Aqueduct delivered to Croton Lake Gatehouse and New Croton Aqueduct via a Catskill branch connection pipe. To minimize the potential for taste and odor complaints from reoccurring, Croton water was blended with Catskill water beginning October 18 and then the percentage of Catskill water was reduced in steps until October 28 when 100 percent Croton water was delivered to the Croton Water Filtration Plant. Samples collected on October 22 and 24 from the Croton Reservoir bottom intake (CRO1B) had detections of these compounds (October 22: MIB=6.8 ng/L and geosmin = 3.0 ng/L, October 24: MIB=5.5 ng/L) that are detectable by humans, while all other sites had no detections. Sampling for geosmin and MIB continued through November 26 with most results being below detection limits. Ultimately, it was concluded that the withdrawal of anoxic water from the bottom inlets was the main cause of the taste and odor problem. Other factors, such as algae blooms on New Croton and Jerome Park reservoirs; switching from using the south basin of the Jerome Park Reservoir to using the north basin of the Jerome Park Reservoir; and increasing the flow from New Croton by opening the second inlet on Croton Lake Gate House, may have contributed.

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 the Filtration Avoidance Determination. To ensure this goal is met, DEP has a routine water quality monitoring strategy for Kensico aqueducts, streams, and the reservoir that is documented in the Watershed Water Quality Monitoring Plan (WWQMP) (DEP 2018). These sampling site locations are shown in Figure 4.1. The WWQMP prescribes monitoring to achieve compliance with all federal, state, and local regulations; enhance the capability to make current and future predictions of watershed conditions and reservoir water quality; and ensure delivery of the best water quality to consumers through ongoing high frequency surveillance.

Table 4.1 summarizes the approximate number of water quality samples collected within the Kensico watershed during 2018. The number of 2018 keypoint influent samples was lower than 2017 totals because the Catskill Aqueduct was offline for rehabilitation for approximately four weeks during the months of November and December. Compliance with the Safe Drinking Water Act Surface Water Treatment Rule (SWTR) (USEPA 1989) is of paramount importance to DEP to maintain the Filtration Avoidance Determination. Fecal coliforms and turbidity are focal points when discussing Kensico water quality. The results of this monitoring are representative of the excellent quality of water leaving Kensico Reservoir during 2018. 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 2018.

Kensico sampling programs	Turbidity	Bacteria	*Giardia/ Crypto-sporidium*	Virus	Phyto-plankton	Other Analyses
SWTR Turbidity compliance	2,189					
Keypoint effluent	365	365	53	12	173	2,507
Keypoint influent	497	497	104	24	101	3,216
Reservoir	652	431			114	2,892
Streams	152	155	111			1,367

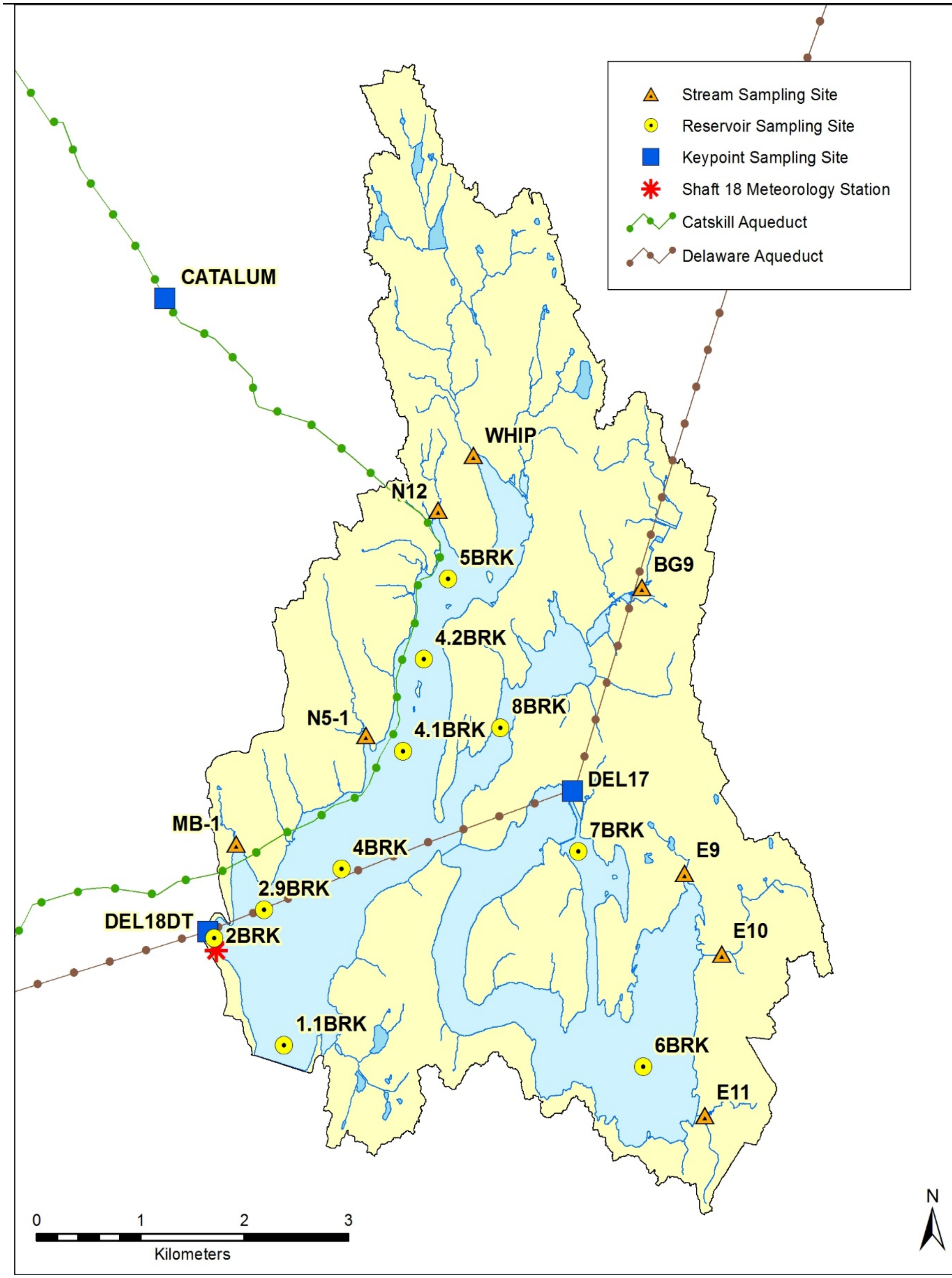


Figure 4.1 Kensico Reservoir showing limnological, hydrological, and keypoint sampling sites, meteorology stations, and aqueducts.

4.2 Reservoir Raw Water Quality Compliance

DEP routinely conducts water quality compliance monitoring at the Kensico Reservoir aqueduct keypoints. The CATALUM and DEL17 influent keypoints represent water entering Kensico Reservoir from the NYC upstate reservoirs via the Catskill and Delaware Aqueducts, respectively. The monitoring for CATALUM and DEL17 include requirements defined by the Catskill Influent Chamber and Delaware Aqueduct (DEL17) SPDES permits, NY-026-4652 and NY-026-8224 respectively. The DEL18DT effluent keypoint represents Kensico Reservoir water entering the Delaware Aqueduct Shaft Building 18 at a point just prior to disinfection; this water ultimately travels down to distribution. Table 4.2 outlines the grab sample monitoring that took place at three active aqueduct keypoint locations during 2018. Keypoint monitoring was increased in August 2018 to begin collecting UV254 and DOC on a weekly basis at CATALUM to more closely monitor potential surrogates for disinfection by-products from the Catskill system. 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 2018.

Site	Fecal and Total Coliforms, 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	W	W	M	Q
DEL17	5D	5D		W	W	W	W	M	Q
DEL18DT	7D	7D	4H	3D	W	M	W	M	Q

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

Table 4.3 shows the median and single sample maximum for Kensico Reservoir influent and effluent turbidity and fecal coliform samples collected during 2018. DEP continues to utilize the reporting procedure for fecal and total coliforms that complies with the Federal Register Vol.

82, No. 165 Method Update Rule that was instituted by DEP on April 1, 2017. The 2018 turbidity values for all three sites were similar to 2017 values. For fecal coliforms, CATALUM had similar values to 2017 median and single sample maximum values while DEL17 and DEL18DT were the same or higher than 2017. Beginning in July 2018 through the end of the calendar year, precipitation was about 45 % greater than the historical average for this period. Throughout the entire upstate watersheds, multiple precipitation events occurred that exceeded three inches of total rainfall during each event.

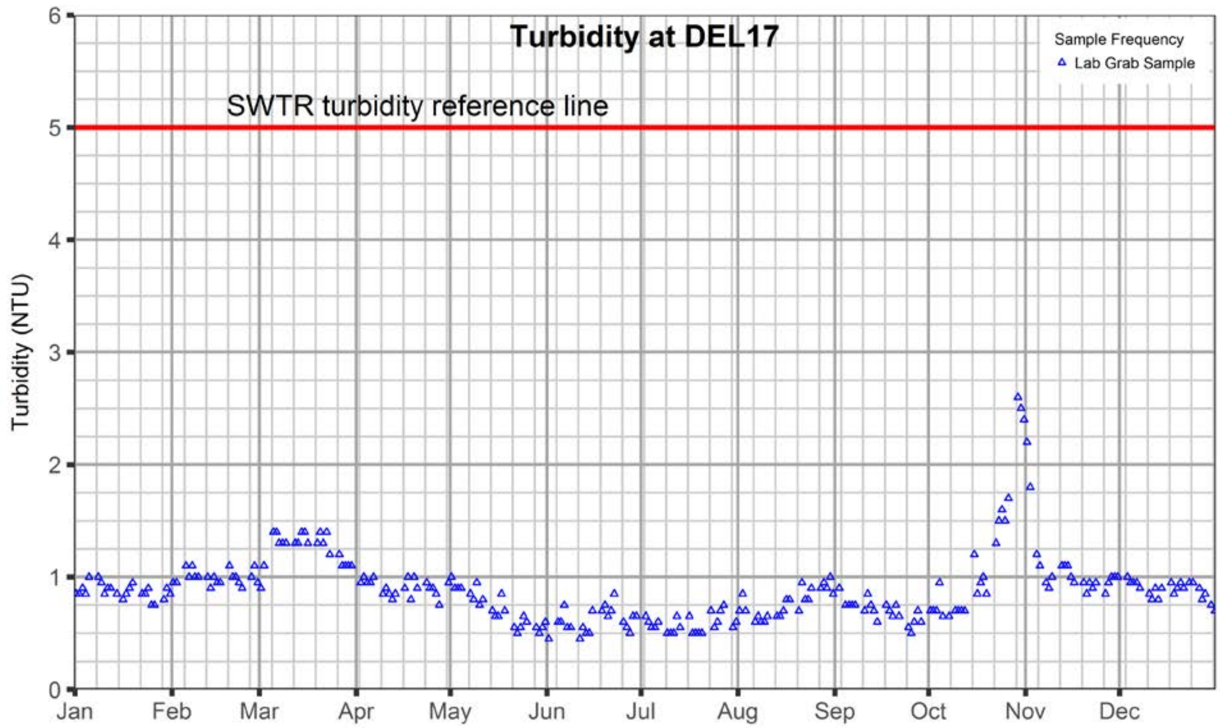
Table 4.3 Kensico keypoint fecal coliform and turbidity results from January 1, 2018, to December 31, 2018.

Analyte	Kensico Sampling Location	Median	Single Sample Maximum
Fecal Coliform (coliforms $100mL^{-1}$)	CATALUM	<1	E9
	DEL17	2	43
	DEL18DT	1	58
Turbidity (NTU)	CATALUM	1.6	3.8
	DEL17	0.8	2.6
	DEL18DT	0.8	1.6

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

For most of 2018, short term increases in turbidity or fecal coliforms could be attributed to changes in reservoir operations and/or rainfall/runoff events. Turbidity values were well below the SWTR turbidity limit at DEL18DT and the influent locations were less than 4 NTU for the entire year. Fecal coliform analyses resulted in five out of 365 sample results greater than 20 fecal coliforms $100mL^{-1}$ at DEL18DT during 2018 with four of the 20 fecal coliforms $100mL^{-1}$ exceedances occurring shortly after the September 24-25, 2018 storm event that deposited almost 4.5 inches of rain in the Kensico watershed. Also, Kensico Reservoir was in "Float" mode for most of the period from September 27 to October 12, 2018, which significantly reduced the amount of water entering the system at DEL18DT. Overall, water quality in 2018 was excellent, with the source water at Kensico meeting the SWTR requirements for both fecal coliforms and turbidity.

The routine grab sample results at CATALUM, DEL17, and DEL18DT for the 2018 turbidity and fecal coliform results are shown in Figure 4.2, Figure 4.3, and Figure 4.4. For the two influent sites, DEL17 and CATALUM, the SWTR limit line is shown only as a reference line because the influent sites are not subject to the SWTR. Results greater than turbidity and fecal coliform y-axis scales were replaced with a value and an arrow pointing toward the top of the chart. Results below the detection limit include a "drop line" connecting the result to the x-axis and the length of the "drop line" goes to the top of the censored range. A "drop line" that goes to five indicates that the result was less than five.



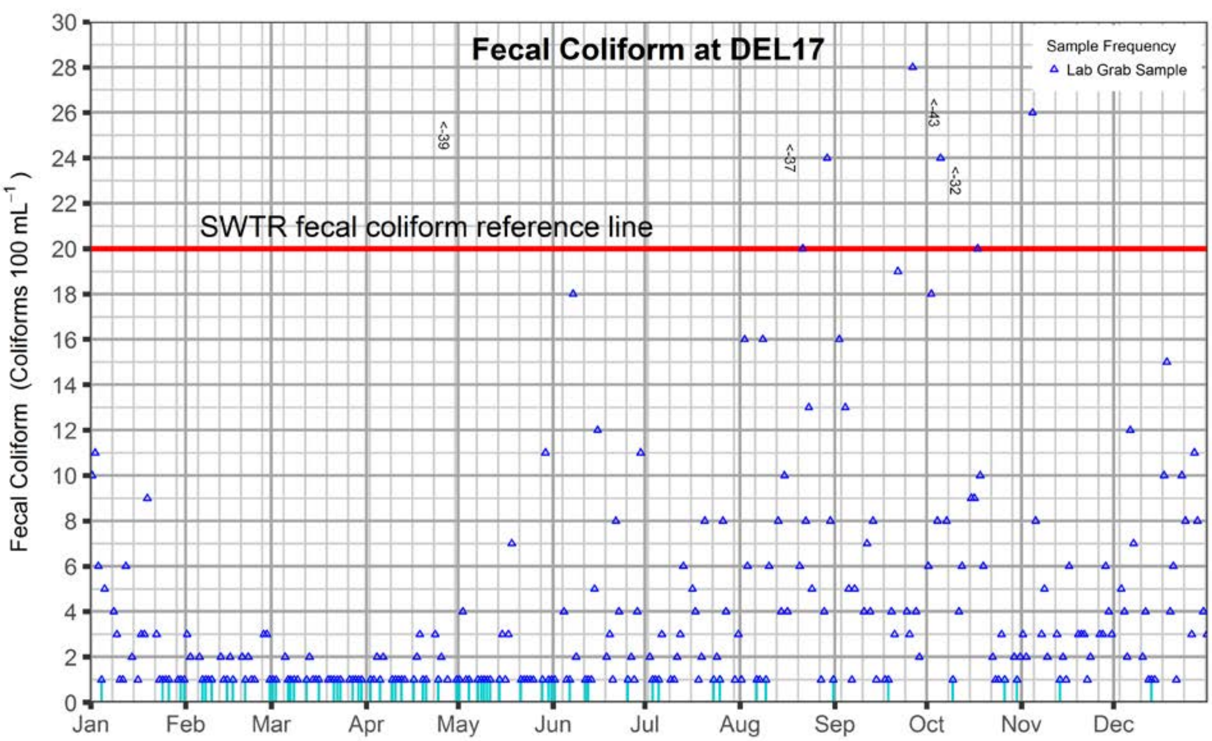
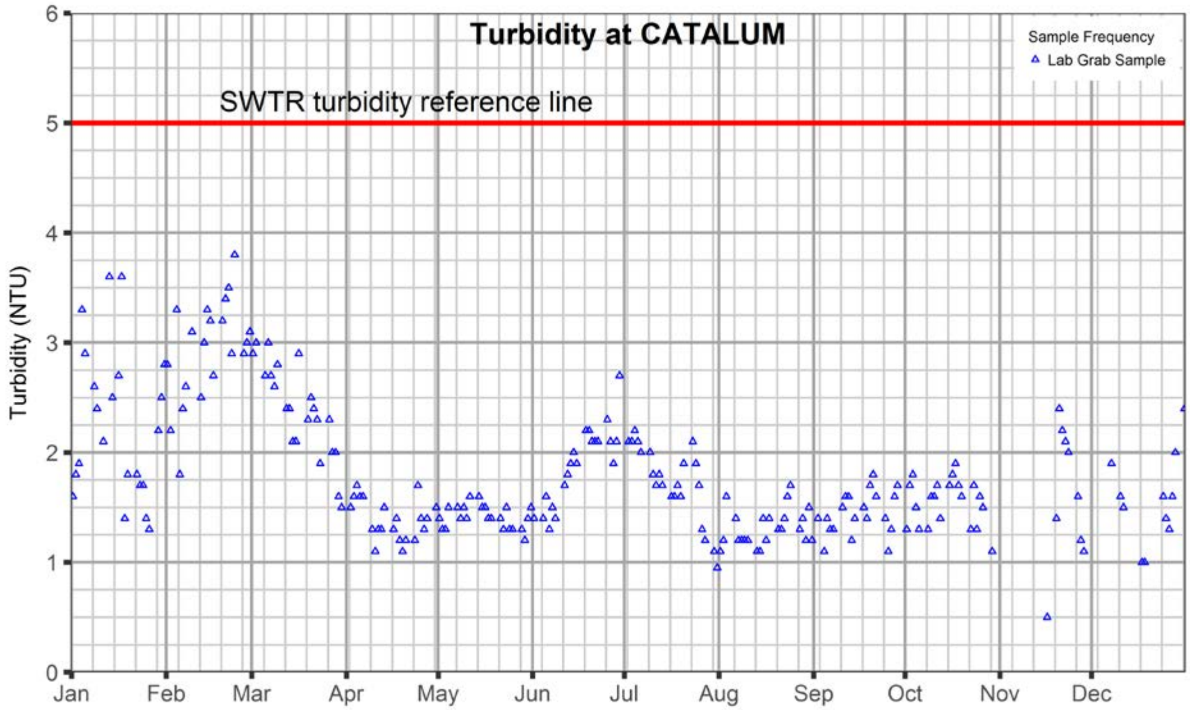


Figure 4.2 Five-day-per-week turbidity and fecal coliform grab samples at DEL17.



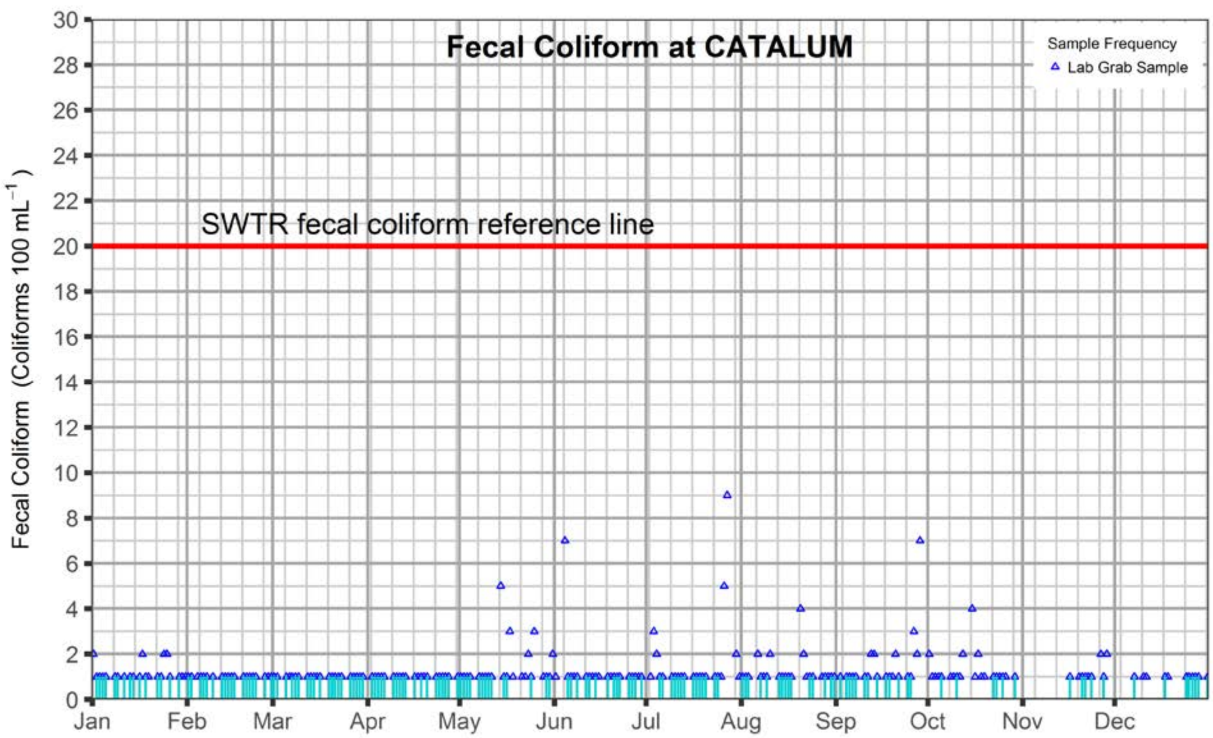


Figure 4.3 Five-day-per-week turbidity and fecal coliform grab samples at CATALUM.

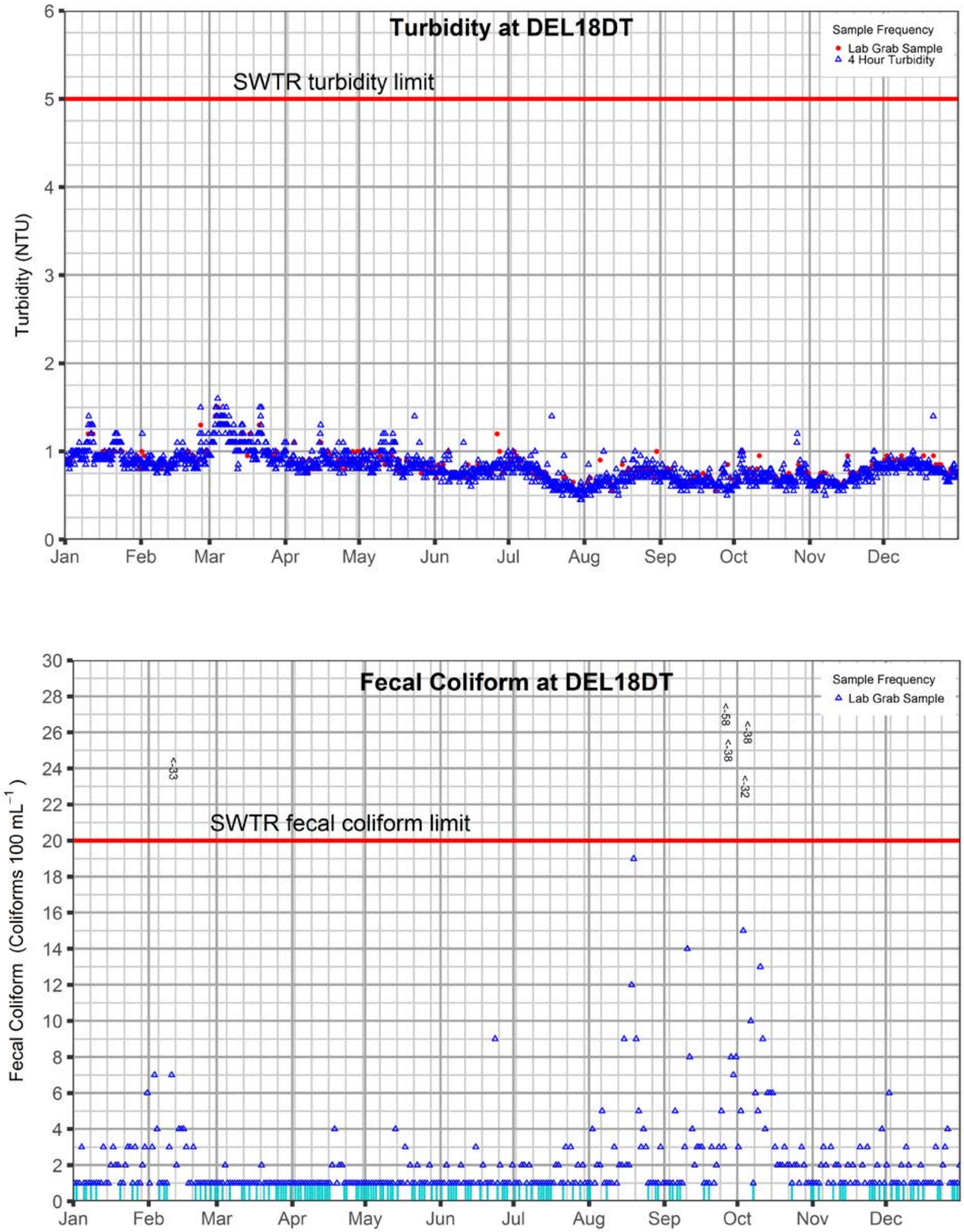


Figure 4.4 Seven-day-per-week turbidity and fecal coliform grab samples at DEL18DT.

4.3 Kensico Watershed Monitoring and Turbidity Curtain Inspections

4.3.1 Kensico Watershed Monitoring

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

Table 4.4 Summary statistics for Kensico watershed streams for 2018.

Analyte	Site	Obs	ND	Minimum	25th Percent-ile	Median	75th Percent-ile	Maximum	Note
NH3 (as N) (mg L^{-1})	BG9	12	2	<0.02	0.02	0.03	0.05	0.14	KM
	E11	12	8	<0.02	<0.02	<0.02	0.02	0.03	ROS
	MB-1	12	2	<0.02	0.02	0.04	0.06	0.14	KM
	N12	12	10	<0.02	<0.02	<0.02	<0.02	0.06	>80%
	N5-1	12	2	<0.02	0.02	0.04	0.06	0.15	KM
	WHIP	12	6	<0.02	<0.02	<0.02	0.02	0.04	ROS
NO3+NO2 (as N) (mg L^{-1})	BG9	12	0	0.09	0.20	0.28	0.35	0.76	
	E11	12	3	<0.02	<0.02	0.04	0.16	0.68	KM
	MB-1	12	0	0.24	0.31	0.51	0.62	1.03	
	N12	12	0	0.82	0.95	1.30	1.44	2.20	
	N5-1	12	0	0.59	0.90	1.33	1.66	2.44	
	WHIP	12	0	0.61	0.82	1.02	1.17	1.67	
Total Nitrogen (as N) (mg L^{-1})	BG9	12	0	0.36	0.39	0.52	0.59	0.88	
	E11	12	0	0.20	0.30	0.36	0.41	0.84	
	MB-1	12	0	0.51	0.58	0.68	0.76	1.15	
	N12	12	0	0.95	1.05	1.36	1.50	2.21	
	N5-1	12	0	0.83	1.12	1.45	1.74	2.50	
	WHIP	12	0	0.79	1.01	1.11	1.29	1.74	
Total Phosphorus	BG9	12	0	13	18	31	38	224	
	E11	12	0	15	23	35	46	49	
	MB-1	12	0	15	23	37	66	80	

Table 4.4 Summary statistics for Kensico watershed streams for 2018.

Analyte	Site	Obs	ND	Minimum	25th Percent-ile	Median	75th Percent-ile	Maximum	Note
(as P) ($\mu g\ L^{-1}$)	N12	12	0	7	15	21	26	44	
	N5-1	12	0	22	27	46	64	104	
	WHIP	12	0	8	15	22	31	66	
Alkalinity ($mg\ L^{-1}$)	BG9	12	0	39.7	60.2	72.4	87.0	124.0	
	E11	12	0	88.8	108.8	119.5	134.5	192.0	
	MB-1	12	0	52.5	77.1	80.7	85.2	99.4	
	N12	12	0	46.0	57.4	67.3	81.3	85.4	
	N5-1	12	0	54.9	72.8	79.4	93.9	120.0	
	WHIP	12	0	39.4	48.1	59.5	72.6	76.5	
Chloride ($mg\ L^{-1}$)	BG9	12	0	25.7	129.8	188.5	229.5	517.0	
	E11	12	0	39.7	58.6	82.3	89.1	124.0	
	MB-1	12	0	56.8	137.8	174.5	256.8	526.0	
	N12	12	0	42.2	82.0	97.5	121.0	147.0	
	N5-1	12	0	10.9	94.9	108.5	136.8	329.0	
	WHIP	12	0	64.1	94.7	105.5	109.0	132.0	
Dissolved Organic Carbon ($mg\ L^{-1}$)	BG9	12	0	2.6	3.2	3.8	4.3	5.5	
	E11	12	0	3.6	4.7	4.9	5.6	7.9	
	MB-1	12	0	1.5	2.8	3.3	4.1	7.3	
	N12	12	0	1.8	2.1	2.2	2.4	3.5	
	N5-1	12	0	1.7	2.4	2.7	3.4	9.5	
	WHIP	12	0	2.2	2.6	2.8	3.1	4.7	
TSS ($mg\ L^{-1}$)	BG9	12	0	1.4	2.1	3.6	6.6	23.7	
	E11	12	1	<1.0	1.3	2.0	4.9	7.4	KM
	MB-1	12	0	1.0	2.0	2.9	4.6	5.9	
	N12	12	8	<1.0	<1.0	<1.0	1.2	16.1	ROS
	N5-1	12	3	<1.0	<1.0	3.1	5.0	7.6	KM
	WHIP	12	5	<1.0	<1.0	1.2	1.8	2.7	KM
Specific Conductivity ($\mu mhos\ cm^{-1}$)	BG9	12	0	483	590	778	964	1860	
	E10	12	0	720	1118	1355	1603	1850	
	E11	12	0	361	428	504	584	723	
	E9	12	0	499	675	845	962	1070	
	MB-1	12	0	556	649	776	1013	1840	

Table 4.4 Summary statistics for Kensico watershed streams for 2018.

Analyte	Site	Obs	ND	Minimum	25th Percent-ile	Median	75th Percent-ile	Maximum	Note
	N12	12	0	404	443	501	581	704	
	N5-1	12	0	361	517	553	651	1240	
	WHIP	12	0	360	466	503	528	624	
Turbidity (NTU)	BG9	12	0	0.7	1.6	2.8	3.3	5.5	
	E10	12	0	0.6	0.7	0.9	1.6	4.4	
	E11	12	0	1.4	2.1	3.4	4.2	5.3	
	E9	12	0	1.0	1.1	2.3	4.4	12.0	
	MB-1	12	0	1.3	2.4	4.3	5.4	8.4	
	N12	12	0	0.4	0.5	0.6	1.0	2.0	
	N5-1	12	0	0.9	1.9	2.8	4.5	7.6	
	WHIP	12	0	0.6	0.8	0.8	1.3	4.2	
Fecal Coliform (Coliforms 100mL^{-1})	BG9	12	2	<10	10	20	150	1600	KM
	E10	12	2	<10	10	50	90	300	KM
	E11	12	2	<10	<10	40	160	1000	KM
	E9	12	0	6	52	75	175	E700	
	MB-1	12	0	10	50	275	728	1400	
	N12	12	0	3	18	40	203	2500	
	N5-1	12	2	<10	10	80	600	E5100	KM
	WHIP	12	1	<10	10	40	50	E250	KM
Total Coliform (Coliforms 100mL^{-1})	BG9	12	0	20	500	655	1075	E1700	
	E10	12	0	200	650	1200	1575	3900	
	E11	12	0	100	550	1050	1775	4500	
	E9	12	1	<100	600	1400	2600	>=4800	KM
	MB-1	12	0	300	825	1500	3100	7200	
	N12	12	0	200	545	1050	2550	4000	
	N5-1	12	0	100	925	1400	2175	>=E56000	
	WHIP	12	0	100	285	750	1225	>=E1800	
Dissolved Oxygen (mg L^{-1})	BG9	12	0	1.6	6.3	8.0	10.1	11.8	
	E10	12	0	7.0	8.8	10.8	12.1	13.9	
	E11	12	0	0.8	5.8	6.5	8.8	11.9	
	E9	12	0	3.6	4.5	5.0	7.4	11.1	
	MB-1	12	0	7.6	9.1	10.6	12.7	13.7	

Table 4.4 Summary statistics for Kensico watershed streams for 2018.

Analyte	Site	Obs	ND	Minimum	25th Percent-ile	Median	75th Percent-ile	Maximum	Note
	N12	12	0	8.5	9.6	11.2	12.6	14.1	
	N5-1	12	0	5.8	8.8	10.6	12.6	13.7	
	WHIP	12	0	8.3	9.5	11.2	12.6	13.8	
pH (SU)	BG9	12	0	6.52	6.94	7.17	7.36	7.49	
	E10	12	0	7.41	7.71	7.76	7.84	8.11	
	E11	12	0	6.71	7.23	7.34	7.48	7.59	
	E9	12	0	6.38	6.90	6.99	7.08	7.59	
	MB-1	12	0	6.92	7.12	7.34	7.45	7.58	
	N12	12	0	7.52	7.74	7.81	7.96	8.57	
	N5-1	12	0	7.12	7.55	7.65	7.70	7.75	
	WHIP	12	0	7.61	7.68	7.72	7.89	8.33	
Temperature (ºC)	BG9	12	0	0.4	5.5	12.3	18.5	24.6	
	E10	12	0	<0.1	6.3	13.0	18.0	22.4	
	E11	12	0	3.2	6.0	12.0	18.8	25.8	
	E9	12	0	0.2	4.3	10.6	16.6	23.6	
	MB-1	12	0	0.6	4.3	10.2	17.4	22.5	
	N12	12	0	0.1	6.9	12.6	16.9	20.5	
	N5-1	12	0	1.3	4.6	10.5	17.5	23.1	
	WHIP	12	0	0.1	5.8	12.4	17.9	23.0	

Summary statistics for data containing non-detects were estimated using techniques recommended in Helsel (2005) using an R program developed for U.S. Environmental Protection Agency (Bolks et al. 2014). The Note column indicates which analysis method was used to determine the statistics when there were censored data. KM indicates Kaplan-Meier, ROS indicates robust regression on order statistics, >80% indicates that greater than 80% of the data are censored and statistics cannot be estimated, so the detection limit, preceded by "<", is reported, and <5 indicates that there were less than five samples so no statistics could be calculated.

"E" indicates that the coliform plate count is estimated based on a non-ideal plate.
">=" indicates that the coliform plate count may be biased low based on heavy growth.

4.3.2 Turbidity Curtain Inspection

The three turbidity curtains in the Catskill Upper Effluent Chamber cove (CAT UEC) are designed to redirect water from the CAT UEC cove into the main waterbody of Kensico Reservoir and minimize impacts of storm events by local streams. Presently, the chamber used to withdraw water from this cove has been off-line since September 2012 with the activation of the Catskill/Delaware UV Treatment facility and a lack of aqueduct pressurization. DEP continues to visual inspect the turbidity curtains, at least monthly from fixed shore locations around the cove, to maintain the infrastructure. Figure 4.5 lists the dates and results of the turbidity curtain inspections carried out in 2018. Due to staffing issues, there were no observations made during December and observations were resumed in January 2019. When inspections indicate that maintenance is required, Bureau of Water Supply Systems Operations is notified and operations staff perform the appropriate repairs or adjustments.

Table 4.5 Visual inspections of the Kensico Reservoir turbidity curtains.

Date	Observations
01/10/18	The curtains appear intact and afloat as seen from shore.
01/25/18	The curtains appear intact and afloat as seen from shore.
02/ 5/18	The curtains appear intact and afloat as seen from shore.
02/21/18	Most of the turbidity curtains in the CAT UEC cove and on the point are attached, afloat, and intact as seen from shore. However, the curtain on the point may have an issue. It appears unusually kinked and there is some fabric or debris on top of the floatation as seen in picture 3 as observed from shore. One curtain the CAT UEC cove from shore appears to have sections that appear sunken or overturned compared to the others around it as observed from shore. Management notified.
03/ 8/18	Most of the curtains appear intact and afloat as seen from shore, except one section of curtains is unraveling shown on the second picture, supervisors notified.
03/20/18	The curtains appear intact and afloat as seen from shore.
04/ 4/18	The curtains appear intact and afloat as seen from shore.
04/19/18	The turbidity curtains in the Catskill UEC cove appear intact and afloat.
05/ 2/18	The turbidity curtains in the Catskill UEC cove appear intact and afloat.
05/16/18	The curtains appear intact and afloat as seen from shore.
05/30/18	Curtains appear intact and afloat as seen from shore, one possibly damaged section at the point.
06/13/18	The curtain appears intact and floating as seen from shore. Turbidity curtain near DEL18 is located closer to shore compared to what we saw before.
06/26/18	The curtains appear intact and afloat as seen from shore.
07/11/18	The curtains appear intact and afloat as seen from shore.

Table 4.5 Visual inspections of the Kensico Reservoir turbidity curtains.

Date	Observations
07/26/18	The curtains appear intact and afloat as seen from shore.
08/ 8/18	Due to lowered water level in Kensico Reservoir the turbidity curtain near Del18 is resting on the shore.
08/23/18	All booms appear intact and afloat from shore with the exception of the DEL18 point boom, which is resting on the shoreline.
09/ 6/18	The turbidity curtains in the CAT UEC cove and on the point appear attached, afloat, and intact as seen from shore. A portion of the curtain on the point appears caught up on rocks and may not be afloat from shore.
09/21/18	The turbidity curtains in the CAT UEC cove and on the point appear attached afloat, and intact as seen from shore. A portion of the curtain on the point is caught up on rocks near shore. The curtains across the cove near the N5 stream site are attached and functioning.
10/ 3/18	The turbidity curtains in the Catskill UEC cove are intact and afloat.
10/17/18	The curtains appear intact and afloat as seen from shore.
11/15/18	No email sent, booms appear intact and afloat as seen from photos.
11/29/18	The turbidity curtains in the Catskill UEC cove are intact and afloat.

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. Continued implementation of the avian dispersal measures have led to reduced waterbird counts and fecal coliform levels, allowing DEP to maintain compliance with the federal Surface Water Treatment Rule (SWTR).

Historic water quality monitoring data collected at the two main water influent and effluent facilities at Kensico demonstrated that higher levels of fecal coliform bacteria were leaving the reservoir than what was contributed through aqueducts from the upstate reservoirs (DEP 1992). It was apparent then that a local source of fecal coliform bacteria was impacting Kensico. Based on these data, DEP determined that waterbirds were the most important contributor to seasonal fecal coliform bacteria loads to Kensico.

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

Avian management techniques include non-lethal dispersal actions by use of pyrotechnics, motorboats, airboats, propane cannons, active nest removals of terrestrial avian species, remote-control boats, and physical chasing. Bird deterrence measures include waterbird reproductive management, shoreline fencing, bird netting, overhead bird deterrent wires, and meadow management.

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.

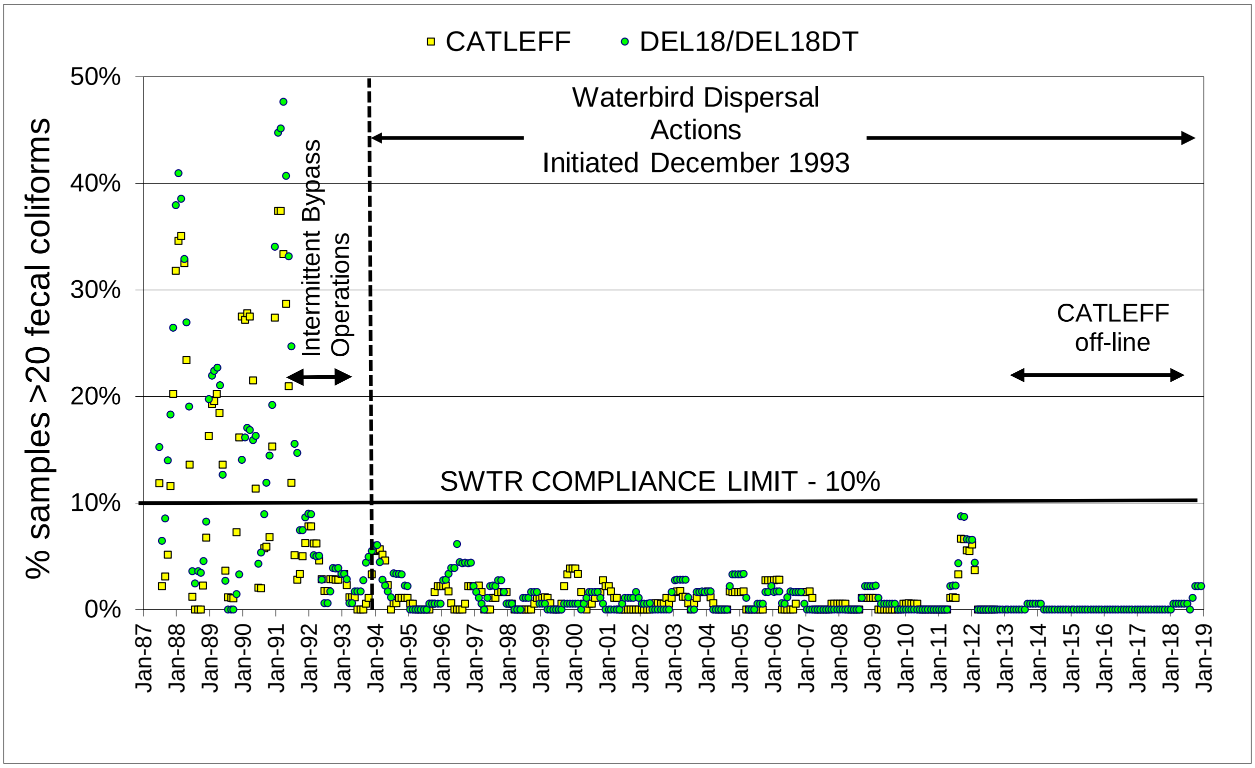


Figure 4.5 Percent of keypoint fecal coliform samples at Kensico Reservoir greater than 20 fecal coliforms $100mL^{-1}$ for the previous six-month period, 1987-2018. The vertical dashed line indicates the year in which the WMP was implemented.

4.5 Kensico Research Projects and Special Investigations

4.5.1 Bryozoans

Background

DEP staff have observed bryozoans in Kensico Reservoir 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 DEL18DT. Moreover, it has been observed in numerous other reservoirs throughout the watershed. The presence of these organisms was inconsequential until autumn 2012, shortly after the UV Disinfection Facility came on line. Bryozoan colonies were found downstream of DEL18DT at the UV facility and caused clogging issues at the 1-inch perforated baffle plates located just prior to the UV lamps. The openings were manually cleared of the gelatinous colonies, but this was very labor intensive. Control of these organisms in a drinking water supply is particularly challenging because many control measures used for other applications are not an option.

Monitoring

DEP staff began monitoring bryozoan colonies in the sluiceways at DEL18 using an underwater video camera in 2014. During each survey an underwater video camera is lowered on a long set of poles down into the sluiceway (upstream of the traveling screens) and high definition (HD) video recordings are created to document the conditions in each of the five sluiceways. Notes on water quality parameters (temperature, turbidity, etc.) and operational conditions (flow rate) are also taken at the time of each visit. Video monitoring is predominantly focused on the access ladder and adjacent wall area in each sluiceway.

As in previous years, the 2018 monitoring began in June to document conditions prior to colony growth. Surveys of the sluiceways were planned for each month with the first survey occurring on June 13. Technical issues arose that prevented the July survey and led to an incomplete August survey where sluiceway 5 was not surveyed. These issues were predominantly caused by leaks in the underwater camera cable system, which allowed moisture to accumulate in the video head and obscure the lens with condensation. During the August 31 survey, it was noted that water had once again penetrated the housing' fogging the lens. After another repair, a final survey was conducted focusing only on sluiceway 5. This happened while divers were removing bryozoans in other sluiceways.

Videos were recorded of each survey and still frame photos were captured to document colony sizes.

Results

Cristatella mucedo were present in considerable numbers during the June 13 survey. As in past years, *C. mucedo* appeared earlier in the season than *Pectinatella magnifica,* and proliferated at lower depths as it appears to tolerate cooler water. *C. mucedo* colonies were still numerous at the time of the August 31 survey, especially at lower depths. Sponges were also present, especially at depths below 20 feet.

P. magnifica colonies were not observed until the August 31 survey but were quite large at that time. Colonies greater than 6 inches in diameter were observed in all four of the sluiceways monitored that day. While sluiceway 5 was not videotaped, three to four six-plus-inch-diameter colonies could be seen on the ladder near the surface from the manhole opening. Several *P. magnifica* colonies in sluiceways 1, 2, and 3 had grown to approximately 20 inches in diameter. These larger colonies were generally found at or above 7 feet in depth.

On October 2, sluiceway 5 was surveyed and several medium-sized (4-to-6-inch-diameter) colonies were observed from near the surface down to about 9 feet deep. One 10-inch-diameter colony was found on the ladder at approximately 12 feet deep. Tendril-like sponges, yellow to white in color, were numerous in this sluiceway at or below 5 feet in depth. One of the most important observations made in the October survey was the condition of the colonies. The colonies all had a darker, brown appearance and several colonies had pieces missing, compared to the much lighter color of those colonies seen in August (Figure 4.6). These differences are important as they are key factors in determining when colonies will begin to slough off, potentially causing problems downstream.

August 31

October 2

Figure 4.6 Still frames from DEL18DT bryozoan monitoring videos showing differences in colony conditions growing on ladder rungs on August 31 (Sluiceway 3 at Rung 13) and on October 2 (Sluiceway 5 at Rung 12). For scale, each of the ladder rungs is about 12 inches across.

4.5.2 Special Investigations within the Watershed

The following special investigations occurred within the Kensico Reservoir watershed during 2018 and are listed below in chronological order. Each of these special investigations were evaluated to determine if there was a potential to impact drinking water quality. A brief summary of each investigation and the corresponding results are shown below.

Storm Event Kensico Reservoir: April 16 – April 17, 2018

During April 16 - April 17, 2018, a storm event of approximately 2.76 inches of precipitation triggered storm event monitoring. This event occurred over a period of approximately 48 hours and was monitored for turbidity, fecal coliforms, conductivity, and Microbial Source Tracking (MST). Discharge increased at both MB-1 and N5-1, peaking at 11.7 and 52 cfs, respectively. MB-1 returned to near baseflow conditions in approximately 16 hours and N5-1 in approximately 6 hours. Fecal coliforms remained relatively elevated during the storm event with MB-1 peaking at E11,000 fecal coliforms $100mL^{-1}$ and N5-1 at 5,200 fecal coliforms $100mL^{-1}$. The “E” indicates that the coliform plate was not an “ideal” plate for performing the coliform counts and that the value is estimated. Turbidity peaked at 190 NTU at N5-1 and 100 NTU at MB-1, stayed elevated during the storm event, then decreased slowly over time. Specific conductivity at N5-1 ranged from 81-615 µmhos/cm and 272-869 µmhos/cm at MB-1. Microbial Source Tracking was performed by analyzing samples (three from MB-1 and three from N5-1) for the *Bacteroides* human marker (H1). Both streams were positive for either trace or low levels of human markers during this event, and were positive for H2 and H3 markers, again at trace levels.

The DEL18DT reservoir effluent had no turbidity or fecal coliform issues as a result of this storm. Turbidity remained equal to or less than 1.0 NTU and fecal coliforms did not exceed 1 fecal coliforms 100mL^{-1}. The impact of the storm event was determined not to be a threat to NYC drinking water quality, however additional sampling was performed again in early May and the human marker tests were negative.

Charles Street/MB-1 (Sampling from Catch Basins): June 11, 2018

On June 11, 2018, EOH WWQO staff were requested by the EOH Storm Water Management Group to sample three catch basins on Charles Street in Valhalla within the Malcolm Brook Watershed. The EOH Storm Water Management Group stated that the catch basins were "exhibiting some signs of gray bacterial growth and slight sewage odor." Samples were collected from three storm drain catch basins (CB1, CB2, and CB3) and analyzed for fecal coliforms, specific conductivity, caffeine, and turbidity. All three sites had similar turbidity values (0.25 – 0.69 NTU). CB1 and CB2 had similar fecal coliform (E22 and 42 coliforms 100mL^{-1}) and specific conductivity (824 and 828 µmhos/cm) values. CB3 had elevated fecal coliforms (440 fecal coliforms 100mL^{-1}) and specific conductivity (1190 µmhos/cm) that was than CB1 and CB2. Due to the elevated fecal coliform count, CB3 was also analyzed for MST. In this case, DEP examined the CB3 sample for a human marker (*Bacteroides dorei*), which was negative. Also, caffeine results at all three sites were negative, further suggesting the fecal coliform source was likely not human. The results were determined not to be a threat to NYC drinking water quality and no further action was taken.

N5-1 Cloudy Discharge: September 18, 2018

During a September 18, 2018, cleanup of the N5 BMP by contractors (weed whacking, trash cleanup, etc), they noticed gray-colored, cloudy (turbid) discharge running into the detention basin from upstream. Staff from the EOH Storm Water Management Group directed the contractor to shut off the detention basin to aid in keeping the turbidity out of the stream water. EOH WWQO staff collected two samples: one at N5-1 and one at N5-1MAIN. These were analyzed for turbidity, fecal coliforms and conductivity. Fecal coliforms were 2,400 fecal coliforms 100mL^{-1} at N5-1 and E6,700 fecal coliforms 100mL^{-1} at N5-1MAIN. Turbidity values were 80 NTU at N5-1 and 150 NTU at N5-1 MAIN. Conductivity values were 261 µmhos/cm at N5-1 and 218 µmhos/cm at N5-1MAIN. The results were determined not to be a threat to NYC drinking water quality and no further action was taken.

Storm Event Kensico Reservoir: September 24 – September 25, 2018

During September 24 - September 25, 2018, a storm event of approximately 4.48 inches of precipitation triggered storm event monitoring. The event occurred in a period of approximately 24 hours and was monitored for turbidity, fecal coliforms, conductivity, and MST. Discharge increased at both MB-1 and N5-1 peaking at 7.2 and 61 cfs; respectively. MB-1 returned to near baseflow conditions in approximately 19 hours and N5-1 in approximately 7 hours. At N5-1, fecal coliforms ranged from a low of E700 fecal coliforms $100mL^{-1}$ at the beginning of the storm event, peaking at 32,000 fecal coliforms $100mL^{-1}$ during the height of the storm event, then decreasing to E14,000 fecal coliforms $100mL^{-1}$ toward the end of the event. At MB-1, fecal coliforms ranged from a low of E250 fecal coliforms $100mL^{-1}$ at the beginning of the storm event, peaking at 40,000 fecal coliforms $100mL^{-1}$ at the height of the storm event, then decreasing to E15,000 fecal coliforms $100mL^{-1}$ toward the end of the event. The "E" indicates that the coliform plate was not an "ideal" plate for performing the coliform counts and the value is an estimate. Turbidity peaked at 100 NTU at N5-1 and 90 NTU at MB-1, stayed elevated during the storm event, then decreased slowly over time. Specific conductivity at N5-1 ranged from 100-507 µmhos/cm and 171-828 µmhos/cm at MB-1.

MST analysis was performed on two of the MB-1 samples, five of the N5-1 samples, and one of the DEL18DT samples surrounding the event. Both MB-1 samples, three of the five N5-1 samples, and the DEL18DT sample were all negative for the *Bacteroides* human marker (H1). Two of the N5-1 samples, however, were positive for the human marker at low, trace levels which were unable to be quantified. This trace human marker detection has been a common result for some storm samples in the N5 basin and many investigations have been conducted to determine the cause. There is either an as yet undetermined minor human influence, or there may be a rare case when some animals in the basin might carry the human marker in low levels. Investigations continue. The DEL18DT reservoir effluent had no turbidity issues as a result of this storm with the turbidity remaining equal to or less than 1.0 NTU. Fecal coliforms peaked on September 26, 2018 at 58 fecal coliforms $100mL^{-1}$ and decreased to E8 fecal coliforms $100mL^{-1}$ by September 28, 2018. The impact of the storm event was determined not to be a threat to NYC drinking water quality and no further action was taken.

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 and using heat dissociation. In 2018, DEP collected and analyzed 581 routine protozoan samples for enumeration, plus an additional 53 samples were collected and analyzed by cell culture immunofluorescent assay (CC-IFA) to study the potential infectivity of any *Cryptosporidium* found at Hillview Reservoir. Samples collected from streams in the NYC watershed made up the largest portion of the sampling effort (32.4%) with reservoir outflow samples from Kensico, New Croton and Jerome Park composing the second largest component (30.5%). Samples collected at the outflow of the CDUV plant and at the Hillview downtake made up 18.2% of samples, and samples taken from the upstate reservoir outflows and wastewater treatment plants combine to make up the remaining 19.0% (Figure 5.1). In addition to monitoring for protozoans, DEP collected and analyzed 40 HEV samples in 2018. All virus samples were analyzed by DEP using a modified version of the Information Collection Rule (ICR) Manual Method (USEPA 1996).

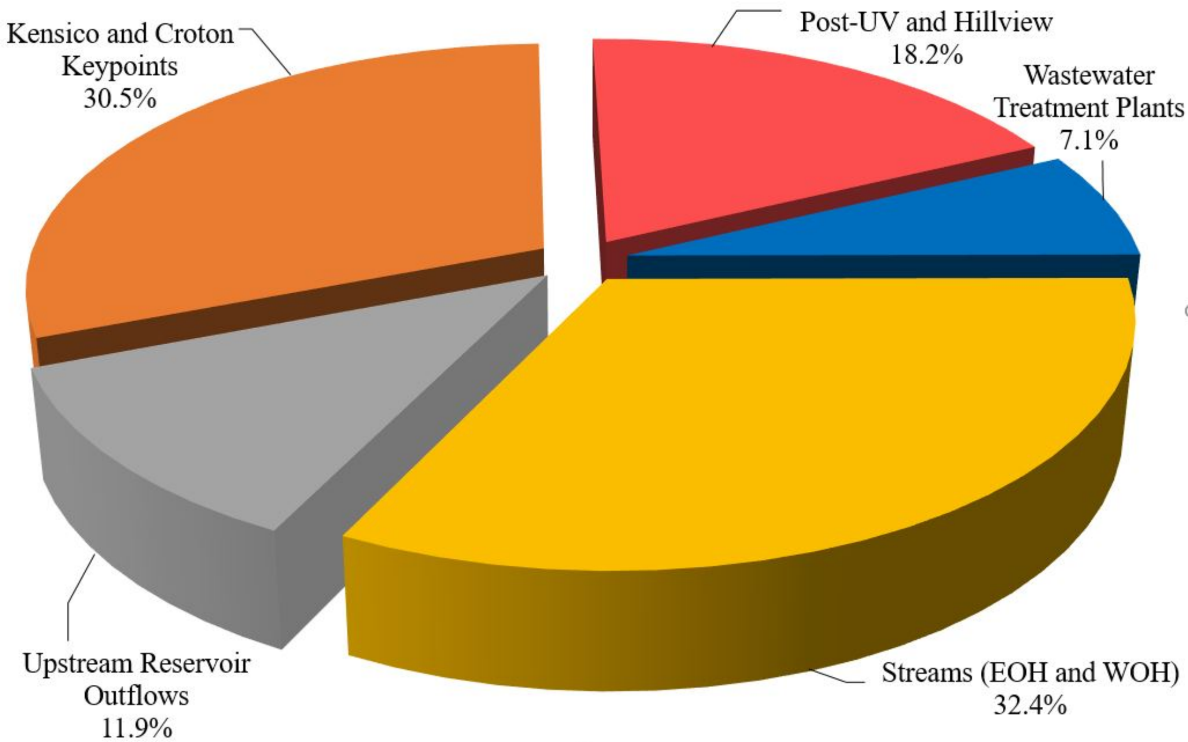


Figure 5.1 DEP protozoan sample collection type distribution for 2018.

Similar to past years, 2018 had its share of notable operational changes or variations in monitoring which warrant mentioning. *Cryptosporidium* LT2 Round 2 monitoring was originally scheduled for a two-year period ending in 2017, but was delayed while the Croton system was offline for periods in 2016 and 2017. Consequently, the remaining Croton system samples were rescheduled for collection during the corresponding months in 2018. Samples were collected from the Jerome Park Reservoir site (1CR21) when it was online or the most representative site for the New Croton Reservoir outflow (CRO143, CRO1B, or CRO1T). DEP began protozoan monitoring at the Catskill Connection Chamber (downstream of CDUV) in December 2017 and continued through 2018. This has now become a routine weekly sampling site. The Catskill Aqueduct upstream of Kensico Reservoir (CATALUM) was shut down for maintenance during portions of the fourth quarter of 2018, so some samples had to be rescheduled or cancelled. As a reminder, the Catskill Aqueduct south of Kensico Reservoir (CATLEFF) remained shut down this year, and has been since 2012. Kensico and New Croton results are posted on DEP's website (https://data.cityofnewyork.us/Environment/DEP-Cryptosporidium-And-Giardia-Data-Set/x2s6-6d2j).

5.2 Source Water Results

Catskill Aqueduct Inflow

Cryptosporidium was found in four out of the 51 samples (7.8%) taken at CATALUM in 2018, more than were found in 2017 (one in 52 samples). Each of the four positives had only one oocyst in each sample (Table 5.1). The mean annual *Cryptosporidium* concentration was 0.08 oocysts $50L^{-1}$ in 2018, compared to 0.02 oocysts $50L^{-1}$ in 2017.

Giardia was detected at the same frequency at CATALUM in 2018 (21 out of 51 samples, or 41.2%) as was detected in 2017. Mean *Giardia* concentrations from 2018 and 2017 were also similar (0.96 and1.02 cysts $50L^{-1}$, respectively).

HEVs were found more frequently at the Catskill inflow to Kensico in 2018 (three out 12 samples, 25.0%) than in 2017 (one in 12 samples, 8.4%). However, mean concentration of HEVs were similar (0.27 and 0.29 MPN $100L^{-1}$, respectively).

Table 5.1 Summary of *Cryptosporidium*, *Giardia*, and HEV compliance monitoring data at the five DEP keypoints for 2018.

	Keypoint Location	Number of Positive Samples	Mean[2]	Maximum
Cryptosporidium (oocysts $50L^{-1}$)	CATALUM (n=51)	4	0.08	1
	DEL17 (n= 53)	9	0.25	3
	DEL18DT (n=53)	5	0.09	1
	CROGH[1] (n= 18)	0	0.00	0
	1CR21 (n= 2)	0	0.00	0
Giardia (cysts $50L^{-1}$)	CATALUM (n=51)	21	0.96	7
	DEL17 (n=53)	43	4.85	25
	DEL18DT (n=53)	37	1.60	6
	CROGH[1] (n=18)	7	0.94	7
	1CR21 (n=2)	0	0.00	0
Human Enteric Virus $100L^{-1}$ (HEV)	CATALUM (n=12)	3	0.27	1.10
	DEL17 (n= 12)	1	0.09	1.06
	DEL18DT (n=12)	1	0.09	1.04
	CROGH[1] (n= 4)	1	0.86	3.42
	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 more *Cryptosporidium* detections at DEL17 in 2018 (nine in 53 samples, 17.0%) than in 2017 (two in 52 samples, 3.8%). Similarly, the mean annual concentration of 0.25 oocysts $50L^{-1}$ was higher than in 2017 (0.04 oocysts $50L^{-1}$) (Figure 5.2). *Cryptosporidium* detections at DEL18DT were higher in 2018 (five in 53 samples, 9.4%) compared to 2017 (three in 52 samples, 5.8%). The mean annual concentration for DEL18DT in 2018 (0.09 oocysts $50L^{-1}$) was higher than in 2017 (0.06 oocysts $50L^{-1}$).

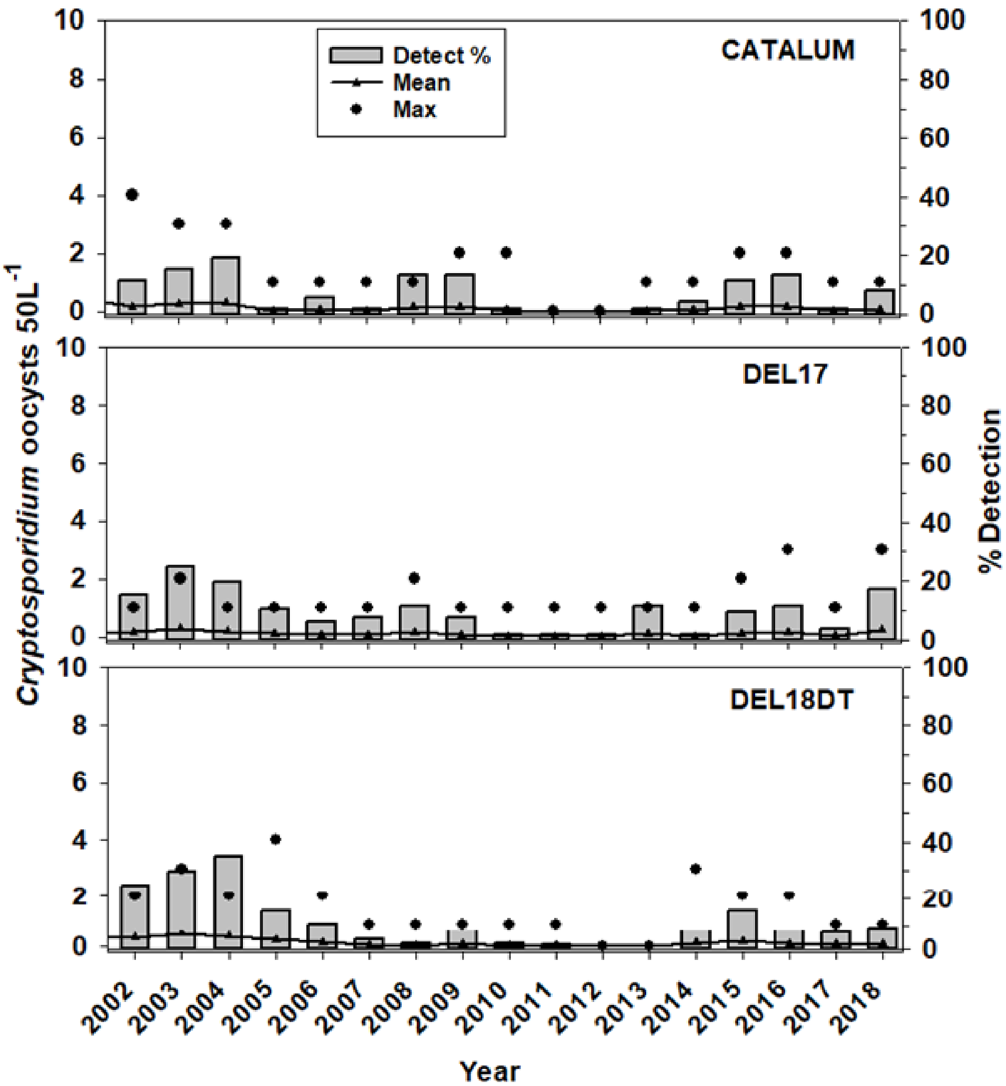


Figure 5.2 *Cryptosporidium* annual percent detection, and mean and maximum concentrations for the Kensico keypoint sites during each year from 2002 through 2018.

The number of DEL17 *Giardia* detections in 2018 (43 out of 52 samples) was higher than in 2017 (25 out 53 samples) and the mean *Giardia* concentration was also much higher in 2018 than 2017 (4.85 and 1.08 cysts $50L^{-1}$, respectively). DEL18DT was similar to DEL17, in that there were more *Giardia* detections in 2018 (37 out of 52 samples) as compared to 2017 (26 out of 52 samples) and the mean *Giardia* concentration was higher as well (1.60 cysts $50L^{-1}$ compared to 2017 (0.92 cysts $50L^{-1}$) (Figure 5.3).

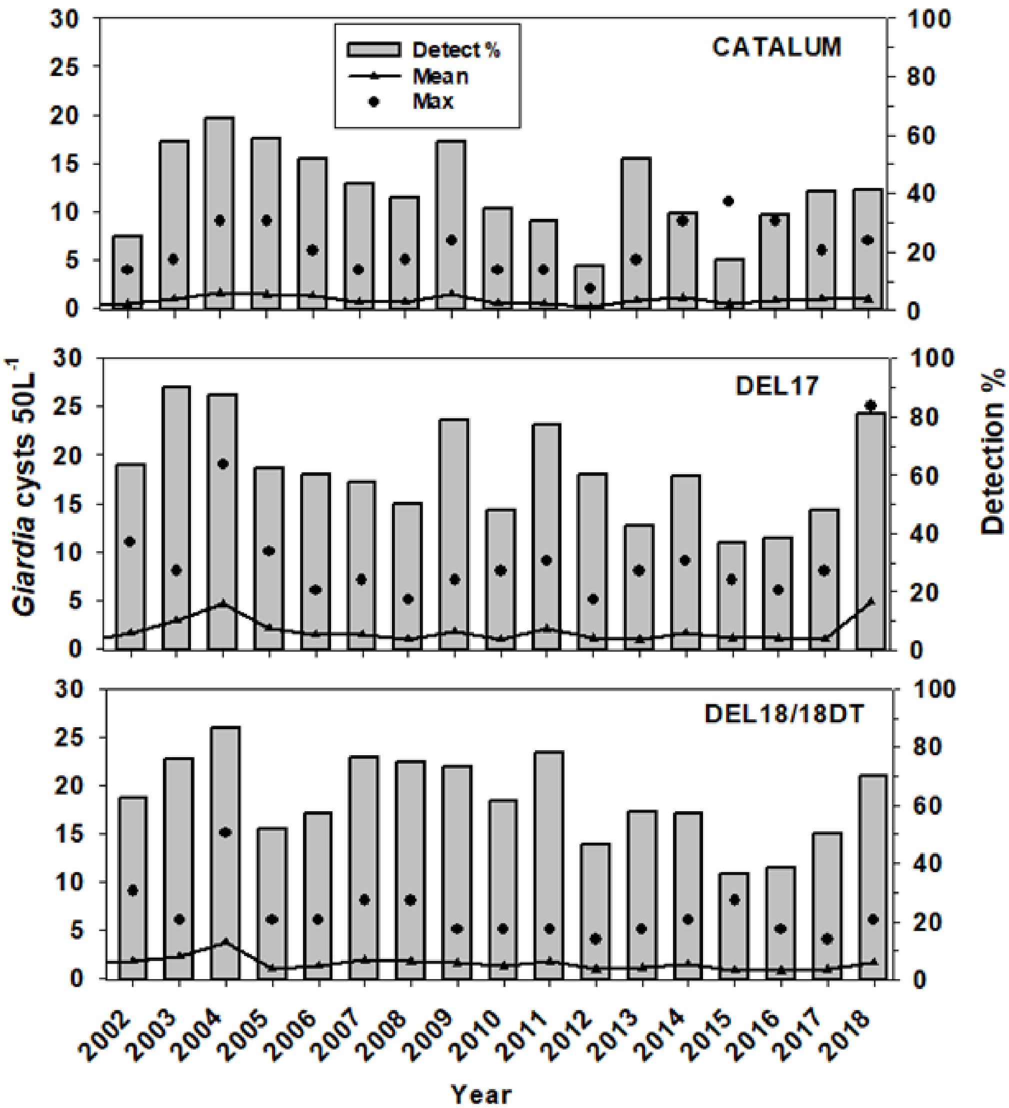


Figure 5.3 *Giardia* annual percent detection, mean concentration, and maximum result for the Kensico keypoint sites during each year from 2002 to 2018.

HEVs were detected in one out of the 12 samples (8.3%) at DEL17, fewer than in 2017 (two out of 12 samples, 16.7%) and the mean HEV concentration was also quite low in 2018 (0.09 MPN $100L^{-1}$) when compared to 2017 (0.61 MPN $100L^{-1}$). DEL18DT 2018 HEV results were the same as those found at DEL17 in 2018, and those found at DEL18DT last year, one out of 12 samples were positive (8.3%) and a mean concentration of 0.09 MPN $100L^{-1}$.

Croton System

The Croton system was shut down for most of 2018, operating only from May 17 to August 15, September 26 to October 14, and October 17 to December 31. As part of the LT2 Round 2 monitoring plan to collect 16 samples missed in 2017, sampling was rescheduled in

2018 during the same period. All rescheduled samples were planned to be collected at the outflow of Jerome Park Reservoir (1CR21); however, there were extended shutdowns of the filter plant during 2018. Alternatively, NYS DOH approved 14 samples that were representative from the New Croton Reservoir outflow sites (CRO1B, CRO143, CRO1T, and CROGH) and the remaining two samples were collected from 1CR21, which was operational during October 2018. The New Croton Reservoir outflow was sampled quarterly (for protozoans and HEV) during 2018. When these quarterly samples were added to the 16 rescheduled LT2 samples, a total of 20 protozoan samples were taken to represent Croton outflows in 2018. As a note, HEV sampling is not required at the 1CR21 location.

Jerome Park Reservoir

Both samples collected at 1CR21 in 2018 were negative for *Cryptosporidium* and *Giardia*. In 2017, nine samples were collected with two *Cryptosporidium* and three *Giardia* detected, 22.2 and 33.3%, respectively. However, 2017 samples were taken in January and February when protozoan levels are seasonally more prevalent, as documented in previous annual reports, and 2018 samples were collected in October. Therefore a comparison between years would be unsuitable.

New Croton Reservoir

In 2018, there were 18 samples collected and analyzed from New Croton Reservoir outflow sites. These were rescheduled LT2 Round 2 monitoring and quarterly routine sampling for the Croton System. Sites included CROGH (n=2), and alternate sites that represented the New Croton Outflow (CRO1B (n=14), CRO143 (n=1), and CRO1T (n=1)). Similar to 2017, all four routine quarterly samples were negative and the other 14 samples were negative for *Cryptosporidium* in 2018 as well (Figure 5.4). *Giardia*, however, were found in seven of the 18 samples (38.9%), unlike 2017 when all samples (n=4) were negative (Figure 5.5).

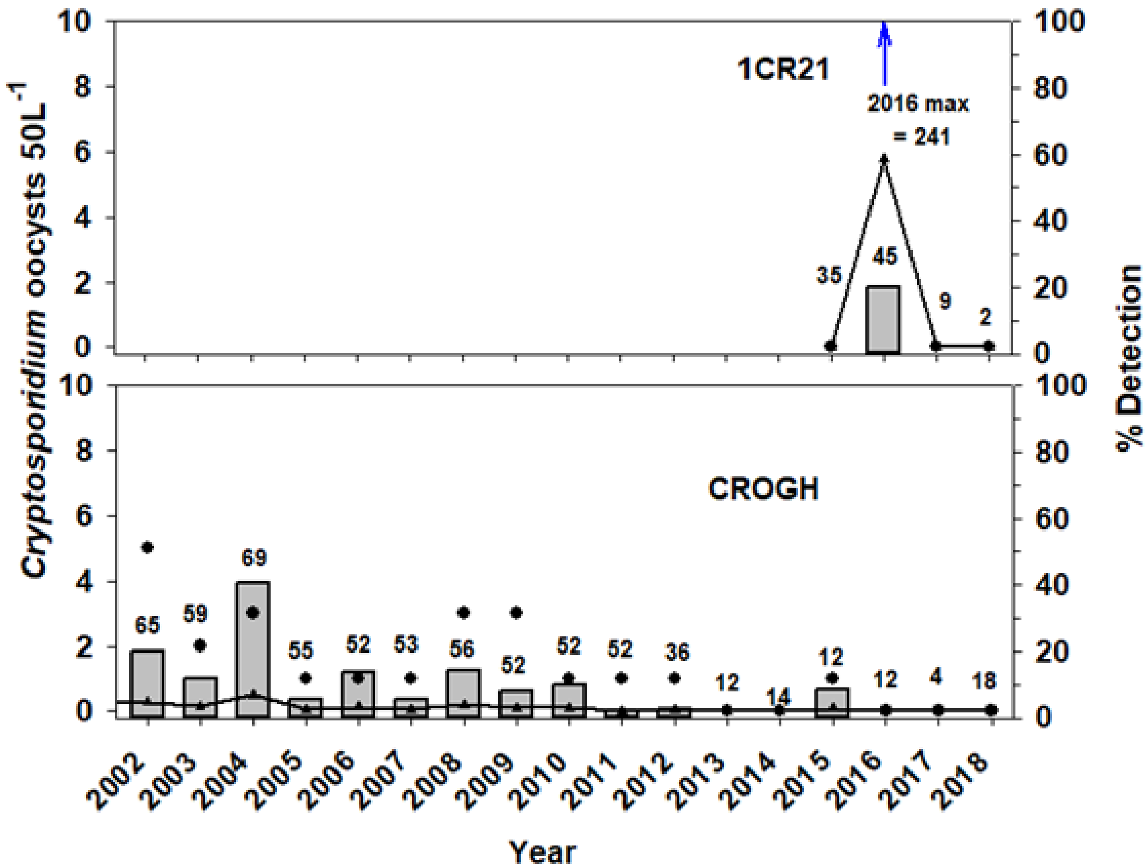


Figure 5.4 C*ryptosporidium* annual percent detection, mean concentration, and maximum result for the Croton keypoint sites during each year from 2002 to 2018. Numbers above each bar on the Croton System plot indicate sample size.

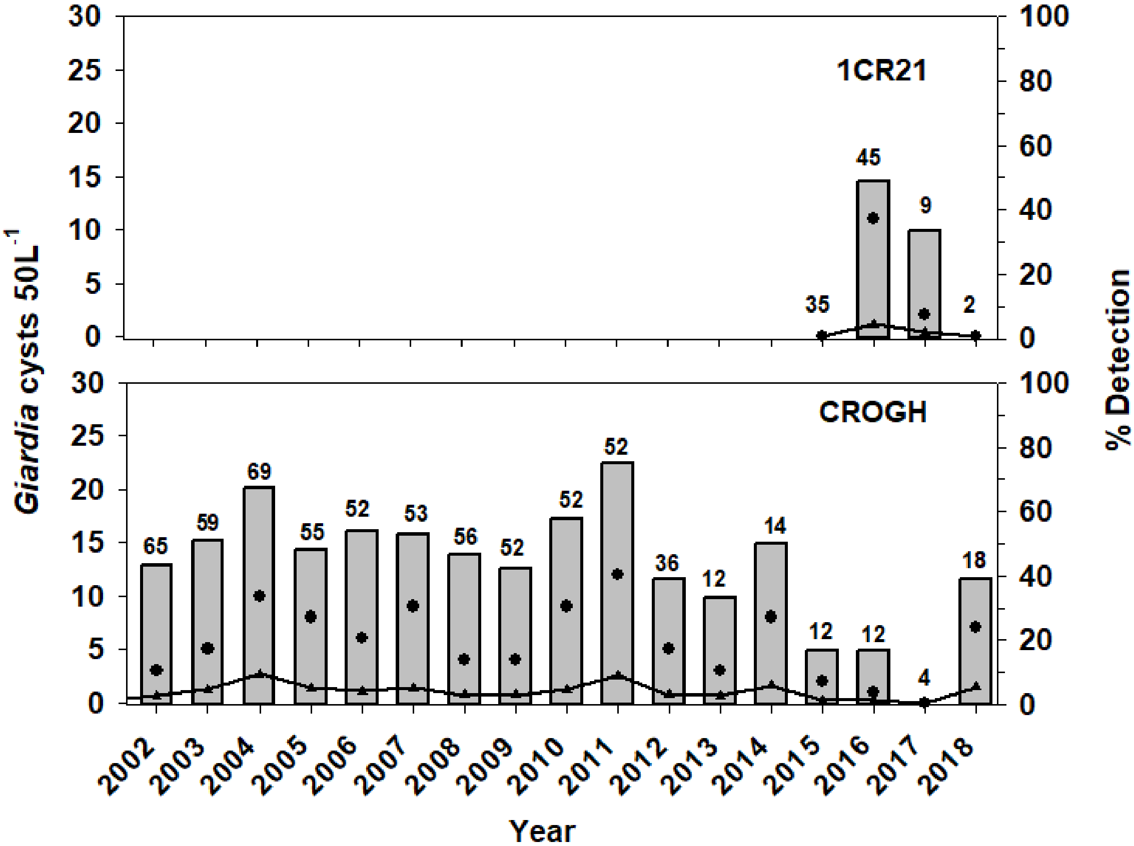


Figure 5.5 *Giardia* annual percent detection, mean concentration, and maximum result for the Croton keypoint sites during each year from 2002 to 2018. Numbers above each bar on the Croton System plot indicate sample size.

As in 2017, HEV were not detected in any of the 2018 quarterly samples at CROGH or the alternate site, CRO1B.

In general, *Giardia* continues to be detected more frequently and at higher concentrations during winter and spring months compared to summer and fall (Figure 5.6), as has been noted in previous reports. It is important to note that changes in *Cryptosporidium* and *Giardia* occurrence and concentration in the last few years may be a result of the analytical changes to Method 1623.1 with EasyStain and the switch from acid to heat dissociation, 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.

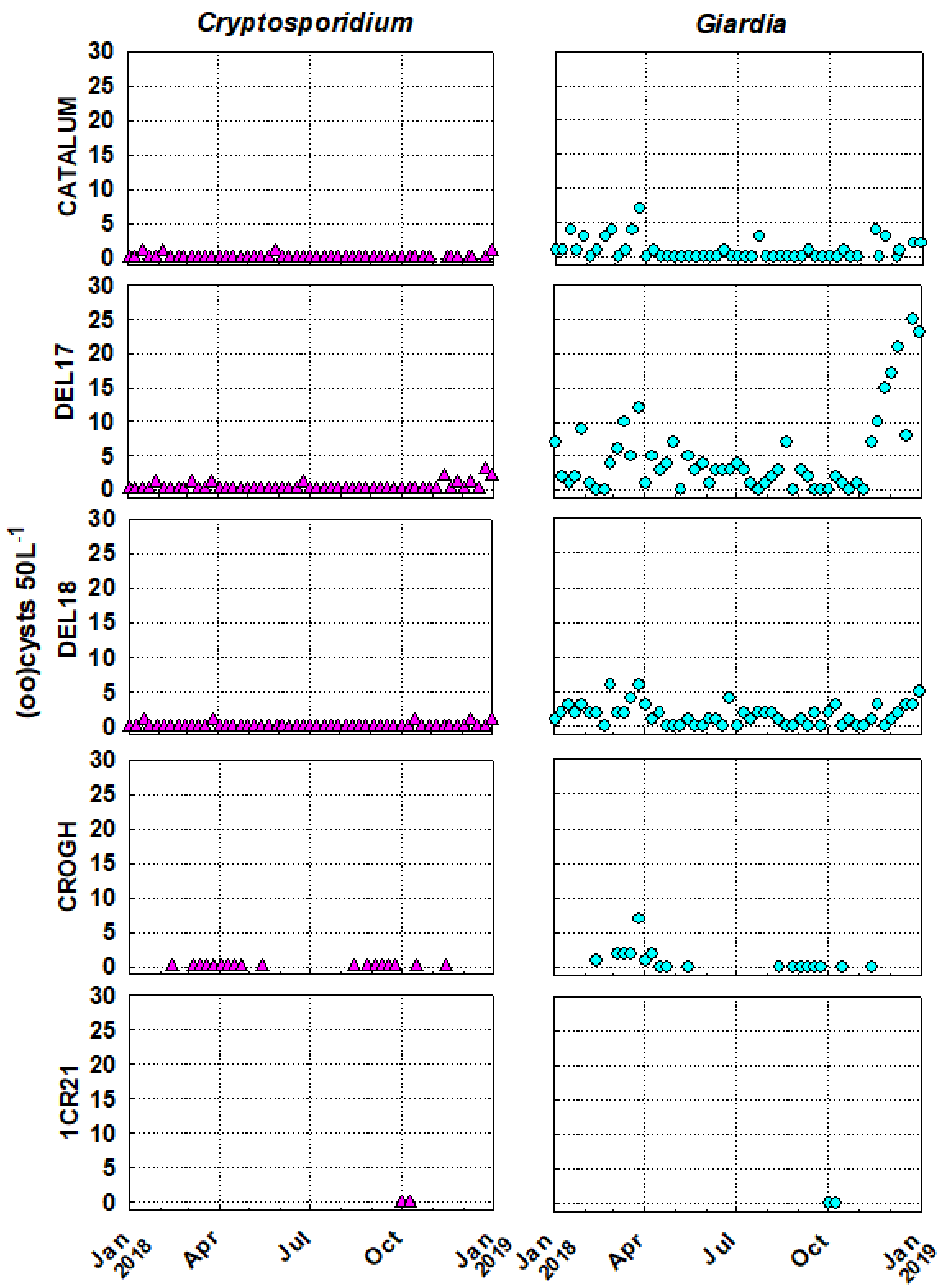


Figure 5.6 Weekly routine keypoint protozoan monitoring results for 2018.

5.2.1 2018 Source Water Compared to Historical Data

Water quality at the different source water sites can vary due to the many influences in their respective watersheds (stormwater runoff, impacts from land use, operational changes, etc.), Beginning in October 2001, source water sites were sampled weekly for protozoans and analyzed using Method 1623HV. Changes that have affected the program since 2001 include: New Croton Reservoir outflow monitoring frequency going from weekly (October, 2001) to monthly (August 2012), and then monthly to quarterly (October 2016); the shutdown of the Catskill Aqueduct outflow from Kensico Reservoir (September 2012), a change in the analytical Method 1623HV to Method 1623.1 with EasyStain (April 2015); the addition of sampling at the Jerome Park Reservoir outflow (1CR21) with the Croton Filtration Plant startup (May 2015); and the laboratory's switch from acid to heat dissociation (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 2018, there were 13 samples positive for *Cryptosporidium* out of 104 (12.5%) pooled influent samples (CATALUM and DEL17, respectively) (Table 5.2) as compared to five positives out of 53 (9.4%) at the outflow site (DEL18DT) (Table 5.3). There were more detects of oocysts at the Kensico inflows in 2018 than in 2017 (three out of 104, 2.9%), but the same as were observed in 2016 (13 out of 104, 12.5%) and well within the historical range from 0.0% to 20.5%. When broken down by system, CATALUM had three more detections than in 2017, but three less than 2016. Whereas *Cryptosporidium* detection at DEL17 in 2018 (nine in 53 samples, 17.0%) was the highest it has been in since 2004 (19.6%). *Cryptosporidium* detections at DEL18DT were slightly higher in 2018 (five in 53 samples, 9.4%) as compared to 2017 (three in 52 samples, 5.8%) and very close to the detection rate for the prior four years (2014-2017, 9.0%, n=210) which is lower than the historical detection rate (2001-2017, 12.0%, n=976).

The mean concentration of oocysts at CATALUM was higher in 2018 (0.08 oocysts $50L^{-1}$) as compared to 2017 (0.02 oocysts $50L^{-1}$) and lower than 2015 and 2016 (0.15 and 0.17 oocysts $50L^{-1}$, respectively). The mean annual concentration at DEL17 in 2018 (0.25 oocysts $50L^{-1}$) was well above the concentration in 2017 (0.04 oocysts $50L^{-1}$) and higher than 2015 and 2016 (0.12 and 0.17 oocysts $50L^{-1}$, respectively) (Table 5.2). DEL17 in 2018 had the highest mean concentration since 2003 (0.28 oocysts $50L^{-1}$). The 2018 *Cryptosporidium* concentration at DEL18DT (0.06 oocysts $50L^{-1}$) was similar to the means observed in 2016 and 2017 (0.10 and 0.06 oocysts $50L^{-1}$, respectively) as well as the mean for the previous 10 years (2007 – 2017 mean = 0.06 oocysts $50L^{-1}$, n=584).

Table 5.2 Annual sample detection and mean oocyst concentration of *Cryptosporidium* at inflow keypoints to Kensico Reservoir 2002-2018.

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

Table 5.3 Annual sample detection and mean concentration of *Cryptosporidium* at Kensico and New Croton Reservoir source water outflows 2002-2018.

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
2018	5	9.4	0.09	0	0.0	0.00

[1]Monitoring at CROGH was modified from weekly to monthly in August 2012, and then to quarterly in Oct 2016.

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

Croton System Reservoirs

There were no positive results for the two *Cryptosporidium* samples at the 1CR21 source water site in 2018. There were also no *Cryptosporidium* detections for the 18 samples at the New Croton Reservoir outflow (CROGH) in 2018. *Cryptosporidium* detections have been very infrequent in the last few years with only one *Cryptosporidium* oocyst found (February 2015) during the past six years (2013-2017, n=72). This is the fifth year out of the last six years with no *Cryptosporidium* detections at this site and only three detections in the last eight years (n=160) with a maximum result of 1 oocyst $50L^{-1}$.

Giardia

Kensico Reservoir

The 2018 CATALUM *Giardia* detection rate of 41.2% was quite similar to 2017 detection rate of 40.4%. The detection rate was higher in the last two years compared to 2015 and 2016 (17.3% and 32.7%, respectively), but close to the historical detection rate of 40.2% (2001-2017, n=849). Annual mean *Giardia* concentrations in 2018 (0.96 cysts $50L^{-1}$) were similar to 2017 (1.02 cysts $50L^{-1}$) and to the historical average from 2001 through 2017 (0.90 cysts $50L^{-1}$).

DEL17 had a much higher *Giardia* detection rate in 2018 (81.1%) compared to the past 6 years (range for 2012-2017; 36.5% – 60.4%), and exceeded the historical detection rate of 60.3% (2001-2017, n=861). This was the highest detection rate since 2004 (87.5%, n=56). The annual mean cyst concentration in 2018 was the highest recorded at 4.85 cysts $50L^{-1}$, which was higher than the previous maximum of 4.55 cysts $50L^{-1}$ in 2004. The 2018 mean was elevated by three samples with results over 20 cysts $50L^{-1}$ in December that are attributed to elevated *Giardia* concentrations being delivered from Rondout Reservoir at that time. Cyst concentrations began to increase in mid-November of 2018 and continued to be elevated for the rest of the year, continuing into 2019. These elevated results at DEL17 were preceded by elevated results at the Rondout Reservoir outflow (RDRRCM), which is discussed in the Upstate Reservoir Outflow section of this report. The maximum concentration observed at DEL17 in 2018 (25.0 cysts $50L^{-1}$) was also the highest *Giardia* result found at this (or any Kensico keypoint) site since Method 1623.1 began in 2001.

At DEL18DT, the 2018 *Giardia* detection rate (69.8%) was higher than the mean of the past six years, (47.5% 2012-2017). Several years prior to 2012 had higher detection rates, such as 2011 (78.0%) and 2004 (86.3%) which was the historical maximum detection. Interestingly, both 2004 and 2011 were years when the watershed experienced significant hurricanes. DEL18DT had a higher annual mean concentration in 2018 (1.60 cysts $50L^{-1}$) compared to means from the past six years (ranging from 0.71 to 1.43 cysts $50L^{-1}$) and close to the overall historical average from 2001 through 2017 (1.54 cysts $50L^{-1}$).

The 2018 *Giardia* cyst detection rate at DEL18DT (69.8%) was slightly higher than the mean of the two inflows (61.2%). The *Giardia* detection rate at DEL17 was 81.1% which was significantly higher than CATALUM at 41.2%. Since the flow from DEL17 is usually higher than the CATALUM flow, it makes sense that the DEL18DT outflow would be more influenced by the increased *Giardia* entering at DEL17 (as well as some influence from the local tributaries). Similarly, mean *Giardia* concentrations at DEL17 and CATALUM inflows (4.85 cysts $50L^{-1}$ and 0.96 cysts $50L^{-1}$, respectively) also bracketed the DEL18DT outflow mean (1.60 cysts $50L^{-1}$). As mentioned in past reports, this suggests that Kensico Reservoir has the ability to reduce protozoan concentrations as water flows across the reservoir. The Delaware Aqueduct inflow to Kensico exhibited the highest concentrations on record during the fall of 2018, yet concentrations at the outflow in the fall did not exceed 5.0 cysts $50L^{-1}$ (the historical 95th percentile for the outflow site).

Year to year comparisons can be difficult with the many possible sources of pathogens and changes in operations, but changes to some of the analytical steps in the method have added to the challenge. In April 2015, DEP switched 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 the human-infective species of *Giardia*, therefore some decreases in *Giardia* results were anticipated going forward. Also adding to the complexity of multi-year data comparison was the change in the method option from acid to heat dissociation with the purpose of improving *Giardia* recovery. Additional years of sampling will be necessary to help determine the overall effect of method changes versus any changes in the abundance of *Giardia* in the environment.

Croton System Reservoirs

Giardia detections and mean concentration at the New Croton Reservoir outflow were higher in 2018 (38.9% and 1.42 cysts $50L^{-1}$, respectively) than the mean for 2015 to 2017 (14.3% and 1.42 cysts $50L^{-1}$, respectively) but with the same concentration. These results are lower than the mean historical detection rate and concentration from 2001 to 2017 (50.2% and 1.27 cysts $50L^{-1}$, respectively). The Croton source water site at Jerome Park (1CR21) was sampled twice during 2018 (October) and both samples were negative for *Giardia*. With this limited data set, a comparison to past years is not suitable. Combining the two 1CR21 samples with the 18 New Croton outflow samples creates a dataset (n=20) of Croton system water samples which covers most of the calendar year, but it does not adequately represent the full year in order to compare it with past years.

Seasonality

Giardia concentrations found at DEL17 in both the early and late months of 2018 made the seasonal variation in *Giardia* results easy to define by a locally weighted regression (LOWESS) smoothed line (Figure 5.7). The seasonal variation is more subtle, but still visible, for the inflow at CATALUM and the reservoir outflow at DEL18DT. 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, back to weekly in 2015, and then a mixture of both quarterly and weekly since February 2017. To maximize the number of samples for Croton, representative data from New Croton and Jerome Park Reservoir outflows were plotted beneath the Kensico plots. Despite trying to utilize this combination of samples and seeing what appears to be seasonality in the sample results, the LOWESS smooth line for Croton does not show an annual variation which would be attributed to seasonality. As has been stated before, this relates to how changes in the frequency of sampling could be creating problems for smoothing analysis.

The LOWESS function uses uniformly specified proportions of the dataset to determine regressions with no mechanism to adapt the proportions to changes in sample frequency.

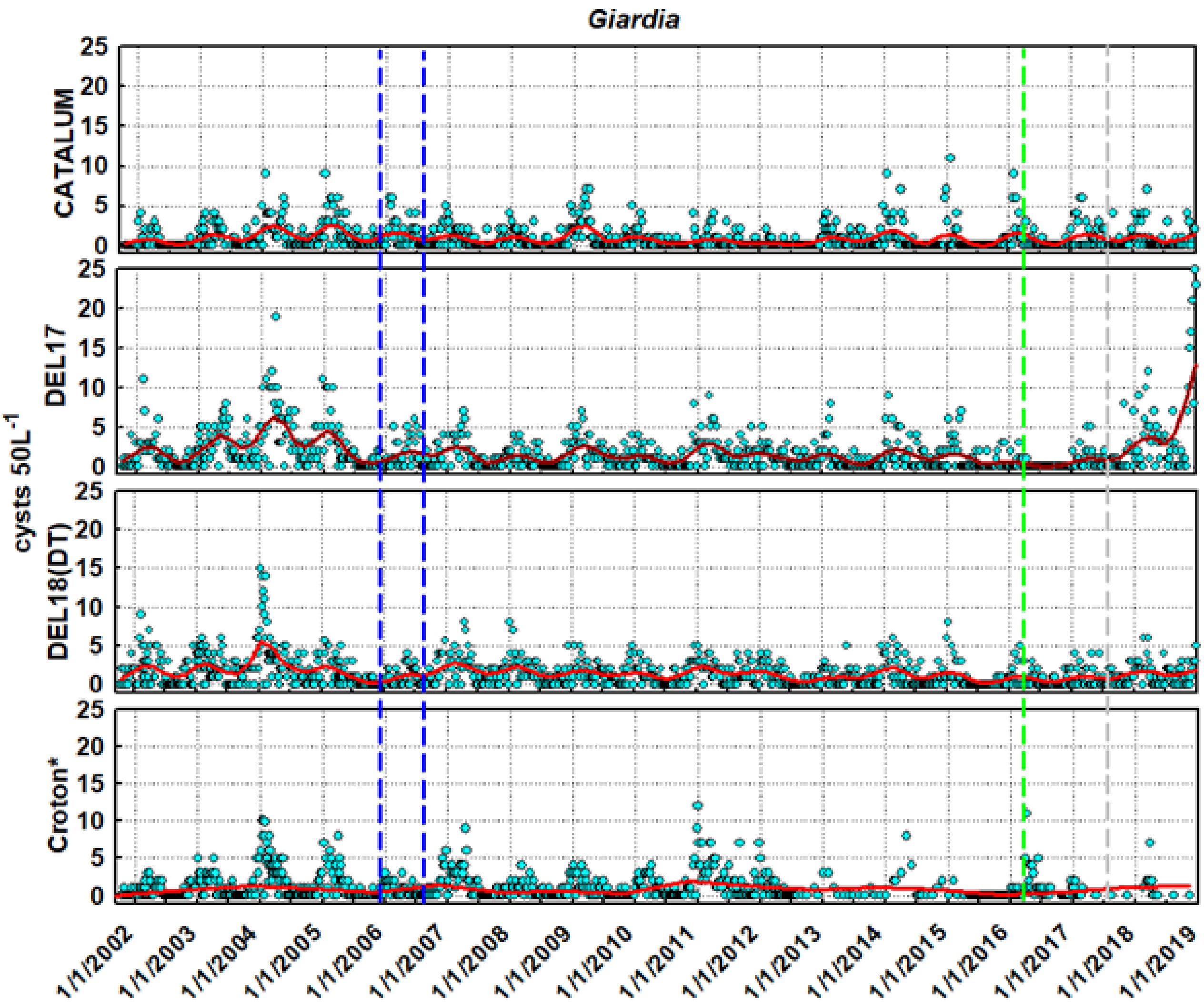


Figure 5.7 Weekly routine source water keypoint results for *Giardia* (circles), and LOWESS 5% smoothed regression (red curved line) from October 15, 2001 to December 31, 2017. The area between the blue dashed lines indicates the period during which DEP temporarily switched to EasyStain. The green dashed 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 2018 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 criteria, “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 the mean of the monthly *Cryptosporidium* mean concentrations at the source water outflows over the course of two 2-year periods. As this report covers through 2018, results have been calculated here using data from the two most recent complete calendar years (January 1, 2017-December 31, 2018) using all analyzed routine and non-routine samples (Table 5.4). As some of the LT2 Round 2 (April 2015 – March 2017) samples from 2017 had to be rescheduled due to Croton System shutdowns, samples in the Croton System were taken at varying frequencies. Also, as the Croton shutdowns continued into 2018, alternate sites were used to represent the Croton outflow.

Table 5.4 Number and type of samples used to calculate the LT2 values from January 1, 2017 to December 31, 2018.

Site	Number of routine samples 2017-2018	Number of non-routine samples 2017-2018	Total n
New Croton (1CR21 with supplemental samples from CROGH, CRO1B, CRO1T, CRO143)	32	0	32
Delaware (DEL18DT)	105	0	105

Unfiltered Supply

The Catskill/ Delaware System is NYC’s unfiltered water supply. The 2017 to 2018 mean of monthly means for *Cryptosporidium* is 0.0014 oocysts L^{-1} for the Delaware outflow, well below the LT2 threshold level of 0.01 oocysts L^{-1} for unfiltered systems (Figure 5.8). These results are consistent with NYC source water historical LT2 calculations, which have always remained below the threshold levels. In general, the monthly means for the Delaware outflow were declining beginning in 2004/2005 and continued through 2013. In 2014, a small increase in the calculated mean value was followed by a larger mean increase in 2015, which coincides with changing to the 1623.1/ EasyStain method for protozoan analysis. This method change, which was predicted to possibly recover more *Cryptosporidium* from samples, likely underlies the increase we have seen over the last four years (2015 – 2018).

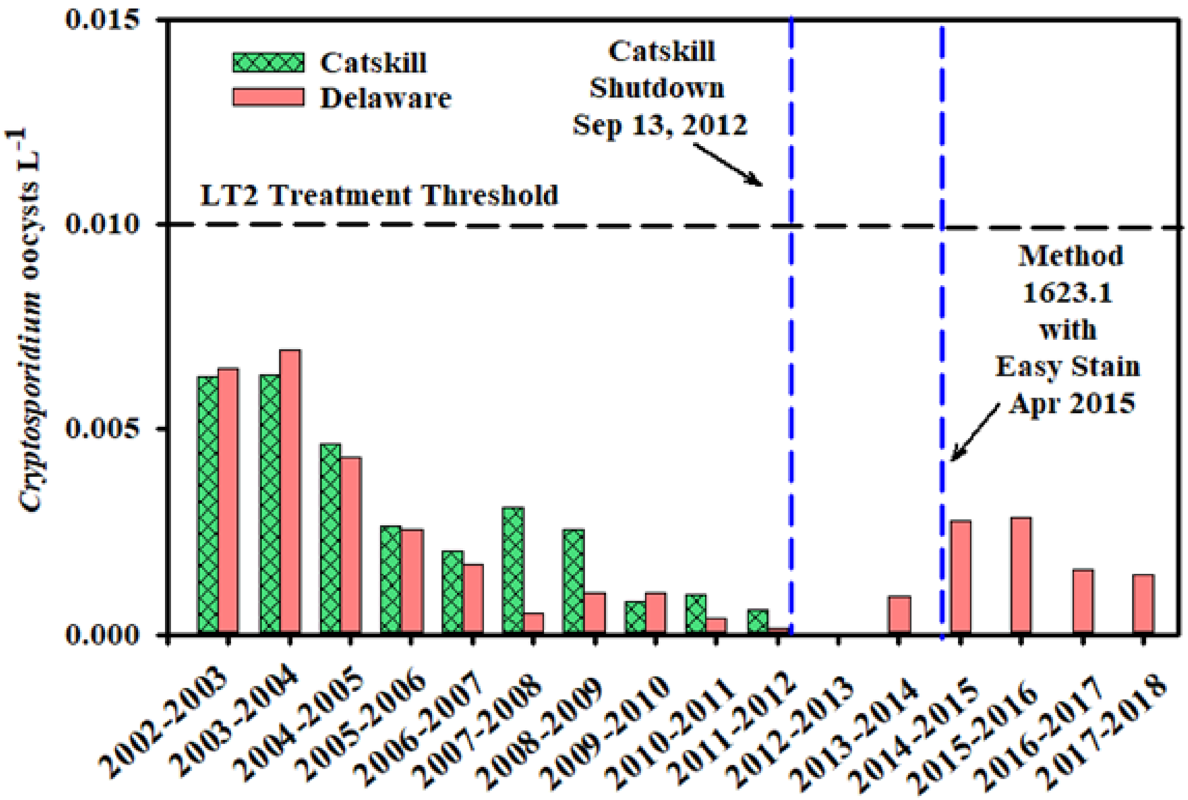


Figure 5.8 *Cryptosporidium* means using LT2 calculation method since initiation of Method 1623HV (1623.1 with EasyStain since April 2015) at the Delaware Aqueduct 2002-2018 and the Catskill Aqueduct 2002-2012.

Filtered Supply

The Croton System is the source of NYC's filtered water supply. The source water site switched to 1CR21 when filtration began in May 2015, prior to which the sampled source water site was the outflow of New Croton Reservoir (CROGH). Since the Croton Aqueduct was offline for several weeks in 2016 and ten months in 2017, DEP received approval from the NYS Department of Health to include New Croton Reservoir outflow samples as acceptable substitute samples for periods when routine monitoring could not be conducted at 1CR21 in 2016-2017. For the two-year period from January 1, 2017 to December 31, 2018, there were 11 representative samples taken at the Jerome Park source water site over three months of sampling (nine in January and February 2017 and two in October 2018). Samples incorporated from the New Croton Reservoir outflow include three 2017 quarterly samples (May, August and November), four 2018 quarterly samples (February, May, August, and November), and 14 weekly samples in 2018 (March, April, August, September and October), all taken while the system was offline. With the addition of the 21 samples from the New Croton Reservoir outflow, there were 32 sample results from 13 months of sampling to meet the requirements for the LT2. The mean of these 13 monthly means was 0.0010 oocysts L^{-1}, which is well 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.

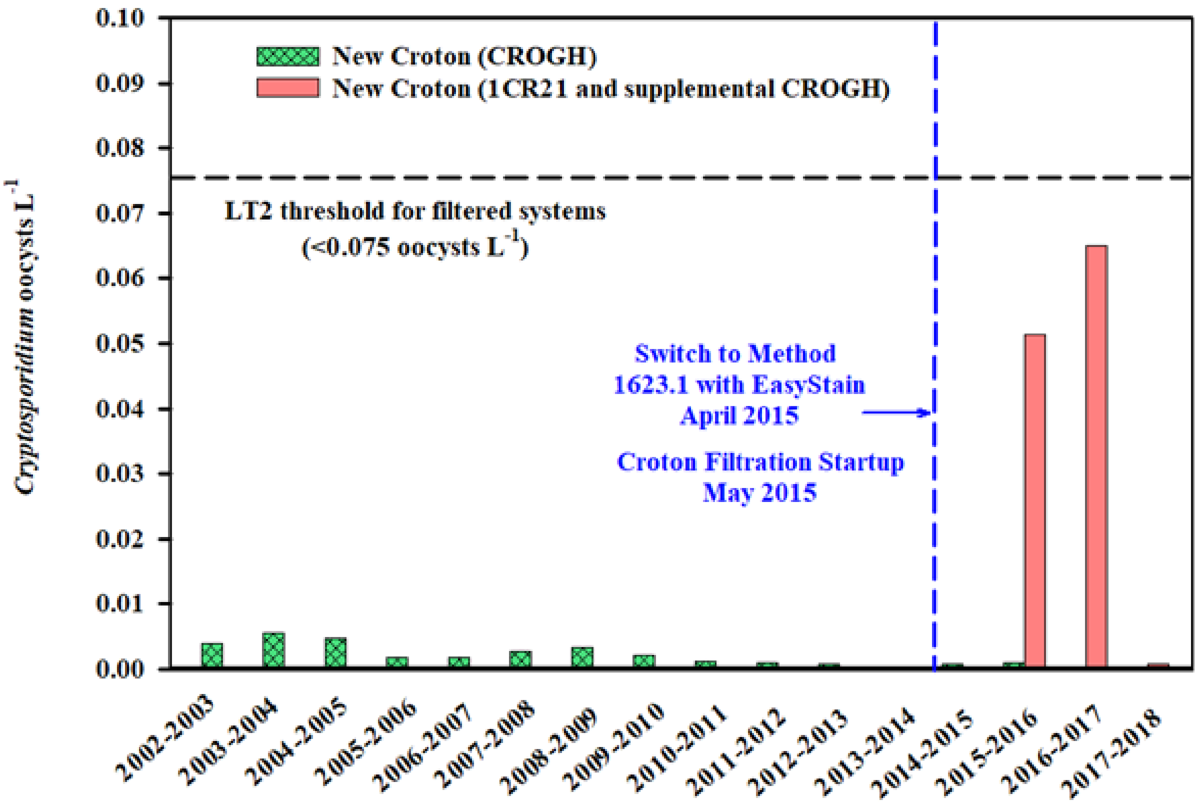


Figure 5.9 *Cryptosporidium* means using LT2 calculation method since initiation of Method 1623HV (1623.1 with EasyStain since April 2015) at the Croton System source water sites 2002-2018.

5.2.3 2018 Source Water Matrix Spike and QC Results

Quality control testing performed during protozoan analyses includes both Matrix Spike samples (MS) and Ongoing Precision and Recovery samples (OPRs). The MS recoveries for the five keypoint sites were determined by spiking the sample matrix with known amounts of oocysts and cysts and ranged from 26-76% for *Cryptosporidium* and 44-76% for *Giardia* (Table 5.5). The lowest *Cryptosporidium* recoveries for the year occurred at CATALUM in June and October (26% and 33%, respectively). Interestingly, the lowest *Giardia* recoveries also occurred at CATALUM and during the same two months (53% and 44% respectively). All MS results for these sites, performed one in every 20 analyses in 2018, were within the acceptable range of the method.

Table 5.5 Matrix spike results from keypoint sites in 2018.

Date	*Cryptosporidium* % Recovery	*Giardia* % Recovery
	CATALUM	
1/22/2018	62	76
6/4/2018	26	53
10/15/2018	33	44
	DEL17	
4/23/2018	73	55
9/4/2018	65	65
12/17/2018	71	50
	DEL18DT	
1/8/2018	76	59
10/1/2018	58	62
	CRO1B	
4/2/2018	67	56

Weekly OPR testing involves the spiking of reagent grade water in the laboratory with known amounts of oocysts and cysts. These samples are important for testing the method reagents and the laboratory process without interference from the sample matrix. In 2018, 66 OPR samples were analyzed. Ranges of OPR recovery for the protozoans in 2018 were 41-84% for *Cryptosporidium* and 12-83% for *Giardia*. On a few occasions, the OPR recoveries did not pass the acceptable method limits on the first try, but acceptable results were always obtained before proceeding with the weekly samples.

5.3 Upstate Reservoir Outflows

The Catskill and Delaware Aqueducts deliver water to Kensico Reservoir from the West of Hudson (WOH) watershed. The WOH watershed consists of six reservoirs in two systems: Ashokan and Schoharie in the Catskill System, and Cannonsville, Neversink, Pepacton, and Rondout in the Delaware System. Five of the six WOH reservoir outflows are monitored monthly, while the Ashokan Reservoir aqueduct is monitored weekly at CATALUM further downstream before it enters Kensico Reservoir. When a reservoir is off-line, monthly reservoir sampling is not required since that particular basin is not being delivered to a downstream reservoir for eventual consumption. For this reason, three of the WOH reservoirs (Schoharie, Neversink and Cannonsville) do not have samples for all 12 months of 2018.

Cryptosporidium

In 2018, there were 110 samples collected at WOH reservoir outflows, which included four samples taken in December 2018 from additional Rondout Effluent Chamber (outflow) elevation taps as part of a special investigation into elevated *Giardia* (

Table 5.6). These four samples were all negative for *Cryptosporidium*. Of the remaining 106 samples, ten (9.4%) were positive for *Cryptosporidium* which was more than in 2017 (6.4%), but bracketed by the detection rates from 2015 and 2016 (13.5% and 9.3%, respectively). Schoharie had the highest oocyst detection rate (25.0%, two positives out of eight samples) of the WOH reservoir outflow sites in 2018, which was the highest at this site since 2015 (33.3%, four out of 12 samples). Neversink and Rondout each had one *Cryptosporidium* detection in 2018. In the last 10 years these two sites have had only nine detections combined (six and three detections, respectively), each with only one oocyst in a sample. Pepacton and Cannonsville Reservoir outflows also had one *Cryptosporidium* detection each in 2018, yielding detection rates of 7.7 and 12.5%, respectively. These rates are similar to their historical records (7.7 and 13.1%, respectively).

Concentrations of *Cryptosporidium* remained very low at the upstate reservoir outflows with no samples containing more than one oocyst; although sample volumes varied. The highest concentration (1 oocyst $25.6L^{-1}$) was found at the Schoharie outflow in February 2018. Ashokan, Cannonsville, Neversink, Pepacton, and Rondout Reservoir outflows had annual mean concentrations below 0.15 oocysts $50L^{-1}$.

Giardia

In 2018, there were 68 *Giardia* detections (61.8%) out of the 110 samples collected at the WOH reservoir outflow sites. Four samples were collected from the Rondout outflow elevation taps as part of a special investigation into elevated *Giardia*. All were positive for *Giardia*. Of the remaining 106 samples collected at routine sampling sites, 64 were positive for *Giardia* (60.4%) in 2018. This is higher than 2015, 2016, and 2017 (27.0%, 30.6% and 43.1%, respectively). Neversink and Rondout Reservoir had the highest detection rates for *Giardia* (88.9% and 88.2% respectively) with both showing an increase of more than 20% from 2017. As for *Giardia* concentrations in the upstate reservoirs, Schoharie had the highest annual mean *Giardia* concentration in 2018 (25.17 cysts $50L^{-1}$) for the third year in a row. The 2018 Schoharie annual mean was higher than the historical mean of 10.30 cysts $50L^{-1}$ (2002-2017, n=181). The Cannonsville 2018 annual mean concentration was 7.21 cysts $50L^{-1}$, which was higher than the 2017 (4.67 cysts $50L^{-1}$) and greater than the historical mean of 4.35 cysts $50L^{-1}$ (2002-2017, n=168). This was the highest annual mean at Cannonsville since 2005 (15.77 cysts $50L^{-1}$). Similarly, mean *Giardia* concentrations at Neversink, Pepacton and Rondout were higher in 2018 than in the past six years.

Table 5.6 Summary of 2018 protozoan results for upstate reservoir outflows.

Site	n	*Cryptosporidium* Mean[1] $50L^{-1}$	% Detects	Max (Liters sampled)	Max L^{-1}	*Giardia* Mean[1] $50L^{-1}$	% Detects	Max (Liters sampled)	Max L^{-1}
Schoharie	8	0.39	25.0	1 (25.6L)	0.04	25.17	75.0	65 (25.6L)	2.54
Ashokan (CATALUM)	51	0.08	7.8	1 (50.0L)	0.02	0.96	41.2	7 (50.0L)	0.14
Cannonsville	8	0.12	12.5	1 (50.2L)	0.02	7.21	75.0	32 (50.2L)	0.60
Pepacton	13	0.08	7.7	1 (50.0L)	0.02	2.52	61.5	10 (50.6L)	0.20
Neversink	9	0.11	11.1	1 (50.6L)	0.02	2.63	88.9	8 (45.5L)	0.18
Rondout	17	0.06	5.9	1 (50.4L)	0.02	8.03	88.2	29 (50.0L)	0.58

[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.

Rondout had the highest mean *Giardia* concentration this year (8.03 cysts $50L^{-1}$) since the implementation of Method 1623 in 2002, with the next highest value being 6.50 cysts $50L^{-1}$ in 2004. Elevated *Giardia* occurred at the outflow in the late winter/early spring and then reappeared in November 2018. The March 2018 sample concentration (6.88 cysts $50L^{-1}$) was over the 10-year 95th percentile value of 4.85 cysts $50L^{-1}$, and a follow-up sample two weeks later was very similar (6.99 cysts $50L^{-1}$). The April sample was lower than March 2018, but still hovered around the 10-year 95th percentile (4.96 cysts $50L^{-1}$). Subsequent sample results tapered off, but returned to higher concentrations later in the year. The November 2018 routine sample had a concentration of 8.75 cysts $50L^{-1}$, which did not seem unusual after large precipitation events in the area during late October and early November. However, when results began to increase above seasonal levels at the Delaware Aqueduct inflow to Kensico Reservoir (DEL17) downstream of the Rondout outflow, follow-up samples were requested for the end of November (Table 5.7). The November 30 sample indicated *Giardia* concentrations (17.48 cysts $50L^{-1}$) had more than doubled at the Rondout outflow. An investigation was launched to determine the source of the elevated *Giardia* and the scope of the issue at Rondout Reservoir. This included additional samples at the routine outflow site (RDRRCM) throughout December, a set of samples from the four Rondout elevation taps (RR1-4), and samples at six tributary streams around Rondout Reservoir. Samples were collected on December 4, 5, 10, and 18 from RDRRCM and showed fluctuating *Giardia* concentrations with the highest on December 10 (29.00 cysts $50L^{-1}$) and the lowest on December 18 (8.96 cysts $50L^{-1}$). The four elevation taps had varying concentrations of *Giardia* with the highest concentration at one of the middle elevation taps (RR2 elevation 763 feet– 30 cysts $50L^{-1}$). The other three taps (elevations 730, 795 and 827 feet) had lower concentrations, ranging from 9.98 to 13.94 cysts $50L^{-1}$. Elevated *Giardia* continued into 2019, along with the investigation to identify the cause(s), and will be the subject of a special investigation report in 2019.

Table 5.7 *Giardia* results for special investigation at Rondout Reservoir and DEL17, 2018.

Other Sites			RDRRCM		DEL17	
Site	**Date**	***Giardia*[1]**	**Date**	***Giardia*[1]**	**Date**	***Giardia*[1]**
			11/7	9	11/5	0
					11/13	2
					11/19	10
					11/26	15
			11/30	18		
			12/4	24	12/3	17
RR1	12/7	10	12/5	16		
RR2	12/7	30				
RR3	12/7	14				
RR4	12/7	11				
			12/10	29	12/10	21
			12/18	9	12/17	8
					12/24	25
					12/31	23

[1]Sample volumes are 50L(+/-2L).

Additional Sampling

Cross River and Croton Falls Reservoirs have pumps which allow water to be pumped from these East of Hudson reservoirs into the Delaware Aqueduct. As part of sampling program that is required before pumping can occur, protozoan samples must be collected. Nine samples were collected under this program in 2018. Seven weekly protozoan samples were collected at Cross River between September 17 and October 28, and two protozoan samples were collected at the Croton Falls Pump Station on October 18 and 28. Cross River Pump Station was operated from October 29 to October 31, but the Croton Falls Pump Station was not activated. All nine of these samples were negative for *Cryptosporidium* and *Giardia*. Additionally, as part of the investigation into the source of elevated *Giardia* at DEL17, a sample was taken at the West Branch Reservoir outflow site (CWB1.5) to determine if the source of *Giardia* was only Rondout Reservoir. This sample result had only one *Giardia* cyst $50L^{-1}$, and was negative for

Cryptosporidium, which indicated that that West Branch Reservoir was not likely a significant source of the *Giardia* at DEL17.

5.4 Watershed Streams and WWTPs

Routine monitoring of protozoa was conducted at 17 stream sites in the WOH and EOH watersheds in 2018, and six additional stream sites were monitored as part of the special investigation for elevated *Giardia* in Rondout mentioned in the previous section. A total of 188 stream samples were collected and analyzed; 77 from the WOH watershed and 111 from the Kensico Reservoir (EOH) watershed. Of the eight stream sites that are part of the monitoring plan objective to determine upstream sources of protozoans, four were sampled monthly and four were sampled bi-monthly. One WOH stream site (PROXG-1, tributary to the East Branch Delaware River) was discontinued due to low *Giardia* results and another site was selected for monthly monitoring (PROXG-3 on the main stem of the East Branch Delaware River). In addition to the eight WOH monitoring locations, EOH stream monitoring continued monthly at the eight perennial tributaries to Kensico Reservoir. Fifteen additional samples were taken at the Kensico streams this year in response to elevated *Cryptosporidium* or *Giardia* concentrations detected in routine samples.

In 2018, 41 samples were collected at WWTPs, with three samples positive for protozoans. A discussion of WWTP results follows the stream results discussion for each corresponding watershed.

West of Hudson Streams

As occurred in the past two years, four of the eight WOH stream sites were sampled monthly (S7i, PROXG, and two upstream PROXG sites) with the remaining four sampled bimonthly (CDG1, S4, S5i, and CBS (formerly WDBN)) in 2018 (Figure 5.10). Two sites sampled monthly (upstream of PROXG) were added in May 2016. As mentioned above, these sites upstream of PROXG were changed in May 2018 after two years of sampling. One routine sample at PROXG was not collected in December 2018 due to freezing conditions. Of the 77 samples taken at WOH streams, six were taken at sites from tributaries to Rondout Reservoir (RDOA, RD4, RD9, RD10, RD11, and RGB) as part of special investigation into elevated *Giardia* at the Rondout Reservoir outflow. Each site was sampled once on either December 11 or 18. Four of these samples (RDOA, RD4, RD10, and RD11) were negative for *Cryptosporidium* and *Giardia* and one sample (RD9) had a very low level of *Giardia* (1.00 cyst 50.1L^{-1}). The sixth sample (RGB) had nine *Giardia* and one *Cryptosporidium* in the 51.2L sample.

The target volume for protozoan monitoring conducted by DEP is 50 liters; however, these streams do not always allow for full target volume to be collected due to filter clogging. The method allows for 10 liters as a minimum acceptable sample volume, so as long as DEP is able to filter at least 10 liters of stream water, samples are still analyzed. Of the 71 routine samples filtered at WOH streams, 52 were between 47 and 55 liters. Nineteen samples had volumes less than 47L due to clogging of filters during sampling. Of these 19 samples, 14 were from either PROXG or sites upstream of PROXG. Two samples were taken from West Branch Delaware River sites (CBS and CDG1) during a precipitation event on January 23 and the samples resulted in volumes less than 20L. In order to normalize data with disparate sample volumes, results are presented in several different ways: mean of all results calculated to a 50L volume, percent detection, maximum count per actual sampled volume, and maximum value per liter (Table 5.8).

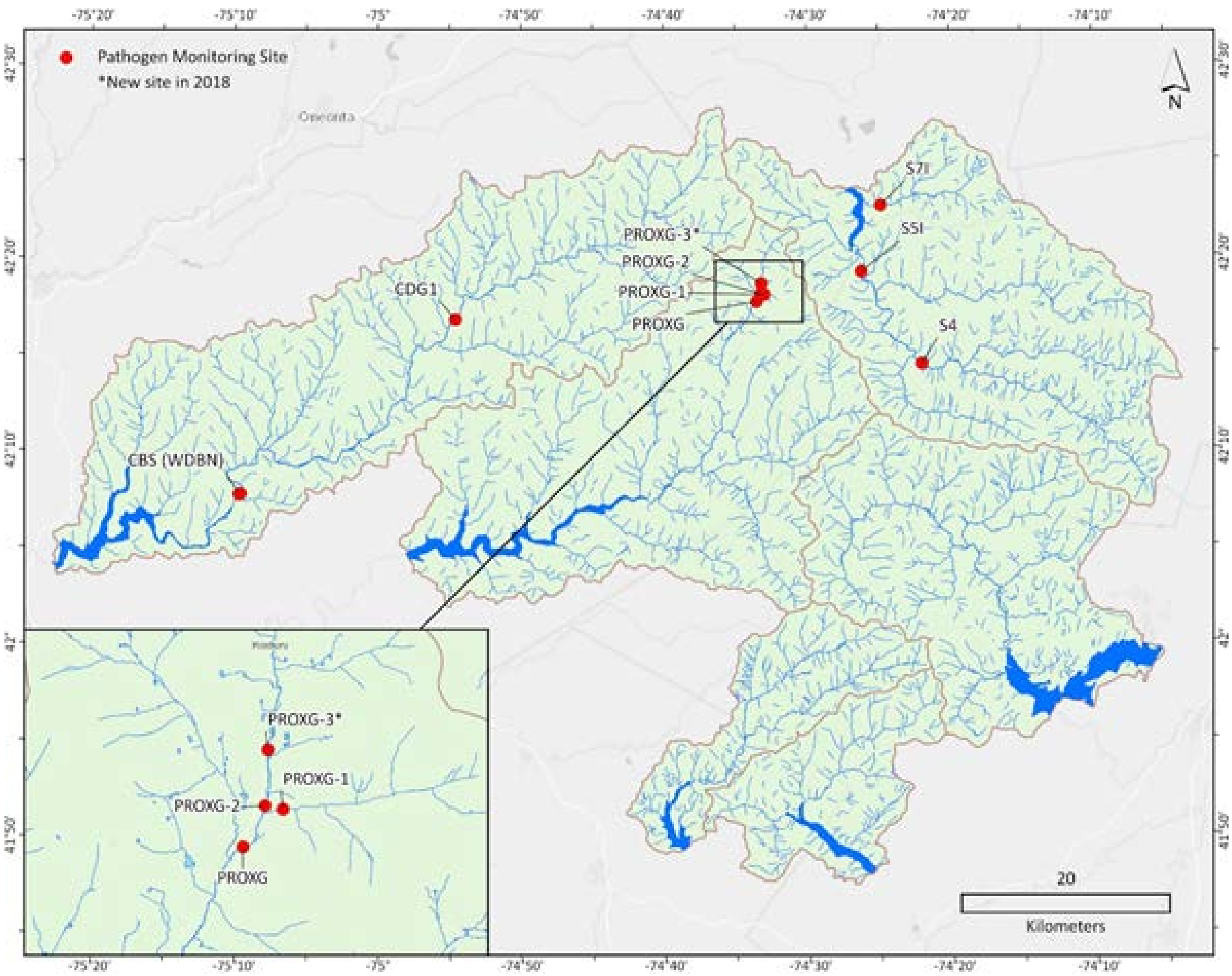


Figure 5.10 WOH stream sites monitored for protozoans in 2018.

Cryptosporidium oocysts were detected in 42 of the 71 routine WOH stream samples (59.2%) in 2018 and this was more than were detected in 2017 (34.7%). The percent detection of oocysts ranged from 0.0 to 83.3% at the different stream sites (Table 5.8). Only PROXG-1 was negative for *Cryptosporidium* detection in 2018. Concentrations at these sites were also quite different from the previous year. In 2018, three of eight sites had annual means below 1 oocyst and five of the WOH stream sites had means above 2.50 oocysts $50L^{-1}$ as compared to 2017, where five of the eight sites had means less than 1 oocyst and all of the WOH stream sites had annual mean *Cryptosporidium* concentrations less than 2.50 oocysts 50L^{-1}. For the second year in a row, CBS had the highest mean concentration (5.85 oocysts 50.0L^{-1}). The highest single concentration in a sample was found in the July 2018 PROXG-2 sample (12 oocysts 22.0L^{-1} normalized to 27.3 oocysts 50L^{-1}) which was collected after greater than 3 inches of rainfall in the previous four days.

Table 5.8 Summary of WOH stream protozoan results in 2018.

		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}**
CBS (WDBN)	6	5.85	83.3	7 (14.0L)	0.50	89.79	100.0	118 (14.0L)	8.43
CDG1	6	3.36	83.3	7 (50.0L)	0.14	155.96	100.0	109 (42.9L)	12.47
PROXG	11	2.67	72.7	5 (28.1L)	0.18	146.38	100.0	460 (36.9L)	12.47
PROXG-1	4	0.00	0.0	0	0.00	1.49	50.0	4 (50.4L)	0.10
PROXG-2	12	5.18	58.3	14 (43.7L)	0.55	107.03	100.0	432 (50.1L)	8.62
PROXG-3	8	4.62	62.5	15 (50.0L)	0.30	170.78	100.0	575 (50.0L)	11.50
S4	6	0.50	33.3	2 (50.1L)	0.02	67.42	100.0	265 (50.4L)	5.26
S5	6	0.90	33.3	4 (50.4L)	0.08	51.22	100.0	134 (50.1L)	2.67
S7i	12	3.82	66.6	28 (52.0L)	0.50	82.70	100.0	298 (50.0L)	5.96

[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 69 of the 71 routine samples (97.2%) collected from the 2018 WOH streams samples, which was slightly higher than the percent positive in 2017 and 2016 (84.7 and 87.0%, respectively). Only PROXG-1 had a detection rate lower than 100.0%. *Giardia* is generally found more frequently and at a higher concentration than *Cryptosporidium* in the NYC Watershed. This pattern holds true for 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-3 had the highest annual *Giardia* mean (170.78 cysts 50L^{-1}) and the highest single sample result

(575 cysts $50.0L^{-1}$) in October 2018. As might be expected, the next two highest sample results were at PROXG and PROXG-2 (460 cysts $36.9L^{-1}$ and 432 cysts $50.1L^{-1}$; respectively) which are sites located downstream of PROXG-3.

As noted previously, sampling upstream of the PROXG site continued in 2018 to help narrow the search for potential sources of *Giardia*. Annual means for PROXG and PROXG-2 remained quite high in 2018 (146.38 and 107.03 cysts 50. L^{-1}, respectively) despite PROXG-2 being lower than 2017 (168.84 cysts $50L^{-1}$). Individual results were frequently elevated with 57% of the results over 50.00 cysts $50L^{-1}$. *Giardia* results at PROXG-1 were low in 2016 and 2017, and averaged only 1.49 cysts $50L^{-1}$ from January through April 2018. Therefore, PROXG-1 was dropped, and a new site approximately 0.5 miles upstream of PROXG-2 was added in May 2018 and called PROXG-3 (Figure 5.10). *Giardia* results fluctuated for the remainder of 2018, with mean concentrations for all three sites from May to December elevated and consistently ranging from 148.88 to 197.56 cysts $50L^{-1}$. It should be noted that the December sample at PROXG was not collected due to freezing weather conditions. Monitoring will continue at these sites for at least a portion of 2019 and then results will be re-evaluated to determine if new sites should be selected.

West of Hudson Wastewater Treatment Plants (WWTPs)

Protozoan monitoring of WWTPs was scheduled on a quarterly basis at the eight WOH WWTPs and 33 samples were collected in 2018. The extra sample was collected at the Grahamsville plant in January 2018 to represent a missed sample in the fourth quarter of 2017 and was discussed in last year's annual report. The remaining 32 samples, satisfying the 2018 quarterly sampling requirement, are discussed here. Three out of 32 samples were positive for *Giardia* (9.7%) and one of those three samples was also positive for *Cryptosporidium* (Table 5.9).

Table 5.9 Protozoan detections at WOH WWTPs in 2018.

Date	Site	Plant	Sample Volume (L)	*Cryptosporidium* Result	*Giardia* Result
1/23/2018	Hunter WWTP	Hunter	50.0	0	1
2/27/2018	Hunter Highlands BD	Trailside at Hunter	52.8	0	73
9/12/2018	Windham WWTP	Windham	50.0	1	4

On January 23 a sample was taken at the Hunter WWTP and found to have one *Giardia* cyst in the 50.0L sample. The facility operator was contacted to attain background information on plant operations during the time of the sample. The operator noted that the flow for the day was 345,000 gallons due to 1.5 inches of rain along with warm weather causing snowmelt. The rain event followed a busy ski weekend and plant storage tanks were full, the plant processing 300 GPM, and the protozoan sample was taken that following Tuesday. Operators had been experiencing coagulant and flocculent issues that day and switched the sand filters (from sand filter #3 to #2) after the sample was taken. The maximum turbidity reached on that day was as high as 0.50 NTU, but only for an instant, and despite the sand filter change, effluent turbidity continued to run up to 0.49 NTU at 5:00PM. A follow-up inspection was conducted on February 1 and the continuous backwash upflow dual sand filters (CBUDS) were working well. The CBUDS have been air lanced quarterly, and prior to the sample, were most recently air lanced at the beginning of January. The #3 filter unit was air lanced again following the positive sample result. No other process abnormalities were noted that may have led to the positive result.

On February 27 a protozoan sample taken at the Trailside at Hunter LLC wastewater plant had 73 *Giardia* cysts in a 52.8L sample. After the positive result, plant operators were asked if there were any operational issues or process abnormalities. Operators noted higher than normal turbidity going into the sand filters due to strainers clogging upstream of the sand filters, which caused the poly aluminum chloride (PAC) to overdose. Overdoses of PAC are known to bind up the filter media and operators suggest this may have caused the higher than normal *Giardia* level. This plant has had three *Giardia* positive samples in the last two years and six positives in the last five years. DEP inspectors visited the Trailside at Hunter plant on March 6 and made the following suggestions for the interim period: not drawing down the equalization lagoon so low as it pulls in detritus; increasing the basket pore size; putting the second filter train online and perhaps using that to test alternate coagulant doses; and working with their chemical supplier to determine the most effective coagulant and dose. A new supervisory control and data acquisition (SCADA) system is planned for this plant to control dosages and turbidities more efficiently.

On September 12 a protozoan sample taken at Windham WWTP was found to have one *Giardia* cyst and four *Cryptosporidium* oocysts in the 50.0L sample. DEP contacted the plant operators about any abnormal processes at the time of, or prior to, the sample. The operator indicated they had recently switched filter beds and may have stirred something up. No other process abnormalities were noted.

Kensico Streams

The Kensico perennial streams were monitored at least monthly for protozoans in 2018. In addition to the 96 routine monthly samples, 15 additional samples were taken at six of the eight sites to follow-up on elevated concentrations found in routine samples.

Cryptosporidium

Cryptosporidium oocysts were detected in 39 out of 96 (40.6%) routine samples at Kensico stream sites in 2018, which was a greater detection rate than in 2017 (29 out of 96 routine samples, 30.0%) and similar to the detections observed in 2016 (45 out of 96 routine samples, 46.9%). For the third straight year, the annual mean concentration at N12 was at or over 5.00 oocysts $50L^{-1}$ (Figure 5.11 and Table 5.10). For the past three years, N12 had the highest annual *Cryptosporidium* mean of the eight streams, but in 2018 it was surpassed by N5-1 which had a mean of 5.36 oocyst $50L^{-1}$. While five oocysts in a stream sample is not alarming, this mean for N5-1is higher than the mean from 2017 (2.18 oocysts $50L^{-1}$) and it is the highest mean since 2004 (12.06 oocysts $50L^{-1}$). The highest concentration in a Kensico stream sample during 2018 was at E11 in November (19 oocysts $22.6L^{-1}$) and this drove the annual mean for E11 (4.23 oocysts $50L^{-1}$) to the third highest of the eight streams in 2018. This year was also the highest annual mean on record for E11, which exceeded the previous high from 2016 (2.09 oocysts $50L^{-1}$). The mean at MB-1 was also higher in 2018 (3.49 oocysts $50L^{-1}$) compared to 2017 (2.70 oocysts $50L^{-1}$). Means for two streams (BG9 and E10) were also higher than those seen in 2017, but bracketed by means from 2015 and 2016. Annual 2018 *Cryptosporidium* means at three of the perennial streams (E9, N12, and WHIP) were equivalent to or lower than those found in 2017 (Figure 5.11). It is possible that the stain variation implemented in 2015 may account for some changes in the detection of oocysts observed at some of the Kensico sites. Additional years of data collection will help to quantify a shift in the data, if one exists.

Table 5.10 Summary of routine Kensico perennial stream protozoan results for 2018.

		Cryptosporidium				***Giardia***			
Site	**n**	**Mean[1] ($50L^{-1}$)**	**% Detects**	**Max[2] ($50L^{-1}$)**	**Max (L^{-1})**	**Mean[1] ($50L^{-1}$)**	**% Detects**	**Max[2] ($50L^{-1}$)**	**Max (L^{-1})**
BG9	12	0.33	16.7%	2	0.04	4.15	75.0%	17	0.34
E10	12	0.67	25.0%	6	0.12	1.08	58.3%	3	0.06
E11	12	4.23	33.3%	19	0.84	9.71	58.3%	26 (22.6L)	1.15
E9	12	1.78	58.3%	9	0.18	29.48	91.7%	139	2.78
MB-1	12	3.49	58.3%	20 (35.3L)	0.57	12.84	83.3%	43 (43.1L)	1.00
N12	12	5.00	50.0%	20	0.40	4.50	75.0%	16	0.32
N5-1	12	5.36	41.7%	23 (39.6L)	0.58	8.18	58.3%	40 (39.6L)	1.01
WHIP	12	0.50	41.7%	2	0.04	1.58	66.7%	6	0.12

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

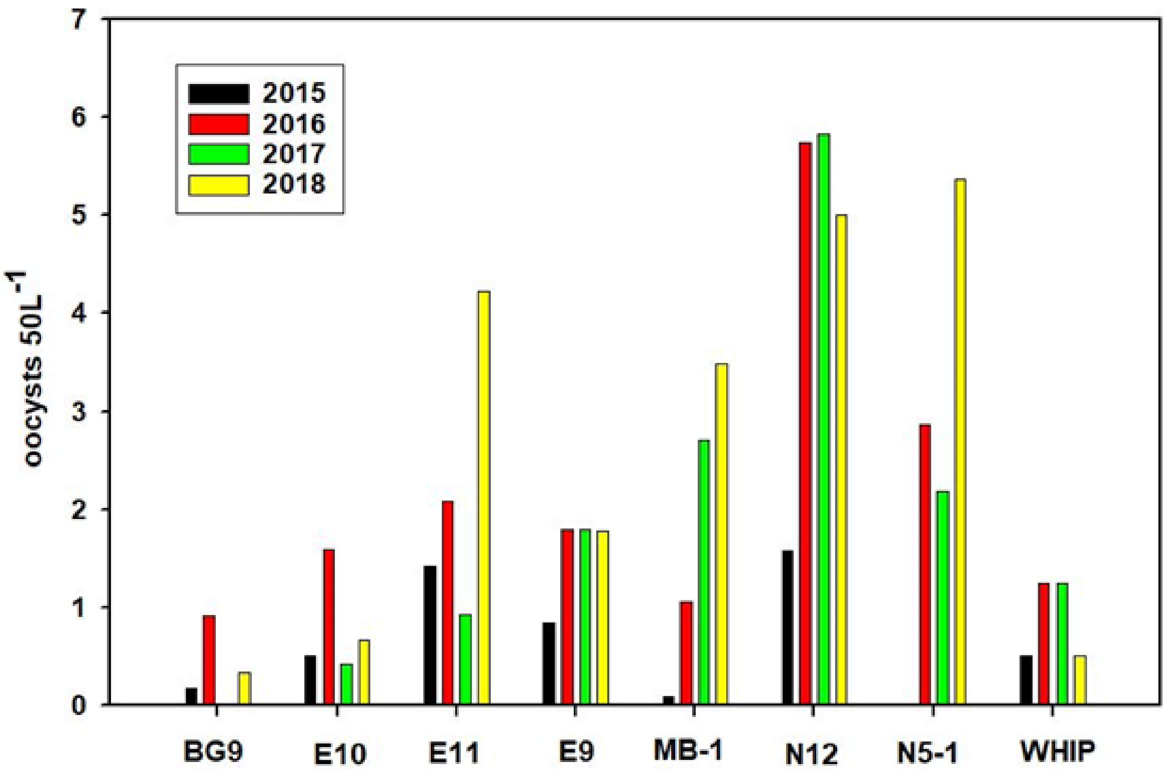


Figure 5.11 Annual mean *Cryptosporidium* concentrations for routine samples taken at the eight Kensico streams from 2015 through 2018.

Giardia

The *Giardia* detection rate for routine samples at Kensico streams in 2018 was 70.8% which was slightly higher than in 2017 (56.3%), but within the detection rates observed in some previous years (2012 to 2016 annual range 34.0 - 75.0%). Three of the Kensico sites (E9, MB-1, and N5-1) exhibited significant increases in annual mean *Giardia* concentrations compared to 2017. Most notably, the 2018 mean for all E9 samples (29.48 cysts $50L^{-1}$) was more than double the 2017 mean (13.63 cysts $50L^{-1}$). This was the highest *Giardia* mean of the Kensico streams in 2018, but still much lower than the historical mean for E9 (2002-2017, 50.84 cysts $50L^{-1}$). The November sample at E9 also had the highest single *Giardia* concentration in a routine sample for 2018 (139 cysts $50L^{-1}$). MB-1 exhibited the largest increase in annual mean from 2017 (4.13 cysts $50L^{-1}$) to 2018 (12.84 cysts $50L^{-1}$). Stream N5-1 also yielded a higher mean concentration than in 2017 (3.33 cysts $50L^{-1}$). Three sites (BG9, E10, and E11) displayed small increases of less than 3 cysts $50L^{-1}$ in 2018. The remaining two sites (N12 and WHIP) showed mean decreases in 2018 when compared to 2017 means. It is unclear whether changes observed are environmental or due to the potentially selective nature of EasyStain, or the increased recovery of heat dissociation, since not all *Giardia* in the watershed originate from the same source (Figure 5.12).

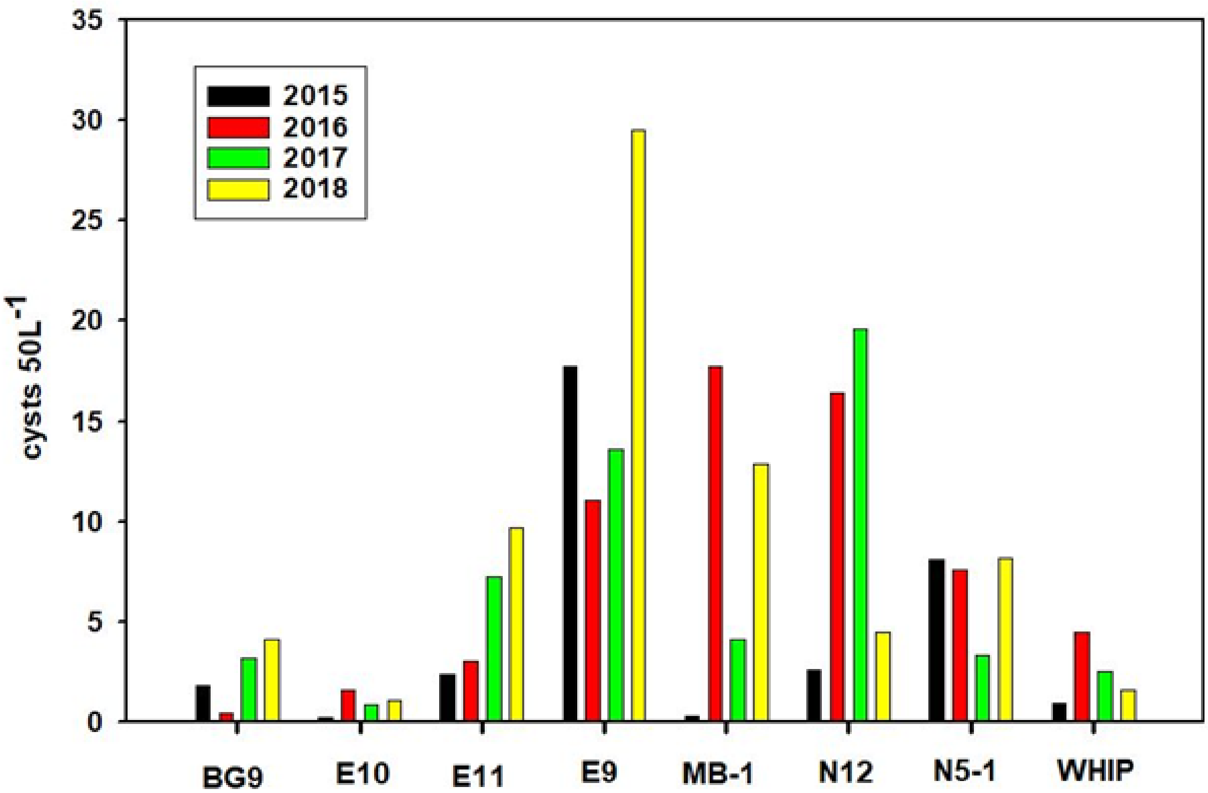


Figure 5.12 Annual mean *Giardia* concentrations for routine samples taken at the eight Kensico streams in 2015 through 2018.

Additional Samples

Fifteen additional samples were collected in 2018 as part of follow-up investigations after some routine samples were found to have elevated levels of (oo)cysts relative to their 10-year 95th percentile values. In nearly all cases, follow up results were lower than the initial result that triggered the sample, indicating that elevated levels of protozoa are episodic and not sustained (Figure 5.13 and Figure 5.14).

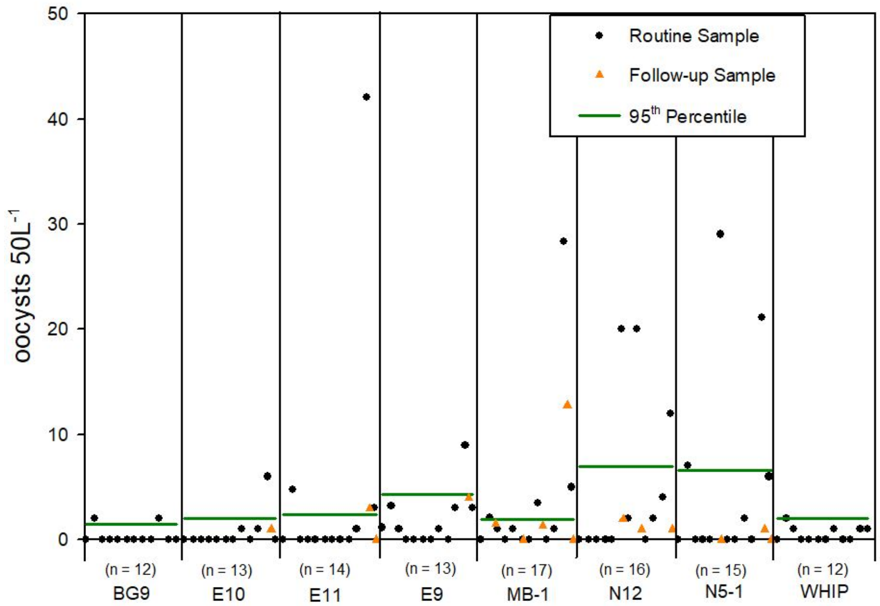


Figure 5.13 *Cryptosporidium* concentrations for routine and additional samples collected in 2018 relative to their ten-year 95th percentile values (horizontal green line).

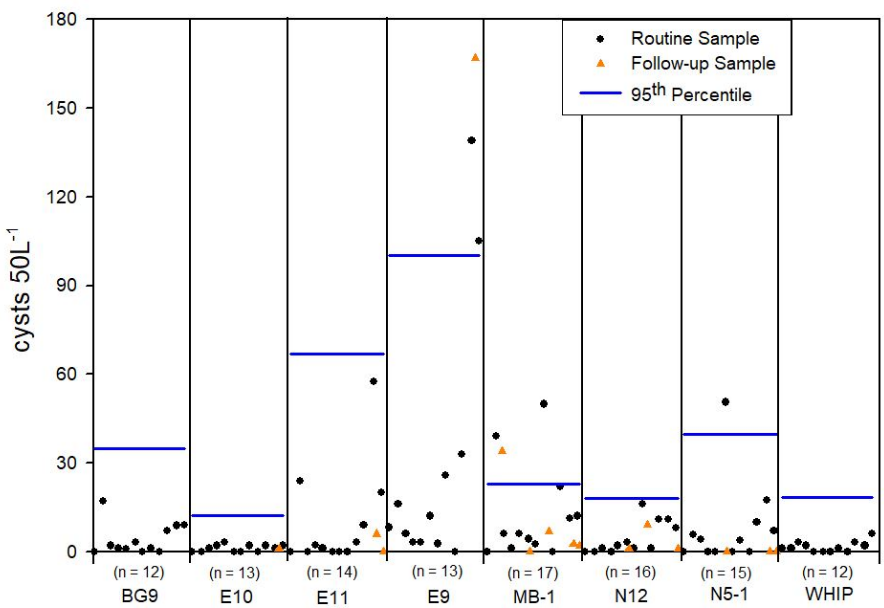


Figure 5.14 *Giardia* concentrations for routine and additional samples collected in 2018 relative to their ten-year 95th percentile values (horizontal blue line).

The first additional sample was taken on February 26 at MB-1 after the routine sample on February 6 showed concentrations of *Cryptosporidium* and *Giardia* at 2.11 and 39.03 (oo)cysts $50L^{-1}$, respectively, which was above the 95th percentile for this site (1.96 and 22.98 (oo)cysts $50L^{-1}$, respectively). The follow-up sample had lower *Cryptosporidium* (1 oocyst $32.5L^{-1}$ or 1.54 oocysts $50L^{-1}$) but still had 22 *Giardia* cysts in the 32.5L sample (normalized to 33.85 cysts

$50L^{-1}$). The next monthly routine sample was taken on March 6 and results were well below the 95^{th} percentile thresholds.

The June 6 samples from N12 and N5-1 had elevated routine results for *Cryptosporidium* and/or *Giardia* above the 95^{th} percentile threshold. The *Cryptosporidium* result from N12 (20.00 oocysts $50L^{-1}$) was above the 10-year 95^{th} percentile value of 7.00 oocysts $50L^{-1}$ and for N5-1 both *Cryptosporidium* and *Giardia* results (29.04 and 50.51 (oo)cysts $50L^{-1}$, respectively) exceeded the 95^{th} percentile thresholds (4.30 and 21.30 (oo)cysts $50L^{-1}$, respectively). Follow-up samples were scheduled at the two sites plus an additional sample at the nearby MB-1 site. The MB-1 sample was taken on June 11 and samples at N12 and N5-1 were scheduled for June 12. The MB-1 and N5-1 follow-up samples were negative for both *Cryptosporidium* and *Giardia*. N12 sample results from June 12 were 1 *Giardia* cyst and 2 *Cryptosporidium* oocysts in the 50.0L sample, well below the 95^{th} percentile threshold.

A similar round of follow-up samples was collected on August 20 after routine samples from MB-1 and N12 had *Cryptosporidium* and *Giardia* above the 10-year 95^{th} percentile threshold. The routine results from MB-1 on August 1 were three oocysts and 43 cysts in the 43.1L sample, exceeding the previously mentioned 95^{th} percentiles for both protozoans. N12 results were 20 oocysts and 16 cysts in $50L^{-1}$, exceeding the 95th percentile for *Cryptosporidium*. The August 20 follow-up samples indicated that all results had dropped below the ten-year 95^{th} percentile ranges at MB-1 and at N12.

In November, five sites (E10, E11, E9, MB-1, and N5-1) were resampled after the routine samples showed *Cryptosporidium* concentrations ranging from 6.00 to 42.04 oocysts $50L^{-1}$. The highest concentration was found at E11 (42.04 oocysts $50L^{-1}$) followed MB-1 (28.33 oocysts $50L^{-1}$). All were above the range of ten-year 95^{th} percentiles for *Cryptosporidium* (range - 1.96 to 4.30 oocysts $50L^{-1}$). The routine sample at E9 also had a *Giardia* result (139.00 cysts $50L^{-1}$) above the ten-year 95^{th} percentile (100.55 cysts $50L^{-1}$). Follow-up samples were scheduled for November 19 at the five sites and results indicated two sites (E10 and N5-1) had dropped below the *Cryptosporidium* ten-year 95^{th} percentile thresholds. The other three sites (E11, E9, and MB-1) had *Cryptosporidium* concentrations which were lower (3.00, 4.00, and 12.79 oocysts $50L^{-1}$, respectively) but still at or above the thresholds. *Giardia* concentrations at E9 had increased in the November 19 sample (167.00 cysts $50L^{-1}$). The next round of sampling fell on the routine monthly collection date for December, so all eight streams were sampled. For this set of samples, E10 and E9 *Cryptosporidium* results were below the 95^{th} percentiles; MB-1 and E11 results remained at or above thresholds; and N5-1 and N12 results were back above thresholds. A second set of special investigation follow-up samples was scheduled for December 12 at MB-1, E11, N12 and N5-1 where *Cryptosporidium* and *Giardia* results from December 12 were negative at E11 and N5-1, and results for *Cryptosporidium* were negative at MB-1 and N12. *Giardia* results at MB-1 and N12 were at or below 2.00 cysts $50L^{-1}$; well below *Giardia* thresholds.

East of Hudson WWTPs

Two EOH WWTPs, Carmel and Mahopac, were sampled quarterly in 2018. All of the WWTP samples at EOH sites were negative for *Giardia* and *Cryptosporidium*.

5.5 CAT/DEL UV Plant and Hillview Reservoir Monitoring

CAT/DEL UV (CDUV)

Monitoring of the outflow of the CDUV began in December 2017 and was conducted weekly throughout 2018 at the tap known as CCCLAB. Of the 53 samples collected in 2018, seven (13.2%) were positive for *Cryptosporidium* (Table 5.11). The annual mean concentration for *Cryptosporidium* was 0.15 oocysts $50.2L^{-1}$ and the highest result was 2.00 oocysts $50.2L^{-1}$. *Giardia* were detected in 27 of the 53 samples (50.9%) and the mean concentration was 0.68 cysts $50L^{-1}$. The maximum *Giardia* at CCCLAB in 2018 was 3.00 cysts $50L^{-1}$. With the exception of the maximum *Giardia* result at Hillview, concentrations for both *Cryptosporidium* and *Giardia* were higher at the CCCLAB site than at Hillview Site 3. *Giardia* was detected almost three times more often at the CCCLAB site than at Hillview Site 3 and the mean concentration for 2018 was more than double.

Table 5.11 Hillview Site 3 protozoan monitoring results summary for 2018.

	***Cryptosporidium* oocysts**	***Giardia* cysts**
n	53	53
Number of Detects	7	27
% Detects	13.2%	50.9%
Mean ($50L^{-1}$)	0.15	0.68
Maximum	2 (50.2L)	3 (50.0L)

The detection of *Cryptosporidium* oocysts and *Giardia* cysts immediately post-UV treatment is a strong reminder that the USEPA method for recovering these protozoans from water (in this case 1623.1) is unable to provide a true measure of public health risk. Cysts and oocysts are counted with this method, and reported, even though they have been deactivated by UV light and are no risk to public health. In order to enhance the assessment of risk, DEP implemented weekly *Cryptosporidium* infectivity testing at Hillview in January 2018, and results are discussed below.

Hillview

Giardia and *Cryptosporidium* have been routinely monitored weekly at Hillview Reservoir Site 3 since August 2011 as part of the Hillview Administrative Order. During 2018, 53 weekly samples were collected and analyzed by EPA Method 1623.1 with EasyStain and heat dissociation and results are presented in Figure 5.15 and Figure 5.16. In addition, 53 100-liter samples were collected weekly as part of an infectivity study at Hillview, and all samples tested negative for *Cryptosporidium* infectivity.

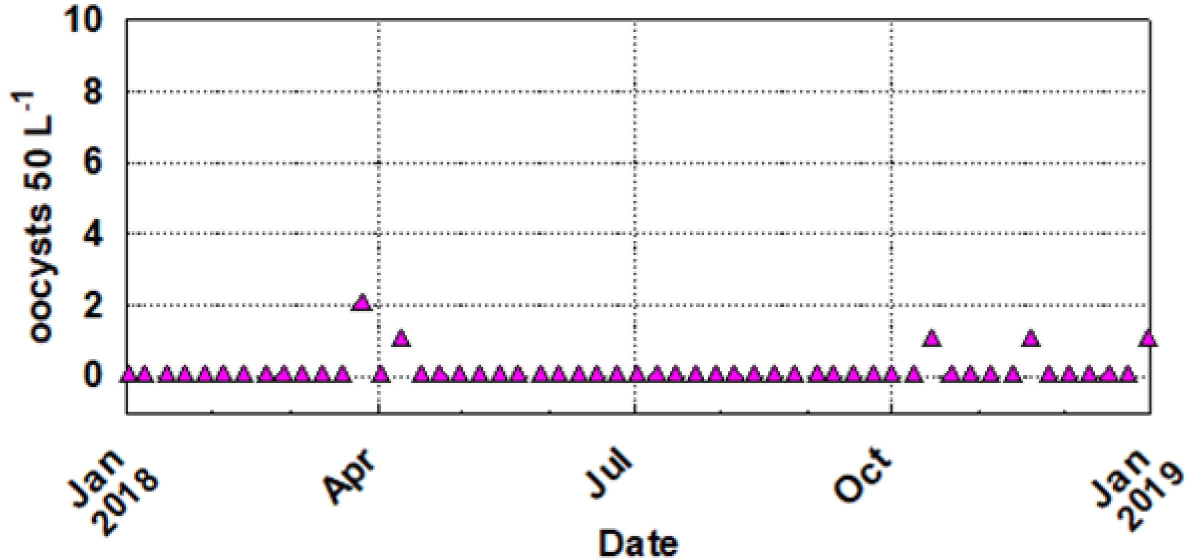


Figure 5.15 *Cryptosporidium* oocyst concentrations for routine samples at Hillview Site 3 in 2018.

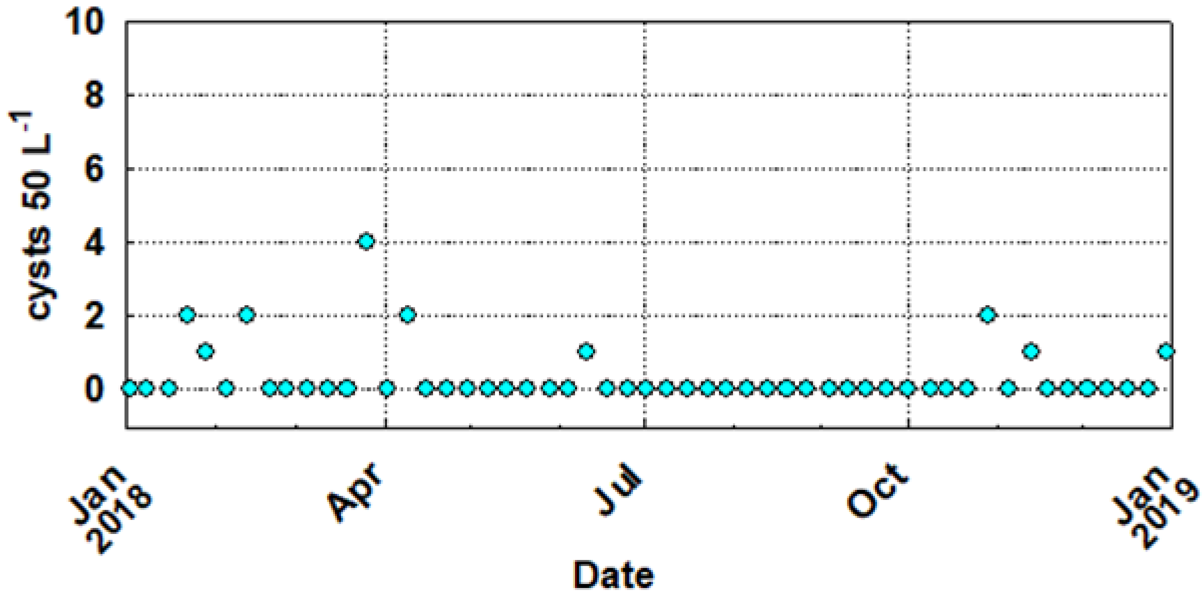


Figure 5.16 *Giardia* cyst concentrations for routine samples at Hillview Site 3 in 2018.

Cryptosporidium was detected in 9.4% of samples and the annual mean concentration was 0.11 oocysts $50L^{-1}$ (Table 5.12). *Cryptosporidium* detection rates in 2018 were higher than those in 2017, but similar to those in 2016 and 2015 (Table 5.11). Likewise mean concentrations were higher in 2018 (0.11 oocysts $50L^{-1}$) than 2017 (0.04 oocysts $50L^{-1}$), but comparable to those from 2016 and 2015 (0.09 and 0.11 oocysts $50L^{-1}$, respectively). The *Giardia* detection rate was quite similar in 2018 (17.0%) compared to 2017 (17.3%), but higher than the detection rates in 2015 and 2016 (9.3% and 11.3%, respectively). Cyst detection rates for the past two years are still lower than most years prior to switching to Method 1623.1 with EasyStain (2011-2014 rate – 31.9%, n=182). Additional years of data are needed to be confident about causes of changes in detection.

Table 5.12 Hillview Site 3 protozoan detections from 2011 to 2018.

	Cryptosporidium		***Giardia***	
Year	**Detects**	**% Detect**	**Detects**	**% Detect**
2011[1]	0	0.0%	4	18.2%
2012	0	0.0%	17	31.5%
2013	2	3.8%	18	34.6%
2014	2	3.8%	18	34.6%
2015	6	11.1%	5	9.3%
2016	4	7.5%	6	11.3%
2017	2	3.8%	9	17.3%
2018	5	9.4%	9	17.0%

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

6. Water Quality Modeling

6.1 Overview

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

This section contains an overview of major activities in the Water Quality Modeling Program that took place in 2018.

6.2 Development of a Stochastic Weather Model to Predict Precipitation for Ungauged Areas

6.2.1 Spatial Variation in Precipitation and Accuracy of Streamflow Prediction

DEP's hydrologic models, such as the Generalized Watershed Loading Function (GWLF) and the Soil and Water Assessment Tool-Hillslope (SWAT-HS), both require data describing the time history of precipitation over a watershed in order to predict streamflow. In the case of a lumped parameter model such as GWLF, a single time series of precipitation, averaged over the area of the watershed, is required. However, in a distributed parameter model such as SWAT-HS, a time series may be specified for individual portions of the watershed, allowing the spatial distribution of rainfall to be specified. Observations from multiple gages may be used in such models. However, increased accuracy in streamflow prediction may be obtained by applying a procedure for estimating the continuous variation of precipitation over the entire watershed (Schuurmans and Bierkens, 2007). A model that considers the geographical and meteorological features of the region in the estimation of the spatial and temporal variation in precipitation over a watershed is described below.

As the first step in describing the spatial properties of daily precipitation, a regionalization technique is applied based on the similarities of both precipitation amount and occurrence at different locations using the combination of Principal Component Analysis (PCA) and Ordinal Factor Analysis (OFA). The PCA/OFA procedure allows identification of regions, within which station observations have similar statistical properties. The observations at stations within each region can then be used to estimate precipitation across the entire region.

In addition to the regionalization analysis, a new stochastic precipitation model was developed and applied to generate daily precipitation series for historical periods at all locations in the Catskill and Delaware watersheds; results for the Ashokan and Rondout watersheds are summarized here. The goal of this model is: when used as input to a distributed hydrologic model such as SWAT, these precipitation time series will result in more accurate predictions of streamflow compared to more traditional approaches such as Thiessen polygons.

6.2.2 A Stochastic Precipitation Model for Ungauged Locations

Data from stations within each region are used to estimate precipitation at other stations, or at ungauged locations, within the region, including probabilistic information derived from using a stochastic model. Like other weather models, the stochastic modeling of the precipitation process is based on the combination of two different components: the modeling of precipitation occurrence and of precipitation amount. Ordinary Kriging (OK) approach is used for determining daily wet/dry process and Kriging with External Drift (KED) for representing spatial variability of daily precipitation amount. To describe the orographic effects on the amount over our study region, elevation is regarded as the external drift in KED model.

To cross-validate the stochastic model, daily precipitation data from stations in the identified homogeneous region during the calibration period (1950s) are used. Each station is deleted one at a time, and the other stations are used to estimate precipitation at the excluded station. After excluding each station, the PCA/OFA model is calibrated, and the daily precipitation series are estimated based on the data available at the remaining stations. The details of the model development are described in Yeo et al. (2019).

6.2.3 Regionalization Analysis and Model Application

Historical precipitation data from the Catskill Mountain region, which includes the watersheds of the West of Hudson reservoirs, were obtained from the Northeast Regional Climate Center (NRCC) and National Climatic Data Center (NCDC) of National Oceanic and Atmospheric Administration (NOAA). The regionalization analysis was performed on data for 1949-1959, a period for which a maximum number of stations (80) were active. PCA/OFA were employed together to analyze the 80 daily precipitation time series, resulting in the identification of 11 climatic regions.

To validate the proposed weather model, the Ashokan and Rondout watersheds were selected because they were identified as one homogeneous region by PCA/OFA. Daily precipitation data from 14 rain gauge stations in this region for the period 1949-1959 were used to establish a model of spatial distribution of precipitation. After generating daily precipitation maps for the region, a comparison study was carried out using the observed and estimated time series in order to evaluate the model performance. Figure 6.1 shows the stochastic weather model results for Ashokan and Rondout watershed. Figure 6.1(a) is the daily precipitation map over the watershed for January 1, 1949, demonstrating that this model predicts the continuous spatial variation over the watershed. Choosing the gage located at Glenford, NY as a test, the model accurately predicts daily precipitation for this period (Figure 6.1 (b)). Figure 6.1(c) and (d) show good performance in prediction of monthly precipitation amount, and the number of wet-days.

In the next step in the evaluation of this weather model, the predicted spatial variation of precipitation for historical periods will be used as input to the SWAT-HS model to evaluate the accuracy of the resulting predicted streamflow.

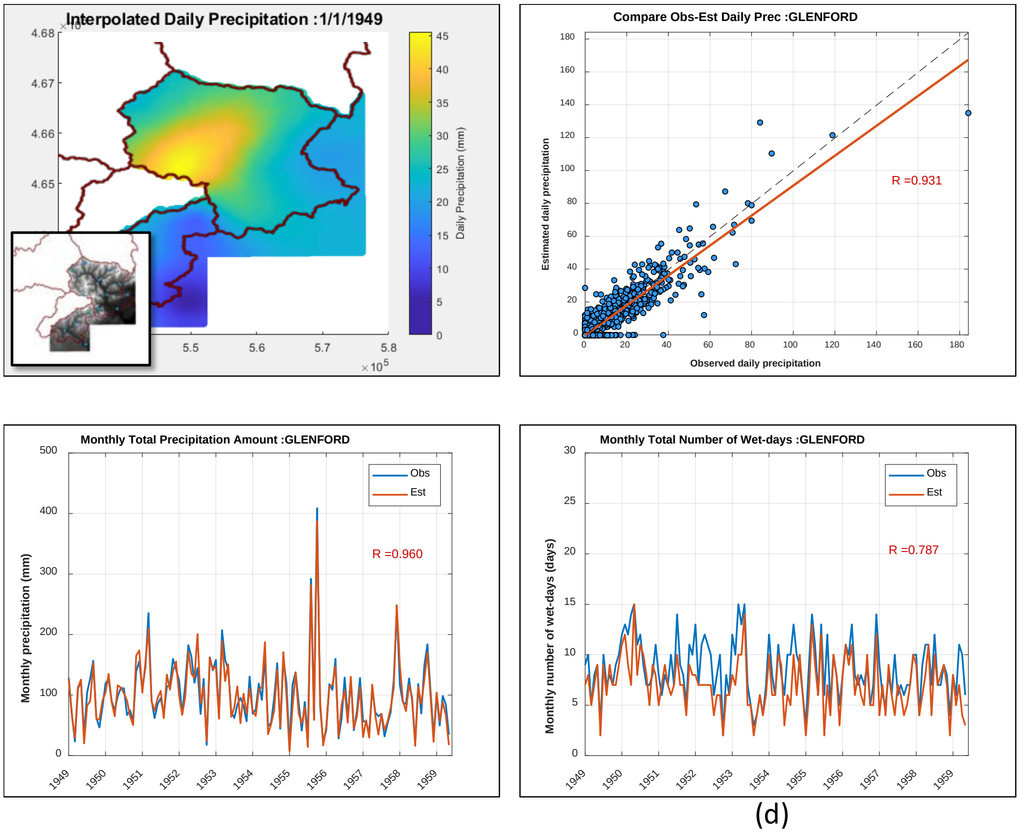


Figure 6.1 Stochastic weather model results for the Ashokan and Rondout watersheds: (a) daily precipitation map for a single day (1/1/1949), (b) observed and predicted daily precipitation at Glenford (dash line indicates perfect agreement between predicted and observed), (c) time series of observed and predicted monthly precipitation at Glenford, and (d) time series of observed and predicted number of wet-days per month at Glenford.

6.3 Progress with RHESSys

In early 2019, a paper describing the application of the Regional HydroEcological Simulation System (RHESSys) to Biscuit Brook was published (Son et al., 2019). The modeling work described in this paper was presented in the previous two (2016 and 2017) versions of this annual report.

Two new projects involving RHESSys were completed in 2018 and early 2019, these being a model intercomparison of RHESSys and SWAT, and an application of RHESSys to study selected components of the watershed protection program.

6.3.1 Intercomparison of RHESSys and SWAT-HS

A model intercomparison study was carried out to compare streamflow simulations by RHESSys, a hydrologic modeling framework that requires detailed spatial input and high computational requirements, and SWAT-HS, a semi-distributed model requiring less detailed spatial input and lower computational needs. Both models were set-up for Biscuit Brook, a 9.2 km^2 watershed in the Neversink basin, and Town Brook, a 37 km^2 sub-basin of the Cannonsville watershed with 32% agricultural land. Results of streamflow simulation by the two models and comparison with observed streamflow are presented below.

The results of the model intercomparison in the form of statistics of model accuracy are summarized in Table 6.1 for Town Brook, and Table 6.2 for Biscuit Brook. Both models were generally able to capture the major features of the variation in streamflow. Although RHESSys performed better than SWAT-HS in its prediction of low flow, the model intercomparison concluded that SWAT-HS generally yielded more accurate predictions of streamflow. These comparisons were for two relatively small watersheds. Given the challenges and complexities involved in setting up RHESSys for a watershed, preparation of input data, and the model's high computational requirements, we have abandoned plans for additional work with RHESSys, including the scale-up to an entire WOH reservoir watershed.

Table 6.1 Model performance statistics for daily streamflow prediction in Town Brook.

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

NSE: Nash-Sutcliffe efficiency for streamflow
NSElog: NSE for log(streamflow)

Table 6.2 Model performance statistics for daily streamflow prediction in Biscuit Brook.

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

6.3.2 Application of RHESSys to Watershed Protection

A study was conducted to test and demonstrate the capability of RHESSys to simulate the impact of a component of the DEP's watershed protection program. The validated RHESSys for Biscuit Brook (Son et al, 2019) was applied to evaluate the impact of forest thinning practices on water balance, including snowpack, evapotranspiration and streamflow. Thinning practices were implemented in two ways; a) spatial uniform thinning and b) spatial varied thinning. Spatial uniform thinning practices applied prescribed percent reduction of leaf area carbon and canopy fraction. Reducing leaf carbon changes the vertical structure of vegetation by decreasing the density of vegetation leaf carbon for the same area, while reducing canopy fraction changes the horizontal structure of vegetation by increasing the open area of the watershed.

To briefly summarize the results, it was determined that forest thinning increased the simulated annual streamflow and decreased the simulated annual evapotranspiration. The reduction of canopy fraction has higher impact on annual/daily water balance than the reduction of leaf carbon. Reducing leaf area carbon did not have impact on daily snowpack simulation, but reducing canopy fraction increased the snowmelt, and its increase results in altering soil water storage in the spring. Thinning has higher impact on evapotranspiration during dry years, but has greater impact on snowpack and streamflow in wet years.

The study was limited to exploring the impact of forest thinning on hydrology at the catchment scale. Attempts were made using RHESSys to simulate the impact of forest harvesting on hydrology and stream nitrate in Shelter Creek watershed, another forested headwater catchment of the Neversink River. These attempts did not lead to realistic results. The inability of the model to generate reasonable results for this practical management scenario provided additional justification for discontinuing further work with RHESSys.

6.4 Integration of Rondout Reservoir Turbidity Model into the Operations Support Tool

The previously developed Rondout Reservoir water quality model was integrated into the Operations Support Tool (OST) in 2018. Similar to Schoharie, Ashokan, and Kensico reservoirs' water quality models in OST, this model is also based on CE-QUAL-W2, with turbidity as the primary water quality variable being simulated. Water quality runs with OST in both the simulation and position analysis (i.e., ensemble forecasts) modes can be made with explicit simulation of turbidity in Rondout Reservoir. This enhancement of OST is particularly useful to guide reservoir operations during high turbidity events in the Delaware system. Furthermore, it provides realistic projections of turbidity for input to the Kensico Reservoir model.

As in 2017, water quality forecast reports were generated in 2018 for use by the Bureau of Water Supply. With the enhanced OST, these reports now include forecasts of turbidity at the diversion from Rondout Reservoir (RDRR; see an example of such reports in Figure 6.2). Predictions of turbidity are generated in a probabilistic format indicating the probabilities of exceedances of selected turbidity levels that are appropriate at the time of forecast.

NYC Environmental Protection — **Water Quality Forecast Summary** — Division of Water Quality Science & Research

Forecast Period: 10/25/2018 - 11/7/2018 — Bureau of Water Supply, Kingston, NY

Rondout Reservoir

	25-Oct	26-Oct	27-Oct	28-Oct	29-Oct	30-Oct	31-Oct	1-Nov	2-Nov	3-Nov	4-Nov	5-Nov	6-Nov	7-Nov
Inflow, MGD	53	69	120	224	172	190	133	118	138	189	185	194	139	135
Div., MGD	600	600	600	600	600	600	600	600	600	600	600	600	600	600
WSE, ft	837.1	837.4	837.8	838.4	838.8	839.3	839.7	840.2	840.6	840.9	840.9	841	841	840.9
Diversion Turbidity (RDRR): Probability of Exceedance (%)														
0.5 NTU	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1 NTU		4	4	6	9	9	13	13	15	21	28	28	32	30
2 NTU		2	4	4	6	6	6	6	9	9	9	9	13	13
3 NTU			4	4	6	6	6	6	6	6	6	4	4	4
4 NTU			4	4	4	4	6	6	4	4	4	4	4	4
5 NTU			2	4	4	4	4	4	4	4	4	4	4	4
Hist. Med.,NTU	0.9	1	1	0.9	0.9	0.9	1	1	1	0.9	0.9	0.8	0.9	1
Hist. 95^{th},NTU	1.5	1.5	1.8	1.6	1.6	1.6	1.9	1.9	1.7	1.7	2	1.4	1.5	2.1

Figure 6.2 Example of a water quality forecast summary report showing probability of exceedances of selected turbidity levels at RDRR.

6.5 Development of Climate Change Scenarios for Watershed and Water Quality Models

Global climate model output is often downscaled to grids of moderately high spatial resolution (~4 – 6 km grid cells). Such projections have been used in numerous hydrological impact assessment studies at watershed scales. However, relatively few studies have been conducted to assess the impact of climate change on the hydrodynamics and water quality in lakes and reservoirs. A potential barrier to such assessments is the need for meteorological variables at sub-daily timescales that are downscaled to in-situ observations to which lake and reservoir water quality models have been calibrated and validated. During 2018, a generalized procedure was developed that utilizes gridded downscaled data (MACA; Multivariate Adaptive Constructed Analogs; Abatzoglou and Brown, 2012), applies a secondary bias-correction procedure using equidistance quantile mapping to map projections to station-based observations, and then implements temporal disaggregation models to generate point-scale hourly air and dewpoint temperature, wind speed, and solar radiation, for use in water quality models. The proposed approach was demonstrated for six locations within New York State, four within watersheds of the New York City water supply system, and two at nearby National Weather Service stations. Disaggregation models developed using observations reproduced hourly data accurately at all locations, with Nash-Sutcliffe efficiency greater than 0.9 for air temperature and dewpoint, 0.4 – 0.6 for wind speed, and 0.7 – 0.9 for solar radiation. A complete description of the development of the methodology, and the results of its application, are given by Gelda et al., 2019. Following is a brief summary.

Overall Strategy: MACA data includes a bias correction (based on empirical statistical technique of quantile mapping) after developing the spatial downscaling as a linear superposition of 10 patterns across the contiguous U.S. This bias correction is used to ensure that the distribution of downscaled data for the historical simulation experiments (1950-2005) match those of the training data for each ~ 4 km grid cell, with the same bias correction applied to RCP4.5 and RCP8.5 scenarios (2006-2100). This methodology was extended to point-scale observations. The first step in this process was to extract daily gridded output co-located with a point-scale observation of interest that was used during calibration and validation of hydrologic and reservoir models. We used the equidistant quantile mapping (EQM) method (Li et al. 2010) to bias correct downscaled climate model output to point-scale observations. This process was done on monthly timescales (e.g., all days in March are pooled and bias corrected), thus ensuring the statistical attributes of historical climate matched those of the observed climate record, and that differences between future and historical data were preserved along quantiles. In the second step, the secondary bias corrected data were temporally disaggregated from daily to hourly values using simple, established methods, which then could be used by lake and reservoir models.

Annual cycle: To illustrate the changes in climate, the recent observed annual climatological cycles (1986-2015 average) of daily maximum and minimum temperature T_{max}, T_{min}, daily maximum and minimum relative humidity RH_{max}, RH_{min}, daily average scalar wind speed components w_x, w_y, and daily average solar radiation SR_{avg}, are compared with the projected cycles (2041-2060 average; RCP 8.5) at Albany Airport site in Figure 6.3. Projections are represented as ranges (minimum and maximum) derived from the ensemble of 20 General Circulation Models (GCMs). An individual ensemble member corresponds to average climatology predicted by a particular GCM. Ensemble average (i.e., average of the 20 GCMs) can also be computed and can be considered as the most likely future scenario (Figure 6.3). The increase (= ensemble average - observed) in T_{max} and T_{min} is expected to be largely uniform throughout the annual cycle, with both expected to rise typically by 1–4 °C (Figure 6.3a–b). RH_{max}, RH_{min}, w_x, w_y, and SR_{avg} do not exhibit any systematic change in the future, as illustrated by their respective ensemble ranges capturing the recent observations (Figure 6.3c–g). Projected ensemble averages of these variables (not shown here) closely track the recent observations, although a particular GCM may show a systematic change in the future. Annual averages and standard deviations of these variables at the six sites for the recent and future time periods are compared in Table 6.3. The magnitude of projected change in annual average T_{max} and T_{min} is similar at the six locations (~ 2.7 °C). The joint inter-annual and inter-model variability is 1.2 °C attributed to the warming trend of the mid-century as well as varying climate sensitivity of GCMs (Table 6.3). No significant changes in other variables are projected in this region (Table 6.3; decrease in RH_{max} and RH_{min} < 1%, no change in w_x and w_y, increase in $SR_{avg} \approx 5$ W m^{-2}).

Long-term trends: Observations for 1986–2015 are compared with the range of projections from 20 GCMs for 1986–2060 for the seven variables at Albany Airport (Figure 6.4). The inclusion of the results for the historical period (1986-2015) offers a form of verification of and a measure of confidence in the GCMs, the primary downscaling method, and the secondary bias correction method. Any one particular GCM is not expected to match the observed annual average values, but the ensemble of 20 GCMs is expected to encompass the observed variability. For example, observations of T_{max} for 1986-2015 are well within the bounds of simulated values from 20 GCMs (Figure 6.4a). Both T_{max} and T_{min} are expected to gradually increase; T_{max} rising from the recent average of 14 °C to within a range of 15–20°C in 2060, and T_{min} from 4.5 °C to within a range of 5–10 °C (Figure 6.4a). As mentioned earlier, although no long-term trend in *RH*, w_x, w_y, and SR_{avg} is evident, wide intermodal range is projected, particularly in w_x, and w_y (Figure 6.4b–e). Decreases in the observed *RH* in the recent years need further investigation.

Table 6.3 Projections of seven weather variables for 2041–2060 compared to current (1986–2015) observations for six locations in New York. Projections are shown for the GHG emission scenario RCP 8.5. Standard deviation (SD) represent inter-annual (30 years) variability in the case of observations, and joint inter-annual (20 years) and inter-model (20 GCMs) variability in the case of future projections.

Site	Name	Time Periods	T_{max} (°C)	T_{min} (°C)	RH_{max} (%)	RH_{min} (%)	w_x (m s^{-1})	w_y (m s^{-1})	SR_{avg} (W m^{-2})
			Avg (SD)	Avg (SD)	Avg (SD)	Avg (SD)	Avg (SD)	Avg (SD)	Avg (SD)
1	Cannonsville Reservoir	1986-2015	12.8 (0.9)	2.8 (0.8)	93.8 (2.4)	53.8 (2.8)	-0.1 (0.0)	-2.1 (0.2)	143.8 (3.8)
		2041-2060	15.5 (1.2)	5.7 (1.1)	92.9 (1.2)	52.9 (3.3)	-0.2 (0.1)	-2.1 (0.1)	148.3 (4.3)
2	Pepacton Reservoir	1986-2015	13.0 (1.1)	2.8 (0.8)	93.0 (3.2)	53.3 (3.5)	-0.1 (0.0)	-1.4 (0.2)	144.7 (3.6)
		2041-2060	15.7 (1.2)	5.7 (1.1)	91.2 (1.4)	52.2 (3.3)	-0.1 (0.1)	-1.4 (0.1)	149.3 (4.2)
3	Neversink Reservoir	1986-2015	12.5 (0.8)	3.4 (0.8)	91.6 (1.8)	53.8 (2.0)	-0.2 (0.0)	-2.7 (0.3)	152.1 (3.7)
		2041-2060	15.2 (1.2)	6.0 (1.0)	90.8 (1.3)	52.2 (3.2)	-0.2 (0.1)	-2.7 (0.1)	156.9 (4.3)
4	Rondout Reservoir	1986-2015	13.5 (1.0)	4.0 (0.8)	92.8 (2.4)	55.4 (3.2)	-0.3 (0.0)	-3.9 (0.5)	153.0 (3.6)
		2041-2060	16.0 (1.2)	6.5 (1.0)	91.8 (1.2)	53.3 (3.1)	-0.3 (0.1)	-4.0 (0.1)	158.1 (4.3)
5	Albany Airport	1986-2015	14.3 (0.8)	4.4 (0.8)	89.4 (2.8)	49.8 (2.4)	1.1 (0.3)	0.1 (0.2)	148.4 (4.7)
		2041-2060	17.1 (1.2)	7.0 (1.1)	90.1 (1.3)	48.9 (2.9)	1.0 (0.2)	0.1 (0.2)	152.4 (4.4)
6	White Plains Airport	1986-2015	15.5 (0.7)	6.6 (0.7)	87.5 (2.3)	48.3 (2.2)	0.9 (0.2)	-0.6 (0.3)	163.6 (4.5)
		2041-2060	18.1 (1.2)	9.0 (1.0)	88.0 (1.4)	47.6 (2.5)	0.8 (0.2)	-0.4 (0.2)	168.7 (4.5)

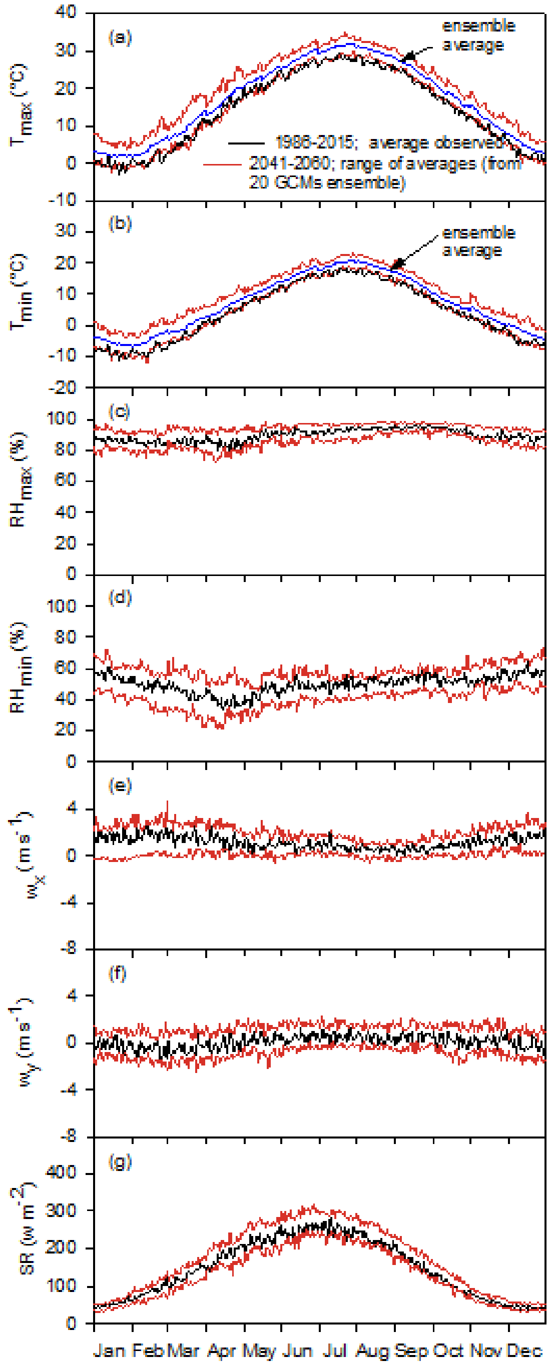


Figure 6.3 Annual climatological cycles of selected weather variables as represented by average of daily observations (1986–2015) and as range of daily projected (2041–2060; RCP8.5) averages derived from an ensemble of 20 GCMs, for Albany Airport. The variables ar e: (a) daily maximum temperature (T_{max}), (b) daily minimum temperature (T_{min}), (c) daily maximum relative humidity (RH_{max}), (d) daily minimum relative humidity (RH_{min}), (e) daily average zonal wind (w_x), (f) daily average meridional wind (w_y), and (g) daily average solar radiation (SR). For T_{max} and T_{min}, average of the 20 GCM ensemble is also shown. For other variables, the ensemble averages closely track the observations, hence not shown.

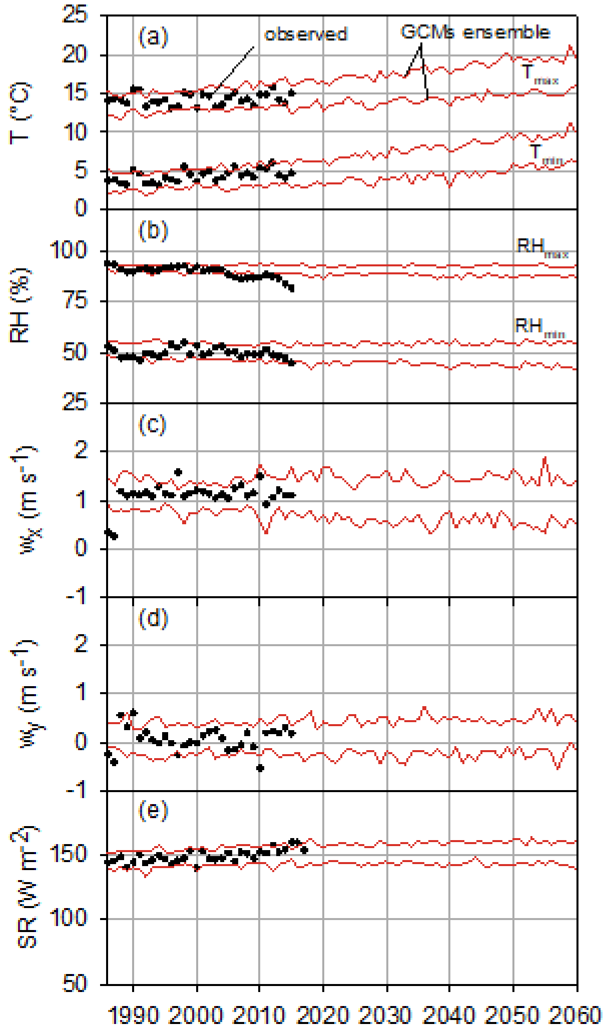


Figure 6.4 Long-term trend in annual average (a) air temperature [daily minimum (T_{min}) and maximum (T_{max})], (b) relative humidity [daily minimum (RH_{min}) and maximum (RH_{max})], (c) zonal wind (w_x), (d) meridional wind (w_y), and (e) solar radiation (SR), for Albany Airport. Observations for 1986–2015 are compared with a range of hindcasts and future projections from an ensemble of 20 GCMs for 1986–2060.

6.6 A Model Evaluation of Oxygen Depletion Rates in the Hypolimnion of Cannonsville Reservoir

Dissolved oxygen (DO) is an important water quality variable that generally quantifies the health of a water body such as a water supply reservoir. During summer thermal stratification, water in the hypolimnion is cutoff or isolated from atmospheric exchange (reaeration) occurring at the water surface, so that depletion of oxygen by respiration or microbial degradation in the water column of the hypolimnion, or in the underlying sediments, results in reduced dissolved oxygen. High oxygen depletion rates (ODRs) in the hypolimnion may lead to hypoxic or even anoxic conditions. Under such conditions, bioavailable forms of phosphorus and nitrogen may be released from the sediments, together with other undesirable compounds such as hydrogen sulfide.

To understand the long-term changes in the ODR in the Cannonsville Reservoir, the General Lake Model (GLM), a one-dimensional hydrothermal lake/reservoir model coupled with the water quality model Aquatic Ecodynamics (AED), was applied to simulate the hydrodynamics and water quality of the reservoir. The model has been previously calibrated and validated for the 1995-2010 time interval, a period defined by active watershed management, reduced phosphorus and nitrogen loads, and improved trophic state. The model predictions of vertical DO profiles in the water column of the reservoir were used as input to the procedure described by Livingstone and Imboden (1996) to compute the describe the rate of oxygen depletion, known as the oxygen depletion rate (ODR, g m^{-3} d^{-1}) as a function of vertical position in the hypolimnion and of time. Model predictions of reservoir DO were used in this calculation because, during these years, the frequency and vertical resolution of observations was not sufficient to describe the variability of DO.

The results (Figure 6.5) show that ODR has reduced gradually from 1995 to 2000, with more rapid decreases occurring from 2000 to 2006. These results are generally consistent with improvements in the water column of the reservoir, including reductions of phosphorus and chlorophyll concentrations in the epilimnion, and increase in transparency.

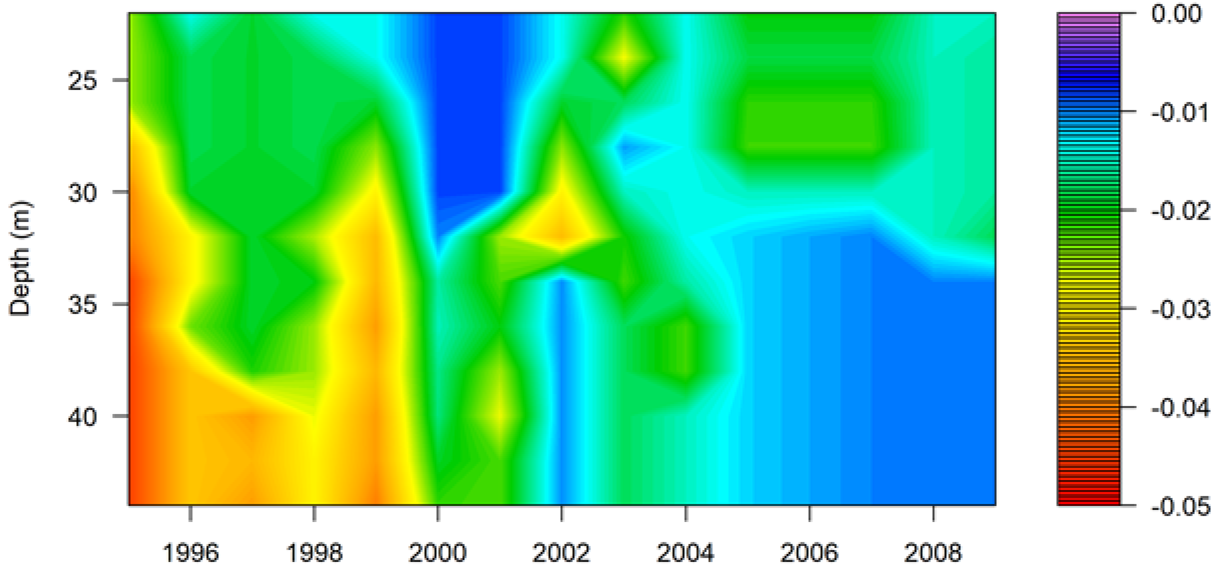


Figure 6.5 Calculated oxygen depletion rates (ODR [g m^{-3} d^{-1}]) between 1995 and 2010 in the hypolimnion of Cannonsville Reservoir.

6.7 East of Hudson Reservoir Bathymetry

Following on the contract completed by the USGS to survey the bathymetry of the six West of Hudson (WOH) reservoirs, NYCDEP awarded a new contract to the USGS to complete surveys of the East of Hudson reservoirs in 2017. The contract is scheduled for completion by 2021. These surveys comprehensively describe the water storage capacity and bathymetry of each of the 13 reservoirs and 3 controlled lakes. The USGS are using multibeam sonar equipment, which is a technological upgrade over the process used for the WOH surveys and will result in a finer spatial resolution for the contract deliverables.

Through 2018, the USGS had completed the initial data collection of all 16 reservoirs and controlled lakes. Data collected to date include the main body of each reservoir and a secondary collection of quality assurance measurements for use in data validation. Special data collection planning was necessary to account for protected bald eagle nests near the reservoirs. Data in these areas were collected after the regulatory nesting season ended on October 1.

Since the completion of primary surveys, USGS have been working to clean and process the data to produce preliminary bathymetry datasets. These preliminary data will be used to identify areas for additional surveys, such as secondary pools and bays with dense macrophytes, as well as areas too shallow for the survey boat. These areas will be resurveyed in 2019, or alternative techniques will be used to fill in data gaps. Data processing will continue throughout the year, and draft deliverables are expected in 2020.

6.8 GWLF Data Automation

6.8.1 Forecast Datasets

In 2017, the Water Quality Modeling Section reported on the results of work completed to incorporate weather forecast data into the Generalized Watershed Loading Function (GWLF) model predictions. The selected forecast data were provided by Weather Underground (https://www.wunderground.com), and were available at a daily timestep, updated hourly for a 10-day forecast period. Because they were available through a programming interface, the data gathering automation scripts can be prepared and implemented quickly.

To provide a range of GWLF forecast values, DEP has begun work to acquire additional weather forecast data. NOAA provides a suite of forecast data, including the Global Ensemble Forecast System (GEFS), which includes up to 21 separate forecasts, which are all equally likely. DEP is using an 11 ensemble member reforecast subset, which provides a 16-day forecast period, issues at sub-daily timesteps, and a spatial resolution of 0.5 degrees latitude/longitude for days 1-8, and 0.66 degrees for days 8-16. GEFS forecasts are available from December 1984 – present, providing DEP with a long historical record to use for verification of the results, and to correct for bias in the data. NOAA data are provided through ftp websites in multidimensional data file formats, which require additional processing before use with GWLF. In 2018, significant progress has been made in writing code that will automate the process of downloading, unpacking, and storing the GEFS data in a local database for use in DEP models. This is an ongoing project, with additional work required to optimize data processing and storage, as well as changes to be made to the GWLF model scripts to accommodate the output range in visualizations.

6.8.2 GWLF Automation

Building on the previous work done to automatically prepare and run the GWLF using Python scripts, work has begun on code to enhance the functionality of the model results. The current workflow reads streamflow predictions from model output files, and calculates a bias-corrected streamflow, which are both plotted alongside USGS gage streamflow observations using base Python charting modules. Although these plots provide a glance at the model results, it is not currently possible to explore the results in this format. Consequently, several popular Python plotting modules have been evaluated for their ability to produce informative, interactive plots to enable end users to more fully explore the GWLF results.

In 2018, several common Python plotting packages have been explored for their capabilities to create interactive plots. An initial script has been developed to prepare GWLF streamflow forecast time series along with USGS gage observations and generates an interactive plot. The script uses the plotly module (https://plot.ly/) to generate javascript code, which can then be embedded into an html web page. Figure 6.6 depicts a sample plot using the plotly module. With this plot style, the user is able to zoom in or out from the default 30-day view to see any time period within the data period of record. Each time series in the plot—observed streamflow, GWLF predicted streamflow, and bias-corrected streamflow—can be individually enabled or disabled for further exploration of the data, and user-defined charts can be re-saved or printed from the web page.

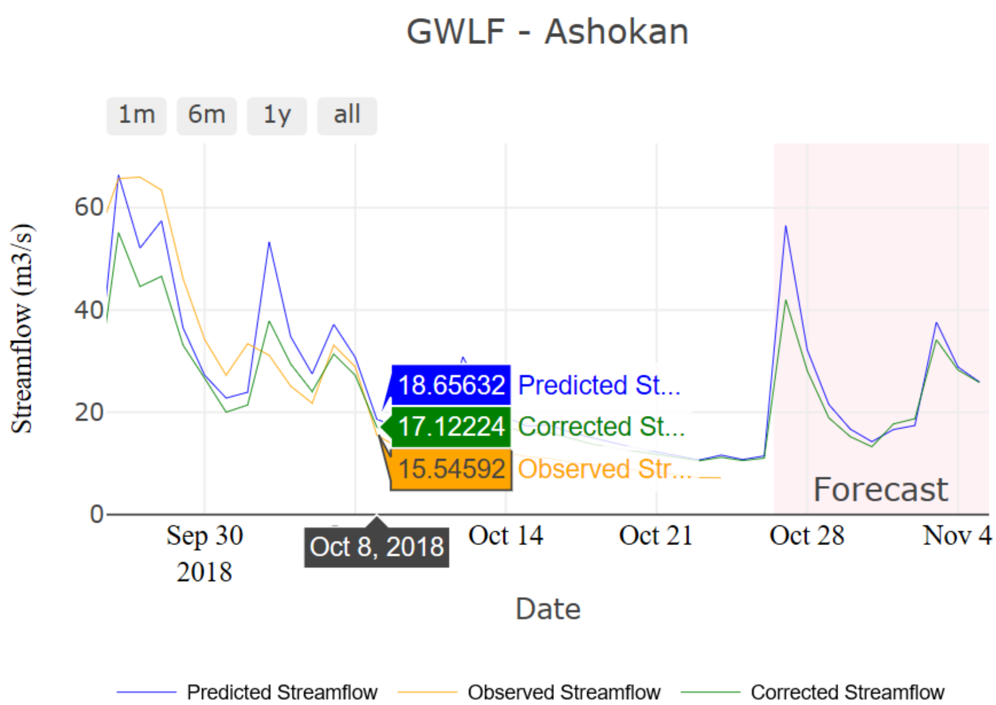


Figure 6.6 Sample interactive plot of GWLF results embedded in html web page.

Following the completion of the projects to incorporate GEFS forecasts and improve interactive results plots, all results will be aggregated into a dashboard. This dashboard will combine raw data from weather forecasts, water quality sampling, and other sources alongside predicted results from GWLF and other models.

6.9 Modeling Climate Change Impact on Streamflow and Stream Turbidity

Two research projects investigated the impact of climate change on the NYC water supply. The first study (Mukundan et al. 2019) is a modeling analysis of the climate change impact on streamflow using a stochastic weather generator (SWG), a hydrologic model, and downscaled future climate scenarios. Streamflow generated using synthetic time series of precipitation and air temperature from the SWG were compared to those simulated from observed historical and projected future weather. Synthetic weather was able to mimic the observed annual streamflow cycle for the six watersheds studied, including the seasonal pattern as well as magnitude and occurrence of extreme hydrologic events (Figure 6.7). Streamflow simulations using projected climate from 20 global climate models (GCM) for the Esopus Creek

(Ashokan) watershed indicate the potential for changes in the hydrologic regime 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. Results indicate that the region may experience an overall increase in mean streamflow in the future despite decreasing peak spring runoff. More importantly, the magnitude and frequency of extreme hydrological events are projected to increase under future scenarios.

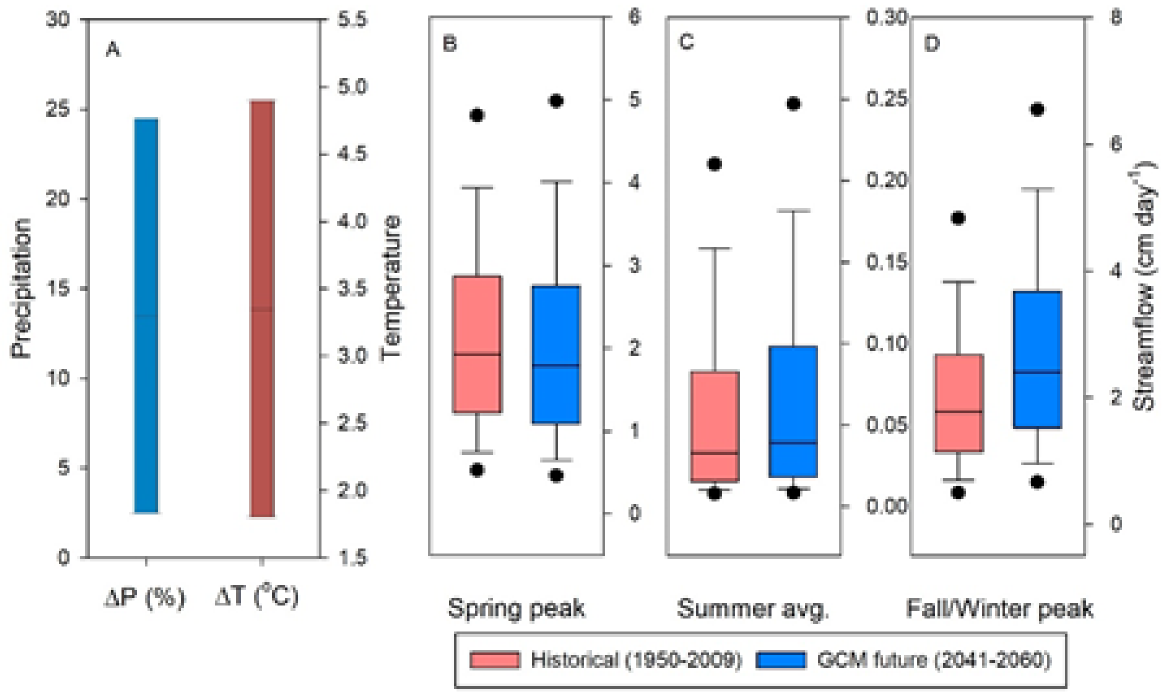


Figure 6.7 (A) GCM projected range in annual average precipitation and air temperature change for 2041-2060; comparison of historical and future streamflow simulations for Esopus Creek using SWG; (B) annual spring (March-April) peak magnitude; (C) July-August average flows; (D) annual fall/winter (November-December) peak magnitude. Boxes indicate inter-quartile range, also shown are the 10th and 90th percentiles (whiskers) and the 5th and 95th percentiles (dots).

A follow-up study (Mukundan et al. 2018) looked at the impact of climate change on stream turbidity in the Esopus Creek that feeds the Ashokan Reservoir. Streamflow-based rating curves are widely used to estimate turbidity or suspended sediment concentrations in streams. However, such estimates are often inaccurate at the event scale due to inter- and intra-event variability in sediment-streamflow relationships. In this study, we use a quantile regression approach to derive a probabilistic distribution of turbidity predictions, using measured daily mean streamflow-turbidity data pairs from 2003 to 2016. While a single regression curve can under-predict or over-predict the actual observation, quantile regression can estimate a range of possible turbidity values for a given value of streamflow. Regression relationships for various quantiles were applied to streamflows simulated by a watershed model to predict stream turbidity under observed historical climate and future climate. Future scenarios using quantile regression in combination with projected climate from 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.

Highlights from these two studies:

- Future streamflow simulations indicate changes in the hydrologic regime for NYC watersheds.
- Quantile regression addresses the uncertainty in the streamflow–turbidity relationship.
- Stochastic weather generator incorporates climate variability in climate change impact analysis.
- Future scenarios show an increase in the frequency and magnitude of high-stream-turbidity events.

6.10 Application of SWAT-HS to Evaluate the Impact of Watershed Protection Programs on Water Quality

In a first application of SWAT-HS in the Cannonsville watershed, the impact of point and nonpoint source reduction programs were evaluated (Hoang et al. 2019). NYC’s drinking water reservoirs supply over 1 billion gallons each day to over nine million consumers in NYC and upstate communities. In the last 25 years, the City has invested more than $1.7 billion in watershed protection programs (WPPs) to maintain high source water quality, allowing NYC to avoid filtration for 90% of the supply. This study involves the use of a model to evaluate the impact of WPPs on phosphorus (P) loading in the Cannonsville Reservoir watershed, one of the unfiltered water supply sources. The model is SWAT-Hillslope (SWAT-HS), a modified version of the Soil and Water Assessment Tool (SWAT) that can realistically predict variable source runoff processes. We applied the SWAT-HS model to this watershed to test its ability to simulate conditions observed after the implementation of watershed protection, and to evaluate the impact of point and non-point source WPPs on watershed export of P. When applied to a 12-year period of WPP implementation, SWAT-HS predicted streamflow very well with a daily Nash Sutcliffe Efficiency (NSE) of 0.85 at the calibrated outlet and values ranging from 0.56 – 0.78 at six other locations within the watershed. Moreover, the monthly predictions of soluble P (total dissolved P, Figure 6.8), particulate P, and sediment (total suspended solids) were good with NSE of over 0.73. Model simulations indicated that the dominant source of soluble P was pastures while particulate P originated from both from croplands and pastures. A significant quantity of P was derived from near-stream areas, particularly from pastures where cattle spent time grazing and had access to streams. SWAT-HS was also used to estimate what the P export would have been over this 12-year period without WPP implementation. Point and non-point source programs were found to be important for P control, with non-point source controls effective during high streamflow, and point source controls more beneficial at low flow.

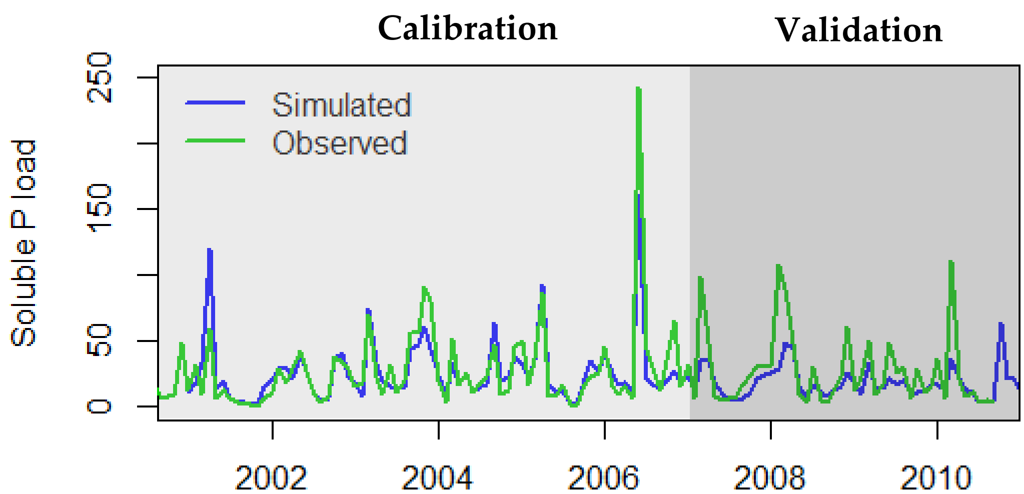


Figure 6.8 Comparison of SWAT-HS simulated and observed monthly loads of soluble P, at the water quality station in Beerston, NY.

Table 6.4 Simulated average reduction in P loads by point and non-point source WPPs during the period 2001-2007.

Average load (ton/month)	**Baseline scenario**	**Scenario 1**	**Scenario 2**	**Percent of P reduction (%) by**	
				Point source WPPs	*Non-point source WPPs*
Soluble P	0.76	0.98	1.19	18	19
Particulate P	5.87	9.19	10.03	8	33
Bioavailable P*	2.87	4.29	4.80	11	30

*Assumes 100% of soluble P, and 36% of particulate P, is bioavailable (Auer et al., 1998); Baseline scenario includes both point and non-point source reduction programs; Scenario 1 includes only point source reduction programs; Scenario 2 includes none of the WPPs.

6.11 Preliminary Application of SWAT-DOC Model in the Cannonsville Watershed

Some of the compounds that make up dissolved organic carbon (DOC) are precursors for carcinogenic disinfection byproducts (DBPs) generated during drinking water disinfection. The Water Quality Modeling section is participating in a research project involving the development and testing of a modified version of the SWAT model (SWAT-DOC) that is capable of simulating stream DOC. The Modeling section is collaborating with Xuesong Zhang and coworkers at the Pacific Northwest Lab, a federal government research organization on this project. The lack of a process-based watershed-scale model for carbon cycling has been a limiting factor impeding effective watershed management to control DOC fluxes to source waters. This study integrated terrestrial and aquatic carbon processes into the widely tested Soil and Water Assessment Tool (SWAT) watershed model to enable watershed-scale DOC modeling. The modifications to SWAT mainly fall into two groups, depicted in Figure 6.9: (1) DOC production in soils and its transport to aquatic environment by different hydrologic processes, and (2) riverine transformation of DOC and their interactions with particular organic carbon (POC), inorganic carbon and algae (floating and bottom). We tested the new SWAT-DOC model in the Cannonsville watershed, using long-term DOC loading data (from 1998 to 2012) derived from 1399 DOC samples. The results indicate that SWAT-DOC achieved satisfactory performance for both streamflow and DOC at daily and monthly scales. The parameter sensitivity analysis indicates that DOC loads in the Cannonsville watershed are controlled by the DOC production in soils, and by its transport in both terrestrial and aquatic environments. Overall, the wide use of SWAT and the satisfactory performance of SWAT-DOC make it a useful tool for DOC modeling at the watershed scale. Du et al. (2019) describe the development of this modified version of SWAT.

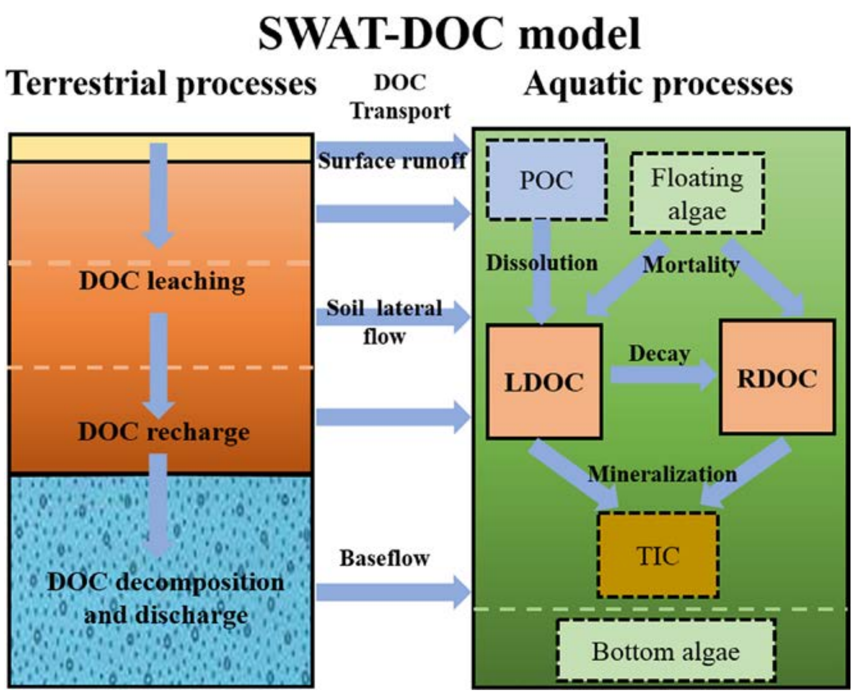


Figure 6.9 Schematic overview of the general DOC cycling processes across terrestrial and aquatic ecosystems in SWAT-DOC.

6.12 An Analysis on the Effect of Input Data Resolution and Complexity on Streamflow Predictions

Uncertainty in hydrological modeling is of significant concern due to its effects on prediction and subsequent application in watershed management. Similar to other distributed hydrological models, model uncertainty is an issue in applying the Soil and Water Assessment Tool (SWAT). Previous research has shown how SWAT predictions are affected by uncertainty in parameter estimation and input data resolution. Nevertheless, little information is available on how parameter uncertainty and output uncertainty are affected by input data of varying complexity. In this study, SWAT-Hillslope (SWAT-HS), a modified version of SWAT capable of predicting saturation-excess runoff, was applied to assess the effects of input data with varying degrees of complexity on parameter uncertainty and output uncertainty. Four digital elevation model (DEM) resolutions (1, 3, 10 and 30 m) were tested for their ability to predict streamflow and saturated areas. In a second analysis, three soil maps and three land use maps were used to build nine SWAT-HS setups from simple to complex (fewer to more soil types/ land use classes), which were then compared to study the effect of input data complexity on model prediction/output uncertainty. The case study was the Town Brook watershed in the upper reaches of the larger watershed of Cannonsville Reservoir; the soil and land use maps of the Town Brook watershed used in this analysis are shown in Figure 6.10. Results show that DEM resolution did not impact parameter uncertainty or affect the simulation of streamflow at the watershed outlet but significantly affected the spatial pattern of saturated areas, with 10m being the most appropriate grid size to use for our application. The comparison of nine model setups revealed that input data complexity did not affect parameter uncertainty. Model setups using intermediate soil/land use specifications were slightly better than the ones using simple information, while the most complex setup did not show any improvement from the intermediate ones. We conclude that improving input resolution and complexity may not necessarily improve model performance or reduce parameter and output uncertainty, but using multiple temporal and spatial observations can aid in finding the appropriate parameter sets and in reducing prediction/output uncertainty. Additional information on this work can be found in Hoang et al. (2018).

Highlights

- A complex model set up using the highest resolution DEM, and detailed soil and land use information may not necessarily improve streamflow simulation.
- Model setups with intermediate complexity are suggested for NYC watersheds.
- Non-uniqueness in parameter set can be reduced by using multiple spatial and temporal observations.

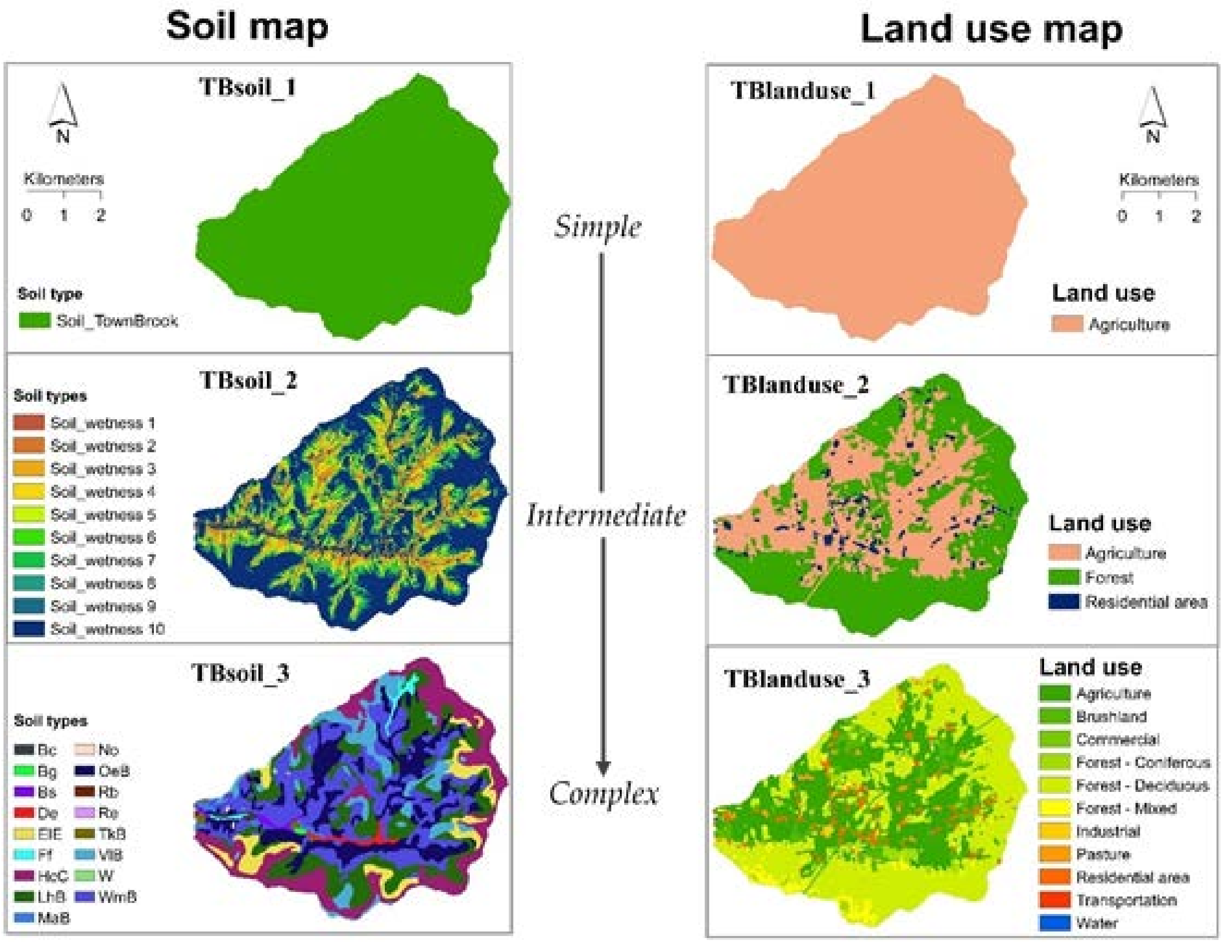


Figure 6.10 Soil and land use maps with increasing levels of complexity to build SWAT-HS model setups for the Town Brook watershed.

6.13 Review of the Operations Support Tool by National Academy of Sciences, Engineering, and Medicine Expert Panel

A review of DEP's Operations Support Tool (OST) by an expert panel of the National Academies of Sciences, Engineering and Medicine (NASEM) was completed in 2018. A series of public meetings over the period from January to September 2017 were held, and members of the Water Quality Modeling section attended and made presentations at these meetings. One of the four goals of this panel was "to review DEP's existing studies of the potential effects of climate change on the City's water supply to help identify and enhance understanding of areas of potential future concern with regard to the use of OST".

The expert panel released their final report in September 2018, which provided a strong endorsement of OST to support DEP's water supply operations. The report contained a number of recommendations to DEP regarding current and future use and ongoing development of OST.

A number of these recommendations directly or indirectly affect the activities of the Water Quality Modeling section. These recommendations, and DEP's responses, are as follows:

Recommendation: Given the Committee's review of the NYC DEP's and other studies on climate change in the watershed region, there is every reason to expect that OST can continue to be used as an effective tool for operational support into the future if the Chapter 2 recommendation to update OST with the most recent data is taken.

Response: DEP agreed with this recommendation, which is related to the fact that, at the time of the expert panel review, the historic data used in OST extended only up to 1997. Since that time, the historic data has been extended to 2017.

Recommendation: As OST is used in simulation mode in future climate change studies, it will be important to consider a range of approaches as inputs to OST, including climate and hydrologic models, historical climate analogs, and current conditions and trends.

Response: DEP agreed with this recommendation. In 2018, the Water Quality Modeling section has begun using OST in simulation mode to evaluate climate change.

Recommendation: NYC DEP should consider structuring future planning studies to identify the range of changes in hydrologic and water quality conditions that would trigger the need for operational changes, and then estimate the likelihood of such conditions.

Response: This is a recommendation that DEP use a "bottom-up" or vulnerability-based approach to climate change evaluations, which seeks to identify the meteorological and hydrologic conditions that lead to challenges in operating the water supply. The Water Quality Modeling section has begun to apply this approach, and has recently published an analysis using this approach (Mukundan et al. 2018).

Recommendation: When using global climate models linked to hydrologic models to generate input to OST for climate change studies, NYC DEP should utilize ensembles of climate and hydrologic models so that model-based uncertainty can be explicitly characterized.

Response: DEP generally agrees with this recommendation. With regard to global climate models, we have and continue to use ensembles of as many as 20 models. With regard to hydrologic models, this recommendation is more difficult to implement, given we currently have only one hydrologic model (GWLF) that is tested and verified for all WOH watersheds. By the end of 2020, we plan to have a second model that is similarly tested and validated (SWAT-HS). Our ability to generate an ensemble of hydrologic models is limited.

Recommendation: When using the global climate model (GCM) approach, NYC DEP should establish selection criteria for GCMs used as inputs based on how well the GCMs reproduce current climate and major climate trends over recent decades in this region.

Response: The Water Quality Modeling section has used selection criteria in the past. Currently, rather than using our own selection criteria, we prefer to use reviews and associated criteria that have been completed by independent outside experts that are available in the open literature.

Recommendation: NYC DEP should consider coordinating with other New York City and regional agencies to create and update a Climate Resiliency Indicator and Monitoring System for the New York metropolitan region and assess climate change.

Response: DEP agrees with the recommendation. The Water Quality Modeling section has begun the development of a program to calculate indicators of climate change based on meteorological, hydrologic, and reservoir operations and water quality data. This program has begun in 2019.

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

A second NASEM expert panel to review DEP's Watershed Protection Program held its first meeting in September 2018, and a second meeting was held the next month. Water Quality Modeling section staff attended these meetings. This panel has continued to hold meetings in 2019 and will issue its final report in 2020.

6.15 Modeling Support Contract with City University of New York

A four-year contract between DEP and the City University of New York (CUNY) to support water quality modeling activities at DEP was due to expire on August 15, 2018. Because there were unspent funds in that contract, a no-cost extension of that contract was signed to extend the contract to June 2019. This contract extension allowed CUNY to continue to employ the four support scientists who work full time in DEP's Kingston office for the remainder of 2018 and into 2019.

In 2018, DEP staff completed a draft version of a new four-year contract and an accompanying Scope of Work to continue this modeling support. This draft document was submitted for internal review by DEP in March 2018. The Scope of Work for this new contract contains some new features, two of which are highlighted here. First, Dr. David Reckhow of the University of Massachusetts-Amherst was added as a project advisor. Second, this contract adds a program of sampling and analysis to be conducted by University of Massachusetts-Amherst staff and overseen by Dr. Reckhow. These two new features are designed to strengthen and accelerate our efforts to develop watershed and reservoir models that are capable of simulating the sources, fate and transport of disinfection byproduct precursors in the NYC water supply. This new contract was executed on April 1, 2019, and will support modeling for four years beginning on that date.

6.16 Annual Water Quality Modeling Progress Meeting with Regulators

The annual meeting with regulators to present and discuss water quality modeling results was held on October 10, 2018 at DEP's Kingston office. Staff from the NYSDOH and from USEPA attended. This annual meeting is a requirement of the 2017 FAD. The meeting began with an overview of the modeling program and significant events occurring during the previous year, followed by a series of presentations on major modeling projects by DEP staff and CUNY support scientists. There was ample time for questions and discussion. The agenda for this meeting was as follows:

1. Overview of the Water Quality Modeling Program – Emmet Owens (DEP staff)
    a. Staff and CUNY Post-Doctoral Researcher Introductions
    b. CUNY-NYCDEP contract to support water quality modeling: status of current contract; overview of proposed new four-year contract
    c. Upcoming FAD requirements: this meeting; Annual modeling report now a part of Watershed Water Quality Annual Report (next submission July 2019)
    d. National Academy of Sciences Expert Panel Reviews: (1) Operations Support Tool (completed; final report received); (2) Watershed Protection Programs (begin Sept. 2018)
    e. Status report and future plans for individual models
    f. Peer-reviewed publications

2. A Stochastic Approach to Generating Daily Precipitation at Ungauged Locations in Catskill Mountain Region – Chris Yeo (CUNY Support Scientist)
3. Development of Climate Scenarios for Watershed and Reservoir Models – Rakesh Gelda (DEP staff)
4. Probabilistic Estimation of Stream Turbidity and Application under Climate Change Scenarios – Rajith Mukundan (DEP staff)
5. Integrating Climate, Forest Ecosystem and Hydrology to Estimate Forested Catchment DOC/Nitrate Export – Kyongho Son (CUNY Support Scientist)
6. Automation of Input Data Collection and Watershed Model Execution for West of Hudson Watersheds – Jordan Gass (DEP staff)
7. Watershed Protection Impacts on Cannonsville Stream and Reservoir Water Quality – Emmet Owens (DEP staff)
8. Modeling Eutrophication and Dissolved Organic Carbon in Cannonsville Reservoir – Theo Kpodonu (CUNY Support Scientist)

6.17 Water Quality Modeling: Publications and Presentations in 2018

6.17.1 Peer-Reviewed Publications

The following papers written by members of the Water Quality Modeling section were published in peer-reviewed journals in 2018:

Hall, D. K., A. Frei, and N. E. DiGirolamo, 2018. On the frequency of lake-effect snowfall in the Catskill Mountains, *Physical Geography* 39(5):389-405. doi:10.1080/02723646.2018.1440827

Hoang, L., R. Mukundan, K.E. Moore, E.M. Owens and T.S. Steenhuis, 2018. The effect of input data complexity on the uncertainty in simulated streamflow in a humid, mountainous watershed. *Hydrology Earth System Sciences* 22, 5947–5965. doi:10.5194/hess-22-5947-2018.

Mukundan R., M. Scheerer, R.K. Gelda, and E.M. Owens 2018. Probabilistic Estimation of Stream Turbidity and Application under Climate Change Scenarios. *Journal of Environmental Quality* 47(6):1522–1529. doi:10.2134/jeq2018.06.0229

Towey, K. L., J. F. Booth, A. Frei, and M. R. Sinclair, 2018: Track and Circulation Analysis of Tropical and Extratropical Cyclones that Cause Strong Precipitation and Streamflow Events in the New York City Watershed. *Journal of Hydrometeorology* 19:1027-1042, doi: 10.1175/JHM-D-17-0199

In addition, members of the modeling section spent significant time in 2018 on production of the following peer-reviewed papers that were ultimately published in 2019:

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

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

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

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

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

Yeo, M.-H., A. Frei, R.K. Gelda, and E.M. Owens 2019. A Stochastic Weather Model for Generating Daily Precipitation Series at Ungauged Locations in the Catskill Mountain Region of New York State. *International Journal of Climatology* (accepted).

Kpodonu, A.T., P.C. Hanson and E.M. Owens, 2019. A 1-Dimensional Modelling Approach to Evaluate the Impact of Watershed Management Programs on a Drinking Water Reservoir. *Journal of Environmental Management* (in review).

6.17.2 Conference Presentations

Gass, J., R. Mukundan and R.K. Gelda. 2018. Automation of input data collection and watershed model execution for West of Hudson watersheds. Watershed Science and Technical Conference, Saugerties, NY September 12, 2018.

Gelda, R.K., R. Mukundan and E.M. Owens 2018. Development of climate scenarios for watershed and reservoir water quality models using the latest CMIP5 climate projections. Watershed Science and Technical Conference, Saugerties, NY September 12, 2018.

Kpodonu, A.T. 2018. A water quality modeling analysis to evaluate the response of reservoirs to watershed management and climate variability. Watershed Science and Technical Conference, Saugerties, NY September 12, 2018.

Mukundan, R., R.K. Gelda, and E.M. Owens 2018. Probabilistic Estimation of Stream Turbidity and Application under Climate Change Scenarios. Watershed Science and Technical Conference, Saugerties, NY September 12, 2018.

Mukundan, R., L. Hoang, E. M. Owens, K. E. B. Moore 2018. Quantifying Sources of Stream Nitrogen in the Cannonsville Watershed using SWAT-HS. American Geophysical Union Meeting, Washington DC December 10-14, 2018.

Owens, E.M., L. Hoang, R. Mukundan and E. Blouin, 2018. Watershed Protection Impacts on Cannonsville Stream and Reservoir Water Quality. Watershed Science and Technical Conference, Saugerties, NY September 12, 2018.

Son, K., L. Lin, E.M. Owens and L.E. Band, 2018. Monitoring and Modeling Forest Disturbance. Society of Environmental Toxicology and Chemistry – Asia Pacific Meeting, Daegu, Korea, September 2018.

Yeo, C. 2018. A multivariate, stochastic approach to generating daily precipitation series at ungauged locations in Catskill Mountain region. Watershed Science and Technical Conference, Saugerties, NY September 12, 2018.

7. Further Research

The analytical, monitoring, and research activities of DEP are supported through a variety of contracts, participation in Water Research Foundation (WRF) projects, 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 and advanced methods into the work of the Water Quality Directorate (WQD), and to apply the most recent science for the benefit of the City’s water supply. WQD contracts and projects with external partners are described below.

7.1 Contracts Managed by the Water Quality Directorate (WQD) in 2018

WQD managed nine 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 2018, EEA analyses for DEP included algal toxins on aqueduct and reservoir samples; total and volatile solids on some aqueduct samples, volatile organic carbon (VOC), semi-volatile 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 the sources of fecal coliforms and protozoans in the watershed, samples were collected during storm events on Malcolm Brook and N5 in the Kensico watershed and sent to this laboratory for microbial source tracking analysis. Analysis includes the search for Bacteroidales genetic markers specific to humans through use of polymerase chain reaction (PCR) and other molecular techniques. The goal is to determine if sources are human or animal so they can be isolated and managed to prevent future contamination. As in past years, the vast majority of samples were negative for the human marker.

Watershed Assessment Associates: Samples of benthic macroinvertebrates collected in Croton, Catskill, and Delaware system streams were sent to this laboratory for identification to levels that meet the taxonomic targets set forth in the New York State Stream Biomonitoring Unit’s Standard Operating Procedure. The 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 City University of New York (CUNY) Modeling Support Contract

The four-year modeling support contract between DEP and CUNY was due to end on August 15, 2018. Due in part to the availability of unspent funds in that contract, a contract extension was put in place in late July 2018 to extend the contract to June 2019. Also in 2018, a draft of a new four-year contract between DEP and CUNY was written, including a Scope of Work. This draft contract was under review by DEP legal and accounting staff through the second half of 2018, and into 2019. One post-doctoral position became vacant in May 2018; due to uncertainty about the status of a new contract to continue support, CUNY was not able to hire a full-time researcher. However, a part-time researcher was hired in November 2018. The remaining three post-doctoral positions were filled for all of 2018. A new four-year contract was written for 2019. This support contract with CUNY continues to be valuable component of our water quality modeling program, as it supports four of the eight full time scientists and engineers in the group. The scope of work for the new contract is similar to the previous contract. Four support scientists who have completed doctoral degrees are to be supported, in the areas of climate data analysis and modeling, watershed modeling with emphasis on nitrogen, phosphorus, organic carbon and precursors of disinfection byproducts, and reservoir modeling. Three program advisors who are university faculty members are also supported by the new contract. These advisors are Allan Frei (Hunter College), David Reckhow (Univ. of Massachusetts-Amherst) and Tammo Steenhuis (Cornell Univ.). The new contract also supports a program of sampling and analysis related to precursors of disinfection byproducts in the New York City water supply, to be conducted by UMass-Amherst under the direction of David Reckhow.

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 contract personnel annually to cover waterfowl management activities at several upstate reservoirs. It ran through July 30, 2018 and DEP exercised the 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 September) due to lower calcium levels and less chance of colonization. In 2018, this work was taken in-house and is no longer done by a contract lab. To date, no infestations have been found in DEP's reservoirs; however, veligers have been found in Amawalk Reservoir at low concentrations. These apparently originate from zebra mussels in Lake Mahopac, which drains into Amawalk Reservoir. To date adult zebra mussels in the Lake Mahopac outflow have been found up to ~250 m downstream of the lake, but no further.

7.1.6 Bathymetric Surveys of All Reservoirs and Controlled Lakes

Under an inter-governmental agreement with United States Geological Survey (USGS), bathymetric surveying work was conducted on the six WOH reservoirs from 2013-2015. In 2018, USGS published their final report for the West of Hudson Reservoirs.

A separate inter-governmental agreement with the USGS was initiated in 2015 to survey the bathymetry of the 13 East of Hudson (EOH) reservoirs and 3 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 waterbodies, 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 2018. Most of the fieldwork was completed in 2018, and final data delivery is due by 2020. The EOH reservoirs were 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 track storage in the reservoirs and to improve volume estimates used in water-quality models for reservoir management.

7.1.7 WISKI Software Support Contract

DEP has continued to expand and enhance usage of the WISKI (Water Information Systems KISTERS) software to collect and view fixed point as well as continuous on-line data on a web Portal, in an effort to provide a management tool that tracks water from rainfall in the watershed, through the streams and reservoirs, and into the distribution 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 WISKI 7.4.5, and the new ESRI Portal is operational. Work has started on the development of "Heat Maps" for select datasets on the Portal. The 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. Build out of Harbor Buoy monitoring is nearing completion and is expected to be available on the Portal web page by late 2019.

7.2 Water Research Foundation Project Participation by WQD in 2018

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 a Participating Utility, to remain current with cutting-edge research for the benefit of the City's drinking water. WQD's current WRF projects are described below.

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

The objective of this project was to expand the knowledge base regarding the effects of wildfire on drinking water quality, treatment, plant performance, and operations. A final report was published in November 2018 and the primary investigator, Dr. Fernando L. Rosario-Ortiz, provided a detailed presentation of the study's findings at the DEP Kingston facility on November 15. The project addressed 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. Rich Van Dreason was a member of the PAC for this project.

7.2.2 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. Sharon Neuman is a member of the PAC for this project.

7.2.3 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 draft report was prepared in 2018 and the final report is pending. 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. Lori Emery is a member of the PAC for this project.

7.2.4 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. Aspa Capetanakis is a member of the PAC for this project.

7.2.5 WRF Project 4713 Full Lead Service Line Replacement Guidance

An RFP was issued for this project in 2016, and proposals were due in May of 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. Comments on periodic report #5 were submitted to WRF in 2018. Carla Glaser is a member of the PAC for this project.

7.2.6 WRF Project 4910 Evaluating Key Factors that Affect the Accumulation and Release of Lead from Galvanized Pipes

This project will develop cutting edge tools that will evaluate links between galvanized iron pipe (GIP) and lead (Pb) release, by (1) scientifically assessing customers' concerns related to GIP corrosion and possible association with Pb in water, (2) characterizing the nature of iron (Fe) and lead (Pb) release to drinking water from known sources, and (3) examining Fe and Pb release from GIP using bench-scale testing. In addition, public education materials will be developed related to GIP and Pb release. The first periodic report was submitted by the research team and it is under review by the PAC. Carla Glaser is a member of the PAC for this project.

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

DEP continues to be one of the 12 large public water utilities that make up the Water Utility Climate Alliance. Alan Cohn from the Bureau of Environmental Policy and Analysis (BEPA) remains DEP's official representative to WUCA. In 2018, interaction between WQSR and WUCA members was generally in the form of interaction with individual members.

In June 2018, Emmet Owens held a phone meeting with Kavita Heyn and Ben Beal from the Portland (Oregon) Water Bureau. DEP discussed how it has used the CE-QUAL-W2 model to simulate turbidity in water supply reservoirs. Portland has used this model for their water supply, but has not used the model to simulate turbidity. E. Owens described DEP's three-component turbidity model approach and the data and process studies that were used to support the development and application of the model to NYC water supply reservoirs.

In November 2018, E. Owens prepared a progress report on climate change modeling by DEP to be presented at the January 2019 regular meeting of the WUCA utility representatives. E. Owens then prepared a presentation and received DEP approval to present in January. As a result of that presentation, representatives from Austin (Texas) Water expressed interest in the stochastic weather generator developed by DEP. This interaction has led to a planned meeting with Austin Water staff Marisa Flores-Gonzalez and Joe Smith to take place in New York City in

July 2019. Also in November, E. Owens participated in webinar by staff from Austin (Texas) Water regarding their recent struggles with storm-induced water quality.

7.3 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 five GLEON “All-Hands” meetings since 2014 (GLEON16, Orford, Québec; GLEON17, Chuncheon, South Korea; GLEON18, Gaming, Austria; GLEON19, New Paltz, New York; and GLEON20, Rottnest Island, Australia).

GLEON20 was held on December 3-7, 2018 and provided an opportunity to follow up on existing projects and discuss potential future collaborations. The GLEON Student Association facilitated a pre-conference workshop on topics that included using the rLakeAnalyzer R package and other techniques to process and curate high-frequency data. One interactive workshop session focused on quality assurance and quality control of high-frequency data using a desktop application called “B3” and its R-programming counterpart “RB3”. These tools have been developed through the collaboration of GLEON partners and are particularly valuable in screening high-frequency sensor data, detecting anomalies, and correcting for sensor offsets. Some additional highlights for 2018 follow.

7.3.1 “Before the Pipe: Monitoring and Modeling DBP Precursors in Drinking Water Sources”

Collaboration on a project to identify important questions on disinfection byproduct precursors and water supply concerns began in 2018 after formation of the project at GLEON19. Efforts in 2018 were focused on a survey of GLEON members to identify common interests and expertise. In September 2018, subject matter expert Dr. David Reckhow, Professor of Civil and Environmental Engineering at the University of Massachusetts-Amherst, provided a webinar on “Characterization of DBP Precursors” to inform group members on the state of the knowledge on this topic. The consensus of the project group was to move forward with a systematic review paper and progress was made toward refining the scope of this review at the GLEON20 meeting.

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

This project focuses on using long-term dissolved oxygen profiles from 400 lakes around the globe to identify trends in dissolved oxygen at different depths, for lakes with different watershed features, and in lakes of different trophic status. DEP contributed data for this study in 2016. Project goals include exploring the response of dissolved oxygen concentrations to changing temperatures and examining how temperature and productivity interact to influence dissolved oxygen. In 2018, significant progress was made toward the project goal and some results were shared at the GLEON20 meeting. A manuscript was in progress at that time, with anticipated publication of results in 2019.

References

Abatzoglou, J. T., and T.J. Brown, 2012. A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology*, 32(5), 772-780.

Alderisio, K. A. and N. DeLuca. 1999. Seasonal Enumeration of Fecal Coliform Bacteria from the Feces of Ring-Billed Gulls (*Larus delawarensis*) and Canada Geese (*Branta canadensis*). Appl. Environ Microbiol. 65: 5628-5630.

Auer, M. T., K. A. Tomasoski, M. J. Babiera, M. Needham, S. W. Effler, E. M. Owens and J. M. Hansen. 1998. Phosphorus bioavailability and P-cycling in Cannonsville Reservoir. *Lake and Reservoir Management* 14(2-3):278-289.

Bolks, A., A. DeWire, and J. B. Harcum. 2014. Baseline assessment of left-censored environmental data using R. Tech Notes 10, June 2014. Developed for U.S. Environmental Protection Agency by Tetra Tech, Inc., Fairfax, VA, 28 p. https://www.epa.gov/sites/production/files/2016-05/documents/tech_notes_10_jun2014_r.pdf (accessed 6/21/2019).

Carlson, R. E. 1977. A trophic state index for lakes. Limnology and Oceanography 22:361-369.

DEP. 1992. New York City Department of Environmental Protection. Kensico Watershed Study 1991-92. Drinking Water Quality Control and Sources Divisions, Valhalla, NY.

DEP. 1997. A Methodology for Determining Phosphorus-Restricted Basins. Valhalla, NY.

DEP. 2002. Continued Implementation of Final Waterfowl Management Plan. Division of Drinking Water Quality Control. Valhalla, NY.

DEP. 2010. New York City Watershed Rules and Regulations. 1997, amended April 4, 2010. Rules and Regulations for the Protection from Contamination, Degradation, and Pollution of the New York City Water Supply and its Sources. RCNY Title 15, Chapter 18.

DEP. 2013a. 2011 Watershed Water Quality Annual Report, revised January 2013. Valhalla, NY. 144 p.

DEP. 2013b. 2012 Watershed Water Quality Annual Report. Valhalla, NY. 156 p.

DEP. 2014. 2013 Watershed Water Quality Annual Report. Valhalla, NY. 168 p.

DEP. 2015. 2014 Watershed Water Quality Annual Report. Valhalla, NY. 165 p.

DEP. 2016. 2015 Watershed Water Quality Annual Report. Valhalla, NY. 171 p.

DEP. 2017. 2016 Watershed Water Quality Annual Report. Valhalla, NY. 181 p.

DEP. 2018a. Watershed Water Quality Monitoring Plan. Directorate of Water Quality (issued October 2008, first revision, May 2009, latest revision December 2018). Valhalla, NY. 240 p.

DEP. 2018b. 2017 Watershed Water Quality Annual Report. Valhalla, NY. 213 p.

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

DEP. 2019b. Ultrasonic Algae Control Reservoir Platform Pilot, Final Report. Research Applications. Kingston, NY. 49 p.

Helsel, D. R. and T. A. Cohn. 1988. Estimation of descriptive statistics for multiply censored water quality data, Water Resour. Res., 24(12), 1997-2004, doi:10.1029/WR024i012p01997.

Helsel D. R. 2005. Nondetects and Data Analysis. John Wiley & Sons, New York.

International Organization for Standardization. 1985. Water quality—determination of electrical conductivity. Geneva, 1985 (ISO 7888:1985).

Li, H., Sheffield, J., & Wood, E. F. (2010). Bias correction of monthly precipitation and temperature fields from Intergovernmental Panel on Climate Change AR4 models using equidistant quantile matching. *Journal of Geophysical Research: Atmosphere*, 115(D10).

McHale, M. R. and J. Siemion. 2014. Turbidity and suspended sediment in the upper Esopus Creek watershed, Ulster County, New York: U.S. Geological Survey Scientific Investigation Report 2014-5200, 42 p. doi.10.3133/sir20145200.

NYSDEC [New York State Department of Environmental Conservation]. 2014. Standard Operating Procedure: Biological Monitoring of Surface Waters in New York State. Albany, NY. 171 p.

NYSDEC [New York State Department of Environmental Conservation]. 2017. DEC HABs program archive summary 2012 – 2017. http://www.dec.ny.gov/docs/water_pdf/habsextentsummary.pdf (accessed 6/21/2019).

NYSDOH [New York State Department of Health]. 2014. New York City Filtration Avoidance Determination. Final Revised 2007 FAD. 99 p. https://www.health.ny.gov/environmental/water/drinking/nycfad/docs/final_revised_2007_fad_may_2014.pdf (accessed 6/21/19).

Schuurmans, J.M., and M. F. P. Bierkens, 2007. Effect of spatial distribution of daily rainfall on interior catchment response of a distributed hydrological model. *Hydrology Earth System Science* 11, 677-693. doi:10.5194/hess-11-677-2007.

Singh, T. and Y. P. Kalra. 1975. Specific conductance method for in situ estimation of total dissolved solids. Journal of the American Water Works Association, 1975, 67(2):99.

USEPA [United States Environmental Protection Agency]. 1989. Drinking Water: National Primary Drinking Water Regulations; Filtration, Disinfection; Turbidity, *Giardia lamblia*, Viruses, Legionella, and Heterotrophic Bacteria; Final Rule. 54 Fed. Reg. 27486. June 29, 1989. WH-FRL-3607-7. Washington, D.C.

USEPA [United States Environmental Protection Agency]. 1996. ICR Laboratory Microbial Manual. EPA 600/R-95/178. Office of Research and Development. Washington, DC. Government Printing Office.

USEPA [United States Environmental Protection Agency]. 2006. Long Term 2 Enhanced Surface Water Treatment Rule. EPAHQ-2002-0039. Washington, D.C. http://www.federalregister.gov/a/06-4 (accessed 6/21/19).

USEPA [United States Environmental Protection Agency]. 2016. Definition and Procedure for the Determination of the Method Detection Limit, Revision 2.EPA 821-R-16-006. Washington, D.C. https://www.epa.gov/sites/production/files/2016-12/documents/mdl-procedure_rev2_12-13-2016.pdf (accessed 6/21/19).

van der Leeden, F., F. L. Troise, and D. K. Todd. 1990. The Water Encyclopedia, 2nd Edition. Chelsea, MI: Lewis Publishers.

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

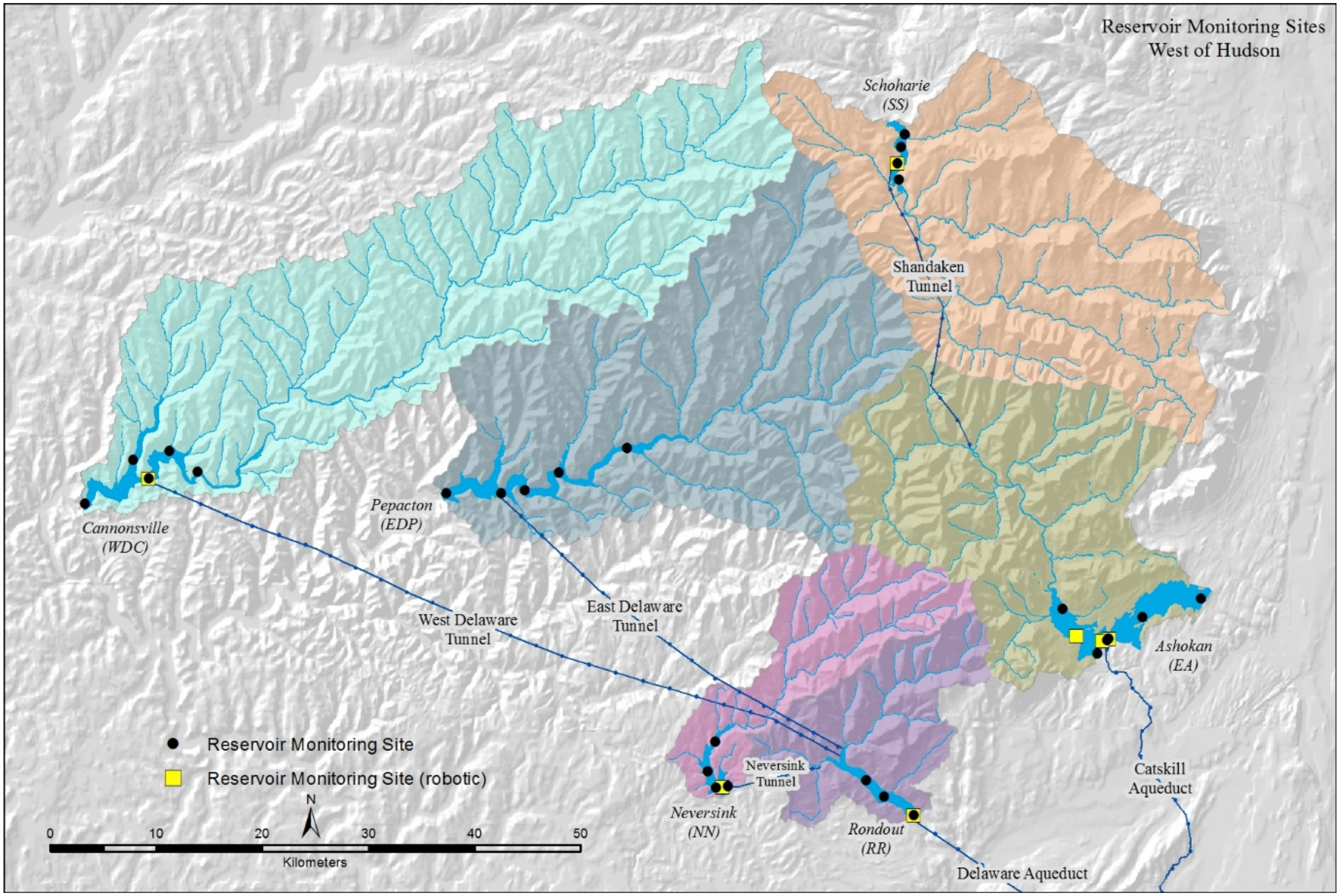
List of sites for Watershed Water Quality Operations (WWQO) Early Warning Remote Monitoring (EWRM).

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	Cat/Del Interconnect at Shaft 4 (Catskill)	Catskill	Raw	
CDIS4-CAT	Cat/Del Interconnect at Shaft 4 (Delaware)	Delaware	Raw	
CDIS4-Combined	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
DEL10	Delaware Shaft 10	Delaware	Raw	Turb, pH, Temp, SpCond, Elev

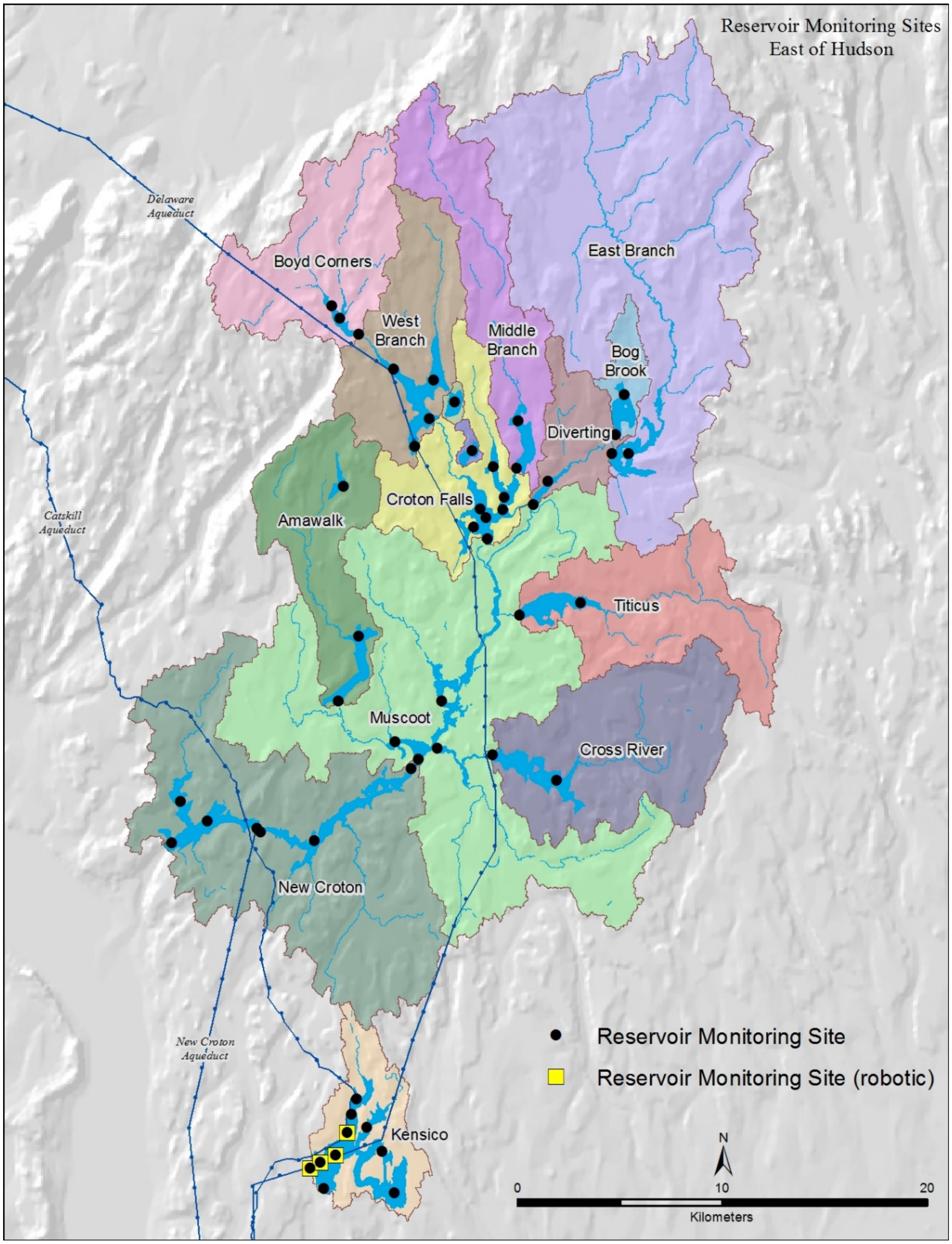
List of sites for Watershed Water Quality Operations (WWQO) Early Warning Remote Monitoring (EWRM).

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

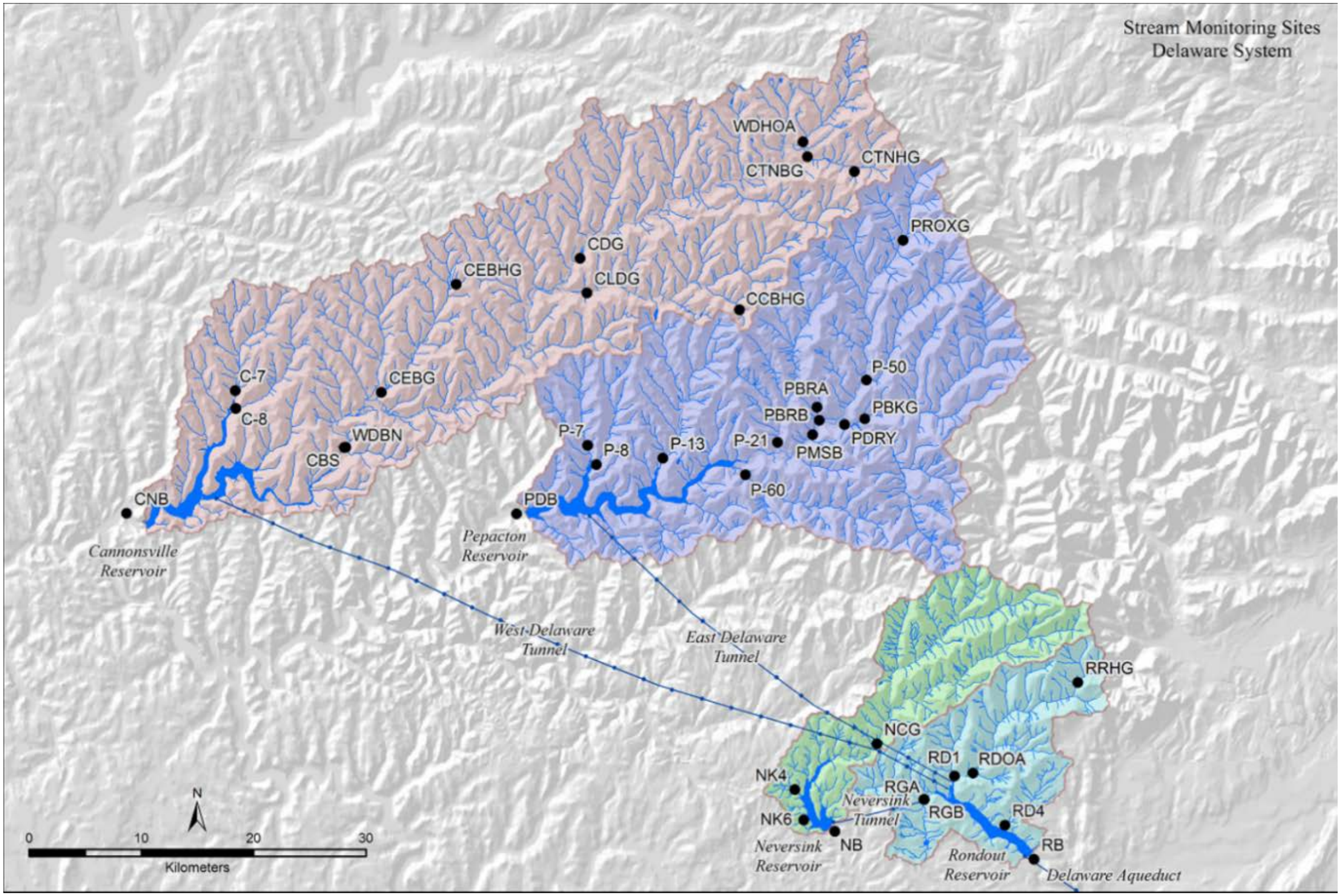
Appendix B. Sampling Locations



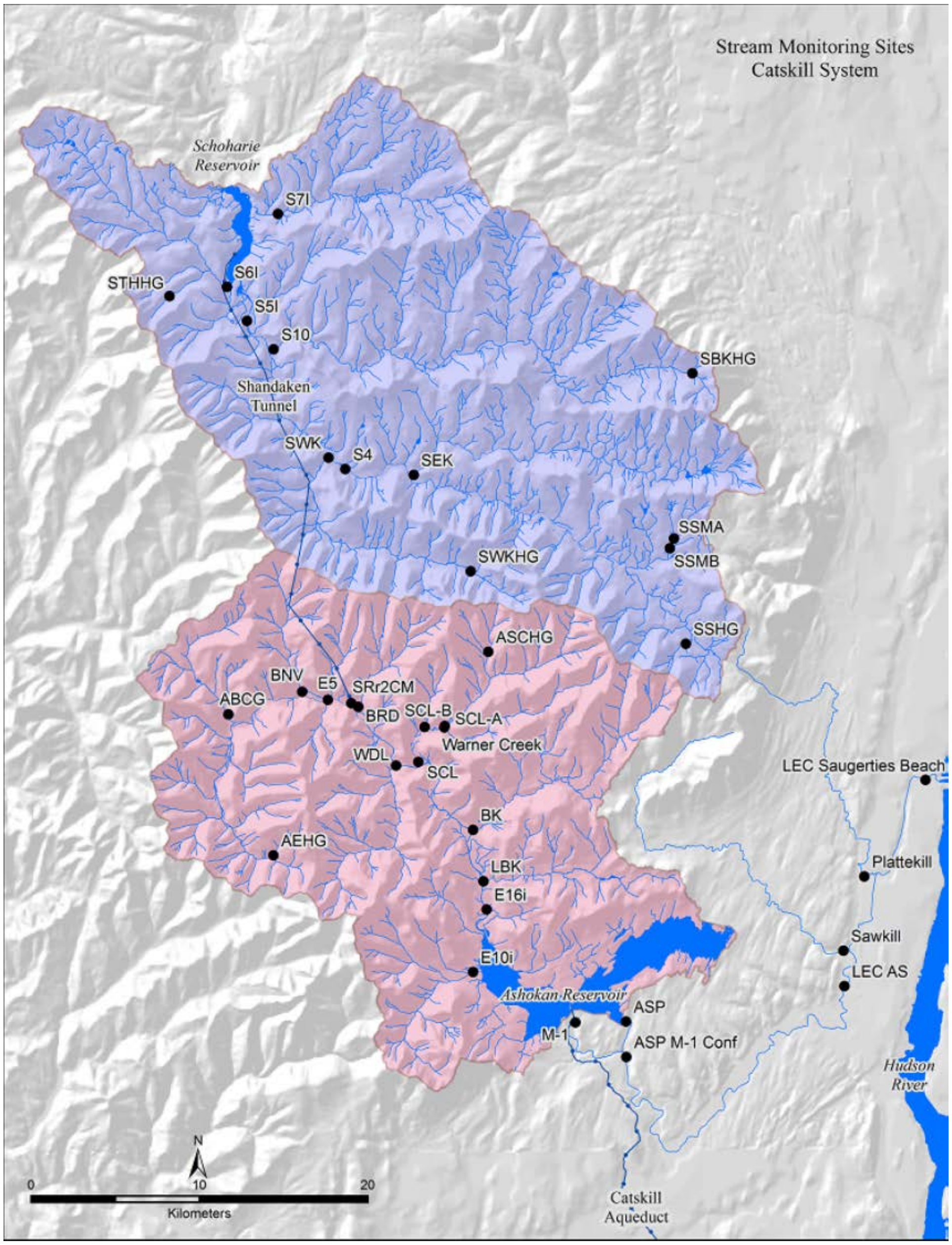
Appendix Figure 1 WOH reservoir monitoring sites [see WWQMP (DEP 2018a) for detailed maps].



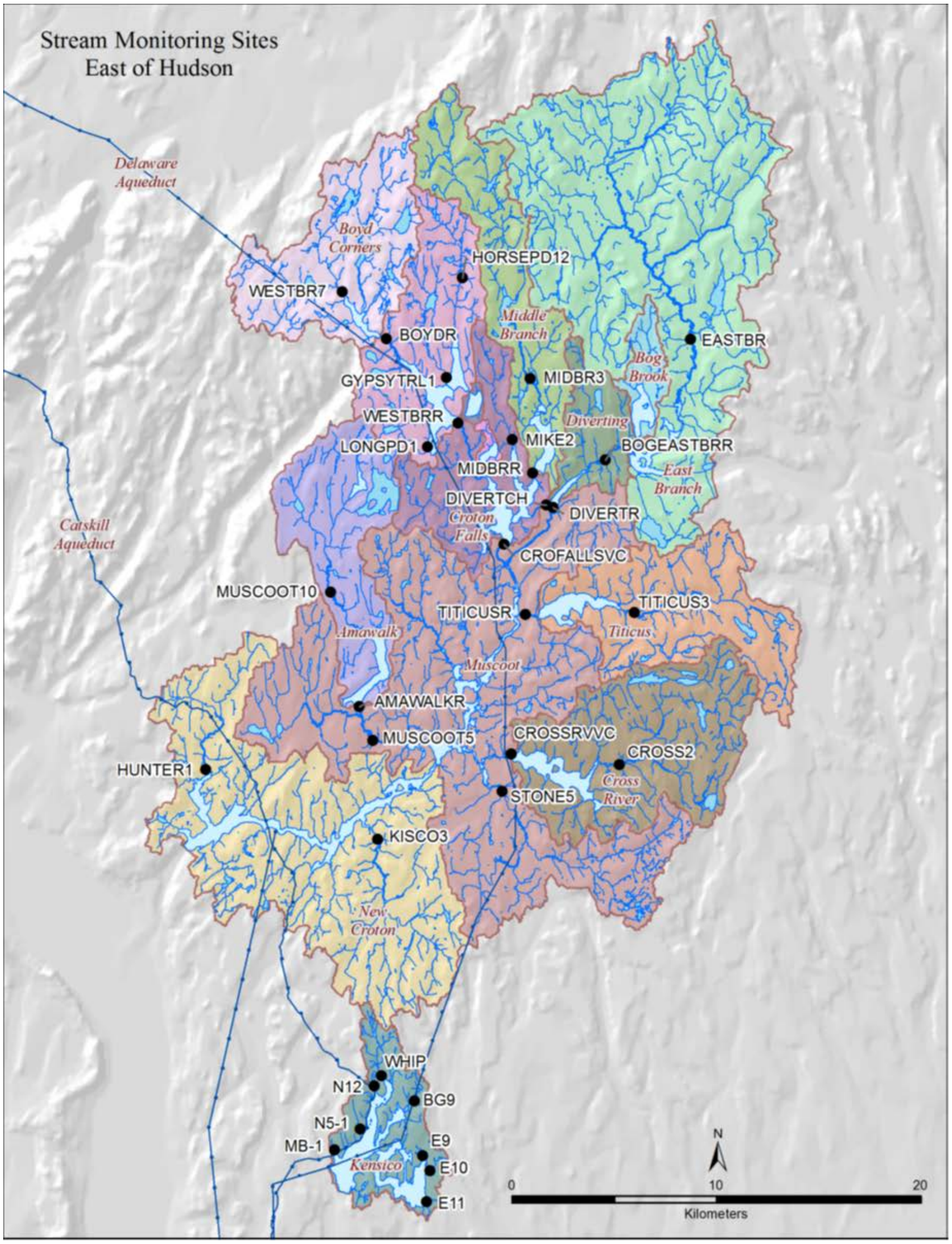
Appendix Figure 2 EOH reservoir monitoring sites [see WWQMP (DEP 2018a) for detailed maps].



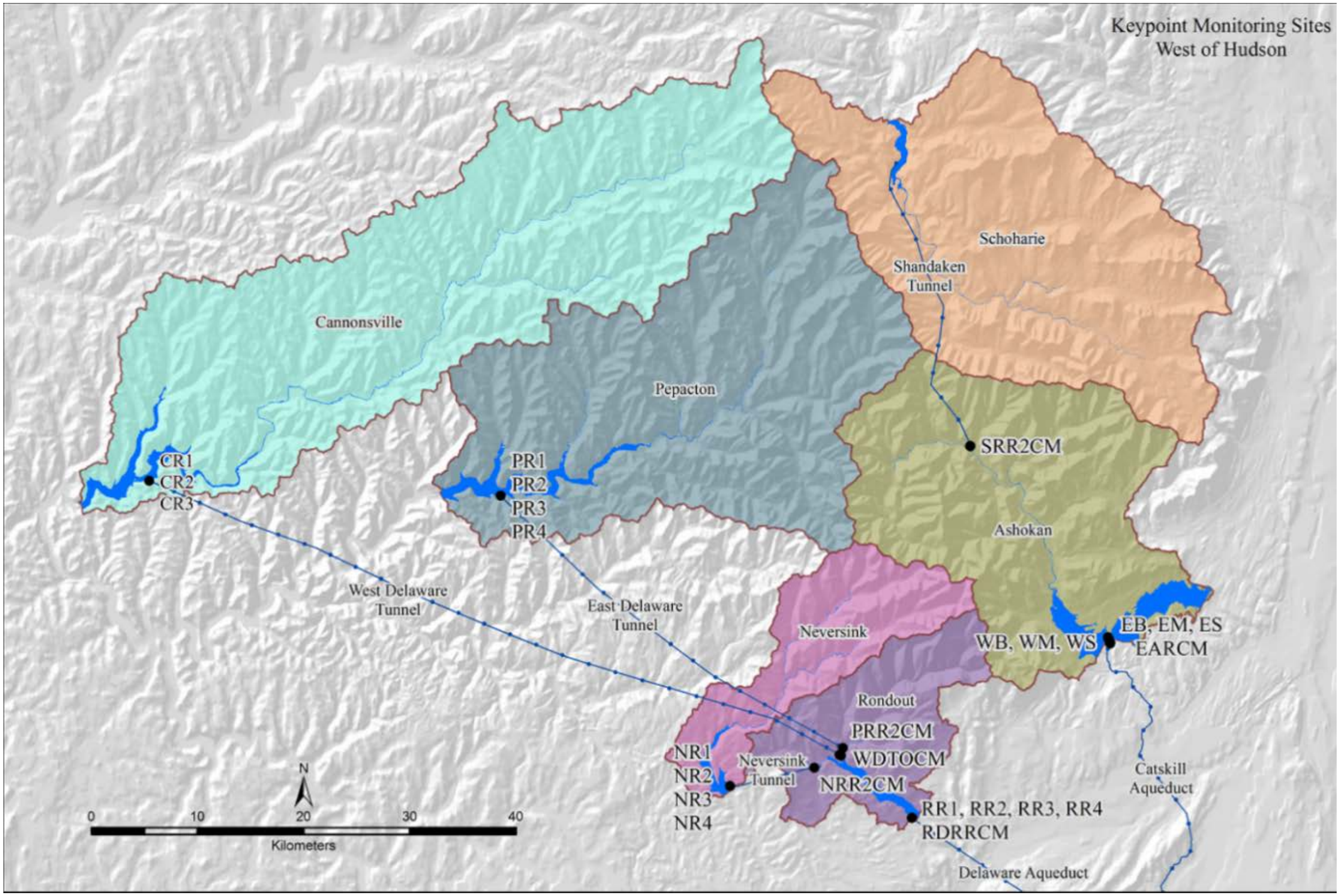
Appendix Figure 3 Delaware System stream monitoring sites [see WWQMP (DEP 2018a) for detailed maps].



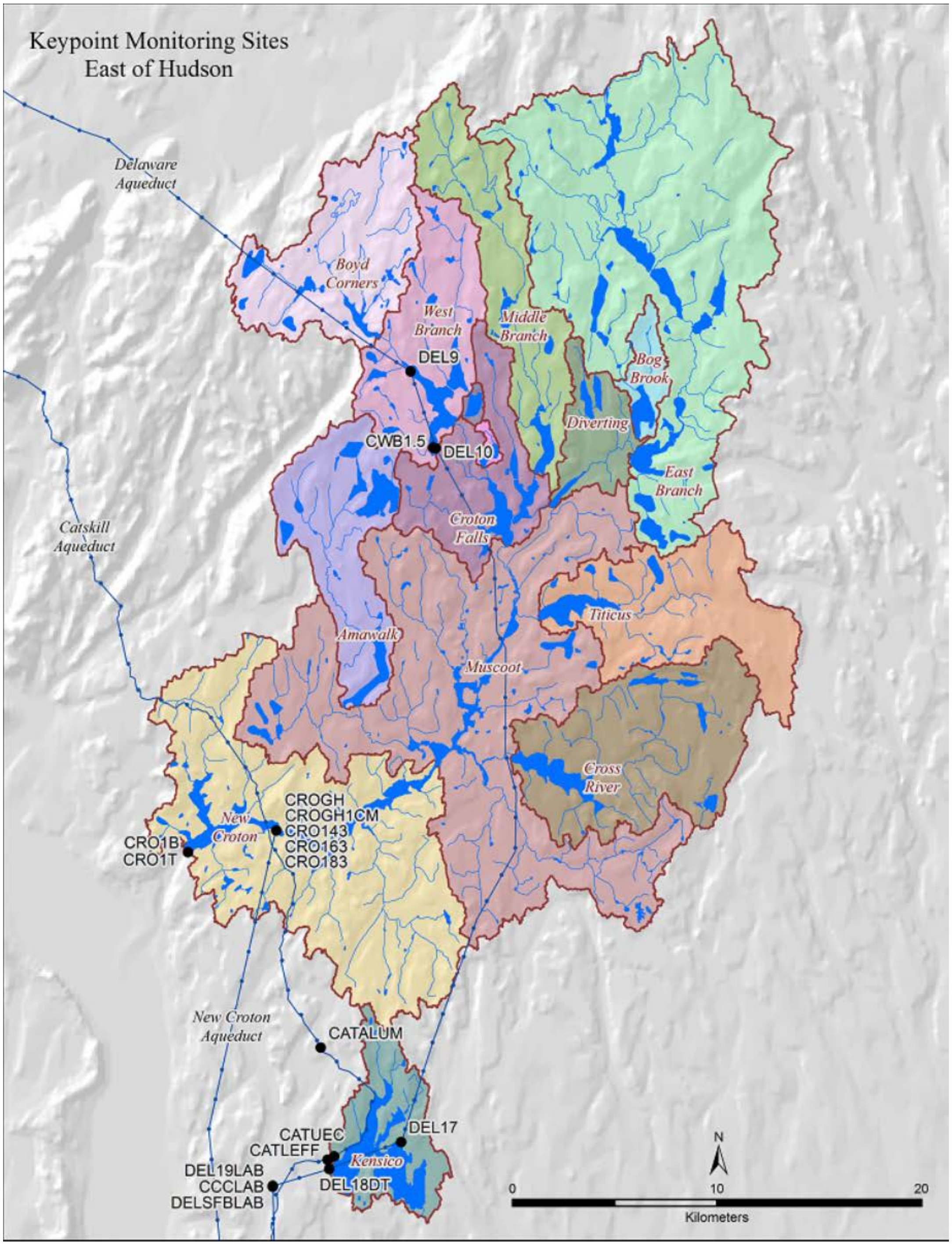
Appendix Figure 4 Catskill System stream monitoring sites [see WWQMP (DEP 2018a) for detailed maps].



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

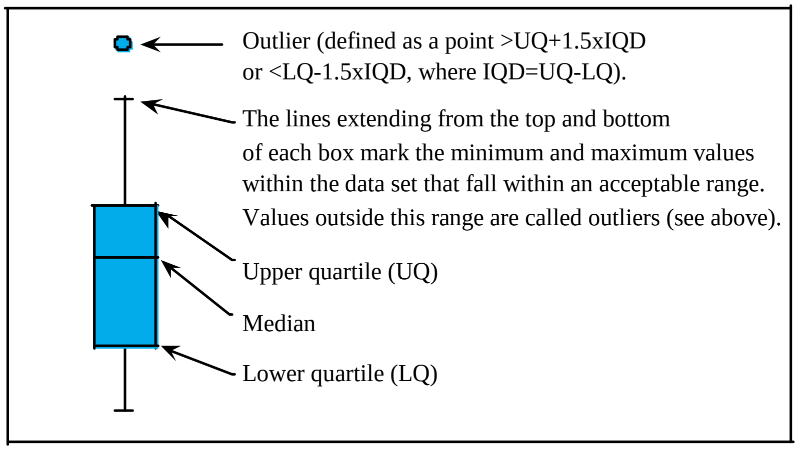


Appendix Figure 6 WOH aqueduct keypoint monitoring sites [see WWQMP (DEP 2018a) for detailed maps].



Appendix Figure 7 EOH aqueduct keypoint monitoring sites [see WWQMP (DEP 2018a) 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-18	5	E40	0
		May-18	5	E25	0
		Jun-18	5	E20	0
		Jul-18	5	E80	0
		Aug-18	5	E20	0
		Sep-18	5	E60	0
		Oct-18	5	E20	0
		Nov-18	5	E80	0
Bog Brook	AA (50, 240)	Apr-18	5	E20	0
		May-18	6	E10	0
		Jun-18	5	E110	0
		Jul-18	5	>=<20	0
		Aug-18	5	>=E100	20
		Sep-18	5	<100	20
		Oct-18	5	E550	60
		Nov-18	6	E60	0
Boyd's Corners	AA (50, 240)	Apr-18	7	E30	14
		May-18	7	E50	0
		Jun-18	7	50	43
		Jul-18	6	E50	0
		Aug-18	6	E100	33
		Sep-18	7	E200	43
		Oct-18	7	E80	29
		Nov-18	7	E60	0
Croton Falls	A/AA (50, 240)	Apr-18	8	E35	25
		May-18	8	E5	0
		Jun-18	8	>=<10	0
		Jul-18	8	E120	25
		Aug-18	8	>=E20	12
		Sep-18	8	<20	0
		Oct-18	8	E80	12
		Nov-18	8	E50	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
Cross River	A/AA (50, 240)	Apr-18	6	E15	0
		May-18	6	E5	0
		Jun-18	6	E10	0
		Jul-18	6	>=<20	0
		Aug-18	6	<100	0
		Sep-18	6	E20	0
		Oct-18	6	E30	0
		Nov-18	6	E20	0
Diverting	AA (50, 240)	Apr-18	5	>=320	80
		May-18	5	E350	60
		Jun-18	5	E3800	100
		Jul-18	5	<50	20
		Aug-18	5	E600	80
		Sep-18	5	E200	40
		Oct-18	5	E200	40
		Nov-18	5	E200	20
East Branch	AA (50, 240)	Apr-18	5	E40	0
		May-18	6	E15	0
		Jun-18	5	E70	0
		Jul-18	5	>=<20	0
		Aug-18	6	E60	17
		Sep-18	5	<100	0
		Oct-18	5	E150	0
		Nov-18	6	E200	33
Lake Gilead	A (2400, 5000)	Apr-18	5	>=<10	0
		May-18	5	<20	0
		Jun-18	5	<20	0
		Jul-18	5	<20	0
		Aug-18	5	<20	0
		Sep-18	5	>=<20	0
		Oct-18	5	E20	0
		Nov-18	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-18	5	<10	0
		May-18	5	<20	0
		Jun-18	5	E20	0
		Jul-18	5	>=E220	0
		Aug-18	5	<20	0
		Sep-18	5	>=<20	0
		Oct-18	5	E20	0
		Nov-18	5	E220	0
Muscoot	A (2400, 5000)	Apr-18	6	1900	0
		May-18	7	E55	0
		Jun-18	7	2800	29
		Jul-18	7	E100	0
		Aug-18	7	<100	0
		Sep-18	7	E400	0
		Oct-18	6	E300	0
		Nov-18	7	680	0
Middle Branch	A (2400, 5000)	Apr-18	5	>=E28	0
		May-18	5	E30	0
		Jun-18	5	>=E10	0
		Jul-18	5	E50	0
		Aug-18	5	E120	0
		Sep-18	5	E60	0
		Oct-18	5	E40	0
		Nov-18	5	E110	0
Titicus	AA (50, 240)	Apr-18	5	E40	40
		May-18	5	E20	0
		Jun-18	5	E10	0
		Jul-18	5	<10	0
		Aug-18	5	<20	0
		Sep-18	5	E20	0
		Oct-18	5	E60	0
		Nov-18	5	E80	0
Cannonsville	A/AA (50, 240)	Apr-18	15	E4	0
		May-18	15	>=E4	0
		Jun-18	15	>=E10	0
		Jul-18	15	E60	20
		Aug-18	15	E60	33
		Sep-18	15	<50	0
		Oct-18	15	>=E50	20
		Nov-18	15	E150	40

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-18	13	E6	0
		May-18	11	>=E4	0
		Jun-18	13	<10	0
		Jul-18	13	E10	15
		Aug-18	13	E40	0
		Sep-18	12	E50	0
		Oct-18	13	30	0
		Nov-18	13	E20	0
Pepacton	A/AA (50, 240)	Apr-18	16	E1	0
		May-18	16	>=<4	0
		Jun-18	16	<10	0
		Jul-18	16	E40	19
		Aug-18	16	E52	12
		Sep-18	16	E20	0
		Oct-18	16	E50	12
		Nov-18	16	E20	0
Schoharie	AA (50, 240)	Apr-18	12	>=E83	8
		May-18	12	>=E10	8
		Jun-18	12	E6	0
		Jul-18	11	>=E10	18
		Aug-18	8	>=E965	100
		Sep-18	12	>=1750	75
		Oct-18	12	E100	33
		Nov-18	9	E30	0

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 $\mu g\ L^{-1}$. The phosphorus concentration data for the reservoirs approaches a lognormal distribution; therefore a geometric mean is used to characterize the annual phosphorus concentrations. Appendix Table 1 provides the annual geometric mean for the past six years.

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

To provide some statistical assurance that the five year arithmetic mean is representative of a basin's phosphorus status, given the interannual variability, the five year mean plus the standard error of the five-year mean is compared to the NYS guidance value of 20 $\mu g\ L^{-1}$ (15 $\mu g\ L^{-1}$ for potential source waters). A basin is considered **unrestricted** if the five year mean plus standard error is below the guidance value of 20 $\mu g\ L^{-1}$ (15 $\mu g\ L^{-1}$ for potential source waters). A basin is considered phosphorus **restricted** if the five year mean plus standard error is equal to or greater than 20 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	2013 μg L^{-1}	2014 μg L^{-1}	2015 μg L^{-1}	2016 μg L^{-1}	2017 μg L^{-1}	2018 μg L^{-1}
Non-Source Waters (Delaware System)						
Cannonsville Reservoir	15.0	13.1	14.9	17.0	15.4	14.3
Pepacton Reservoir	7.9	7.8	9.0	10.8	10.3	10.1
Neversink Reservoir	6.0	6.2	6.5	8.0	7.3	6.5
Non-Source Waters (Catskill System)						
Schoharie Reservoir	15.0	15.3	11.9	12.5	12.2	14.9
Non-Source Waters (Croton System)						
Amawalk Reservoir	22.3	19.4	19.3	29.8	26.3	25.4
Bog Brook Reservoir	20.0	14.4	19.4	28.4	27.8	19.4
Boyd’s Corners Reservoir	10.7	9.0	9.0	11.3	15.1	14.0
Diverting Reservoir	29.5	29.1	25.8	37.4	31.6	28.7
East Branch Reservoir	27.5	24.2	21.3	23.5	25.1	27.5
Middle Branch Reservoir	32.5	35.3	27.4	34.1	28.4	29.4
Muscoot Reservoir	29.9	28.7	28.5	30.6	36.5	30.6
Titicus Reservoir	24.4	24.8	19.5	23.7	25.2	25.0
Lake Gleneida	22.2	19.8	35.0	27.0	25.5	21.5
Lake Gilead	26.7	32.8	27.1	34.6	33.6	32.7
Kirk Lake	24.9	32.8	30.8	27.3	23.3	20.9
Source Waters (all systems)						
Ashokan West Basin	7.3	8.1	8.8	12.6	8.2	8.3
Ashokan East Basin	6.4	7.5	7.9	10.3	8.1	7.6
Cross River Reservoir	15.4	17.6	15.7	19.0	23.2	21.1
Croton Falls Reservoir	23.0	19.9	19.4	18.0	23.2	21.5
Kensico Reservoir	6.2	5.7	7.4	7.6	8.8	7.9
New Croton Reservoir	17.0	16.0	16.8	22.1	22.5	26.2
Rondout Reservoir	7.2	6.6	7.9	10.0	9.0	8.1
West Branch Reservoir	12.6	11.2	11.3	13.4	14.2	11.8

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	2018 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	1	6	10	9.8
Color (Pt-Co units)	15	5	5	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7	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	35	4	11	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})	0.1	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	417
Total phosphorus (µg L^{-1})	15	40	39	98	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	0	0	na	na
Total suspended solids (mg L^{-1})	8	9	0	0	5	2.3
Turbidity (NTU)	5	40	3	8	na	na
Bog Brook Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	7	na	na	>40	75
Chloride (mg L^{-1})	40	7	7	100	30	76.2
Chlorophyll a (µg L^{-1})	15	8	2	25	10	8.3
Color (Pt-Co units)	15	3	3	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7	20	0	0	6	4.0
Fecal coliforms (coliform 100mL^{-1})	20	42	1	2	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	20	0	0	0.3	0.02
pH (units)	6.5-8.5	21	3	14	na	na
Sodium, undig., filt. (mg L^{-1})	20	7	7	100	15	38.4

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2018 Mean[1]
Soluble reactive phosphorus (µg L^{-1})	15	20	0	0	na	na
Sulfate (mg L^{-1})	25	7	0	0	15	9.6
Total ammonia-N (mg L^{-1})	0.1	20	1	5	0.05	0.02
Total dissolved phosphorus (µg L^{-1})	15	20	1	5	na	na
Total dissolved solids (mg L^{-1})[3]	175	20	20	100	150	277
Total phosphorus (µg L^{-1})	15	20	17	85	na	na
Total phytoplankton (ASU mL^{-1})	2000	8	0	0	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	7	0	0	5	1.8
Turbidity (NTU)	5	20	0	0	na	na
Boyd's Corners Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	7	na	na	>40	34
Chloride (mg L^{-1})	40	7	5	71	30	43.4
Chlorophyll a (µg L^{-1})	15	8	0	0	10	7.3
Color (Pt-Co units)	15	3	3	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7	21	0	0	6	4.1
Fecal coliforms (coliform 100mL^{-1})	20	54	3	6	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	21	0	0	0.3	0.05
pH (units)	6.5-8.5	19	0	0	na	na
Sodium, undig., filt. (mg L^{-1})	20	7	7	100	15	26.2
Soluble reactive phosphorus (µg L^{-1})	15	21	0	0	na	na
Sulfate (mg L^{-1})	25	7	0	0	15	6.2
Total ammonia-N (mg L^{-1})	0.1	21	0	0	0.05	0.01
Total dissolved phosphorus (µg L^{-1})	15	21	0	0	na	na
Total dissolved solids (mg L^{-1})[3]	175	21	0	0	150	154
Total phosphorus (µg L^{-1})	15	21	9	43	na	na
Total phytoplankton (ASU mL^{-1})	2000	8	0	0	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	7	0	0	5	0.9
Turbidity (NTU)	5	21	0	0	na	na
Cross River Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	49
Chloride (mg L^{-1})	40	9	9	100	30	50.8

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	2018 Mean[1]
Chlorophyll a (µg L^{-1})	15	16	4	25	10	11.3
Color (Pt-Co units)	15	6	6	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7	48	0	0	6	3.9
Fecal coliforms (coliform $100mL^{-1}$)	20	48	0	0	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	48	0	0	0.3	0.06
pH (units)	6.5-8.5	48	3	6	na	na
Sodium, undig., filt. (mg L^{-1})	20	9	9	100	15	25.2
Soluble reactive phosphorus (µg L^{-1})	15	48	0	0	na	na
Sulfate (mg L^{-1})	25	9	0	0	15	8.1
Total ammonia-N (mg L^{-1})	0.1	48	14	29	0.05	0.09
Total dissolved phosphorus (µg L^{-1})	15	48	5	10	na	na
Total dissolved solids (mg L^{-1})[3]	175	48	42	88	150	185
Total phosphorus (µg L^{-1})	15	48	39	81	na	na
Total phytoplankton (ASU mL^{-1})	2000	16	0	0	na	na
Primary genus (ASU mL^{-1})	1000	16	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	16	0	0	na	na
Total suspended solids (mg L^{-1})	8	9	0	0	5	2.3
Turbidity (NTU)	5	48	6	13	na	na
Croton Falls Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	18	na	na	>40	72
Chloride (mg L^{-1})	40	18	18	100	30	89.7
Chlorophyll a (µg L^{-1})	15	27	14	52	10	19.1
Color (Pt-Co units)	15	8	8	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7	64	0	0	6	3.8
Fecal coliforms (coliform $100mL^{-1}$)	20	64	5	8	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	64	10	16	0.3	0.26
pH (units)	6.5-8.5	68	13	19	na	na
Sodium, undig., filt. (mg L^{-1})	20	18	18	100	15	47.9
Soluble reactive phosphorus (µg L^{-1})	15	64	0	0	na	na
Sulfate (mg L^{-1})	25	18	0	0	15	10.0
Total ammonia-N (mg L^{-1})	0.1	64	7	11	0.05	0.05
Total dissolved phosphorus (µg L^{-1})	15	70	6	9	na	na
Total dissolved solids (mg L^{-1})[3]	175	64	64	100	150	337
Total phosphorus (µg L^{-1})	15	70	56	80	na	na
Total phytoplankton (ASU mL^{-1})	2000	24	3	13	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	2018 Mean[1]
Primary genus (ASU mL^{-1})	1000	24	3	13	na	na
Secondary genus (ASU mL^{-1})	1000	24	0	0	na	na
Total suspended solids (mg L^{-1})	8	8	0	0	5	2.3
Turbidity (NTU)	5	64	9	14	na	na
Diverting Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	6	na	na	>40	80
Chloride (mg L^{-1})	40	0			30	
Chlorophyll a (µg L^{-1})	15	17	8	47	10	16.4
Color (Pt-Co units)	15	5	5	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7	0			6	
Fecal coliforms (coliform 100mL^{-1})	20	40	15	38	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	0			0.3	
pH (units)	6.5-8.5	40	0	0	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})	0.1	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	276
Total phosphorus (µg L^{-1})	15	34	33	97	na	na
Total phytoplankton (ASU mL^{-1})	2000	16	2	13	na	na
Primary genus (ASU mL^{-1})	1000	16	2	13	na	na
Secondary genus (ASU mL^{-1})	1000	16	1	6	na	na
Total suspended solids (mg L^{-1})	8	6	0	0	5	3.6
Turbidity (NTU)	5	34	1	3	na	na
East Branch Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	79
Chloride (mg L^{-1})	40	9	9	100	30	55.9
Chlorophyll a (µg L^{-1})	15	8	3	38	10	16.3
Color (Pt-Co units)	15	3	3	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7	24	1	4	6	4.6
Fecal coliforms (coliform 100mL^{-1})	20	24	1	4	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	24	0	0	0.3	0.05
pH (units)	6.5-8.5	21	1	5	na	na
Sodium, undig., filt. (mg L^{-1})	20	9	9	100	15	28.9

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2018 Mean[1]
Soluble reactive phosphorus (µg L^{-1})	15	24	2	8	na	na
Sulfate (mg L^{-1})	25	9	0	0	15	8.5
Total ammonia-N (mg L^{-1})	0.1	24	5	21	0.05	0.06
Total dissolved phosphorus (µg L^{-1})	15	24	8	33	na	na
Total dissolved solids (mg L^{-1})[3]	175	24	24	100	150	248
Total phosphorus (µg L^{-1})	15	24	20	83	na	na
Total phytoplankton (ASU mL^{-1})	2000	8	0	0	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	9	0	0	5	2.1
Turbidity (NTU)	5	24	0	0	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	110.3
Chlorophyll a (µg L^{-1})	15	3	1	33	10	12.5
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})[2]	7	3	0	0	6	4.3
Fecal coliforms (coliform 100mL^{-1})	20	40	2	5	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	3	0	0	0.3	0.09
pH (units)	6.5-8.5	15	0	0	na	na
Sodium, undig., filt. (mg L^{-1})	20	3	3	100	15	55.1
Soluble reactive phosphorus (µg L^{-1})	15	3	0	0	na	na
Sulfate (mg L^{-1})	25	3	0	0	15	9.1
Total ammonia-N (mg L^{-1})	0.1	3	1	33	0.05	0.27
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	2	67	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	3	0	0	na	na
Total suspended solids (mg L^{-1})	8	3	0	0	5	4.7
Turbidity (NTU)	5	3	0	0	na	na
Lake Gilead						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	47
Chloride (mg L^{-1})	40	9	9	100	30	64.2

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	2018 Mean[1]
Chlorophyll a (µg L^{-1})	15	3	0	0	10	3.8
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})[2]	7	9	0	0	6	3.3
Fecal coliforms (coliform $100mL^{-1}$)	20	40	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	0	0	na	na
Sodium, undig., filt. (mg L^{-1})	20	9	9	100	15	33.9
Soluble reactive phosphorus (µg L^{-1})	15	9	2	22	na	na
Sulfate (mg L^{-1})	25	9	0	0	15	7.9
Total ammonia-N (mg L^{-1})	0.1	9	3	33	0.05	0.15
Total dissolved phosphorus (µg L^{-1})	15	9	3	33	na	na
Total dissolved solids (mg L^{-1})[3]	175	9	9	100	150	209
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	3	0	0	na	na
Total suspended solids (mg L^{-1})	8	9	0	0	5	1.3
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	112.3
Chlorophyll a (µg L^{-1})	15	3	0	0	10	3.5
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})[2]	7	9	0	0	6	2.8
Fecal coliforms (coliform $100mL^{-1}$)	20	40	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	60.8
Soluble reactive phosphorus (µg L^{-1})	15	9	1	11	na	na
Sulfate (mg L^{-1})	25	9	0	0	15	6.7
Total ammonia-N (mg L^{-1})	0.1	9	2	22	0.05	0.13
Total dissolved phosphorus (µg L^{-1})	15	9	2	22	na	na
Total dissolved solids (mg L^{-1})[3]	175	9	9	100	150	332
Total phosphorus (µg L^{-1})	15	9	5	56	na	na
Total phytoplankton (ASU mL^{-1})	2000	3	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	2018 Mean[1]
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	9	0	0	5	0.9
Turbidity (NTU)	5	9	0	0	na	na
Middle Branch Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>40	66
Chloride (mg L^{-1})	40	0			30	
Chlorophyll a (µg L^{-1})	15	16	2	13	10	11.3
Color (Pt-Co units)	15	5	5	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7	0			6	
Fecal coliforms (coliform 100mL^{-1})	20	40	3	8	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	0			0.3	
pH (units)	6.5-8.5	40	3	8	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})	0.1	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	358
Total phosphorus (µg L^{-1})	15	40	40	100	na	na
Total phytoplankton (ASU mL^{-1})	2000	16	0	0	na	na
Primary genus (ASU mL^{-1})	1000	16	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	16	0	0	na	na
Total suspended solids (mg L^{-1})	8	9	0	0	5	2.7
Turbidity (NTU)	5	40	1	3	na	na
Muscoot Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	6	na	na	>40	79
Chloride (mg L^{-1})	40	6	6	100	30	97.7
Chlorophyll a (µg L^{-1})	15	32	6	19	10	11.8
Color (Pt-Co units)	15	6	6	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7	54	2	4	6	4.3
Fecal coliforms (coliform 100mL^{-1})	20	54	18	33	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	54	8	15	0.3	0.27
pH (units)	6.5-8.5	54	2	4	na	na
Sodium, undig., filt. (mg L^{-1})	20	6	6	100	15	51.7

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2018 Mean[1]
Soluble reactive phosphorus ($\mu g\ L^{-1}$)	15	54	5	9	na	na
Sulfate ($mg\ L^{-1}$)	25	6	0	0	15	8.6
Total ammonia-N ($mg\ L^{-1}$)	0.1	54	8	15	0.05	0.18
Total dissolved phosphorus ($\mu g\ L^{-1}$)	15	54	11	20	na	na
Total dissolved solids ($mg\ L^{-1}$)[3]	175	54	54	100	150	310
Total phosphorus ($\mu g\ L^{-1}$)	15	54	53	98	na	na
Total phytoplankton ($ASU\ mL^{-1}$)	2000	32	4	13	na	na
Primary genus ($ASU\ mL^{-1}$)	1000	32	4	13	na	na
Secondary genus ($ASU\ mL^{-1}$)	1000	32	0	0	na	na
Total suspended solids ($mg\ L^{-1}$)	8	6	0	0	5	3.2
Turbidity (NTU)	5	54	5	9	na	na
New Croton Reservoir						
Alkalinity ($mg\ CaCO_3\ L^{-1}$)	na	30	na	na	>40	71
Chloride ($mg\ L^{-1}$)	40	30	30	100	30	89.9
Chlorophyll a ($\mu g\ L^{-1}$)	15	56	16	29	10	11.7
Color (Pt-Co units)	15	41	41	100	na	na
Dissolved organic carbon ($mg\ L^{-1}$)[2]	7	167	0	0	6	3.9
Fecal coliforms (coliform $100mL^{-1}$)	20	167	22	13	na	na
Nitrate+Nitrite-N ($mg\ L^{-1}$)	0.5	167	7	4	0.3	0.20
pH (units)	6.5-8.5	167	14	8	na	na
Sodium, undig., filt. ($mg\ L^{-1}$)	20	30	30	100	15	47.3
Soluble reactive phosphorus ($\mu g\ L^{-1}$)	15	167	14	8	na	na
Sulfate ($mg\ L^{-1}$)	25	30	0	0	15	9.8
Total ammonia-N ($mg\ L^{-1}$)	0.1	167	45	27	0.05	0.15
Total dissolved phosphorus ($\mu g\ L^{-1}$)	15	167	29	17	na	na
Total dissolved solids ($mg\ L^{-1}$)[3]	175	167	167	100	150	302
Total phosphorus ($\mu g\ L^{-1}$)	15	167	144	86	na	na
Total phytoplankton ($ASU\ mL^{-1}$)	2000	56	0	0	na	na
Primary genus ($ASU\ mL^{-1}$)	1000	56	0	0	na	na
Secondary genus ($ASU\ mL^{-1}$)	1000	56	0	0	na	na
Total suspended solids ($mg\ L^{-1}$)	8	49	0	0	5	1.7
Turbidity (NTU)	5	167	12	7	na	na
Titicus Reservoir						
Alkalinity ($mg\ CaCO_3\ L^{-1}$)	na	9	na	na	>40	73
Chloride ($mg\ L^{-1}$)	40	0			30	

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2018 Mean[1]
Chlorophyll a (µg L^{-1})	15	16	1	6	10	8.9
Color (Pt-Co units)	15	5	5	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	7	0			6	
Fecal coliforms (coliform 100mL^{-1})	20	40	1	3	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	0			0.3	
pH (units)	6.5-8.5	35	4	11	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})	0.1	0			0.05	
Total dissolved phosphorus (µg L^{-1})	15	0			na	na
Total dissolved solids (mg L^{-1})[3]	175	37	37	100	150	222
Total phosphorus (µg L^{-1})	15	37	34	92	na	na
Total phytoplankton (ASU mL^{-1})	2000	16	0	0	na	na
Primary genus (ASU mL^{-1})	1000	16	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	16	0	0	na	na
Total suspended solids (mg L^{-1})	8	9	0	0	5	2.1
Turbidity (NTU)	5	37	4	11	na	na
Catskill System						
Ashokan East Basin Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>10	13
Chloride (mg L^{-1})	12	9	0	0	8	9.5
Chlorophyll a (µg L^{-1})	12	24	0	0	7	3.1
Color (Pt-Co units)	15	8	0	0	na	na
Dissolved organic carbon (mg L^{-1})[2]	4	63	0	0	3	1.8
Fecal coliforms (coliform 100mL^{-1})	20	64	1	2	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	64	0	0	0.3	0.05
pH (units)	6.5-8.5	64	13	20	na	na
Sodium, undig., filt. (mg L^{-1})	16	9	9	100	3	5.5
Soluble reactive phosphorus (µg L^{-1})	15	64	0	0	na	na
Sulfate (mg L^{-1})	15	9	0	0	10	3.3
Total ammonia-N (mg L^{-1})	0.1	64	0	0	0.05	0.01
Total dissolved phosphorus (µg L^{-1})	15	64	0	0	na	na
Total dissolved solids (mg L^{-1})[3]	50	64	2	3	40	45
Total phosphorus (µg L^{-1})	15	63	4	6	na	na

Comparison of reservoir water quality results to benchmarks.

Reservoir/Analyte	Benchmark Single sample maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2018 Mean[1]
Total phytoplankton (ASU mL^{-1})	2000	24	0	0	na	na
Primary genus (ASU mL^{-1})	1000	24	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	24	0	0	na	na
Total suspended solids (mg L^{-1})	8	64	0	0	5	<u>1.6</u>
Turbidity (NTU)	5	64	5	8	na	na
Ashokan West Basin Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	11	na	na	>10	10
Chloride (mg L^{-1})	12	11	0	0	8	7.8
Chlorophyll a (µg L^{-1})	12	24	0	0	7	3.7
Color (Pt-Co units)	15	9	0	0	na	na
Dissolved organic carbon (mg L^{-1})[2]	4	73	0	0	3	1.8
Fecal coliforms (coliform 100mL^{-1})	20	73	6	8	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	73	0	0	0.3	<u>0.13</u>
pH (units)	6.5-8.5	73	15	21	na	na
Sodium, undig., filt. (mg L^{-1})	16	11	11	100	3	4.7
Soluble reactive phosphorus (µg L^{-1})	15	73	0	0	na	na
Sulfate (mg L^{-1})	15	11	0	0	10	3.1
Total ammonia-N (mg L^{-1})	0.1	73	0	0	0.05	<0.02
Total dissolved phosphorus (µg L^{-1})	15	73	0	0	na	na
Total dissolved solids (mg L^{-1})[3]	50	73	0	0	40	39
Total phosphorus (µg L^{-1})	15	73	5	7	na	na
Total phytoplankton (ASU mL^{-1})	2000	24	0	0	na	na
Primary genus (ASU mL^{-1})	1000	24	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	24	0	0	na	na
Total suspended solids (mg L^{-1})	8	73	2	3	5	<u>2.4</u>
Turbidity (NTU)	5	73	12	16	na	na
Schoharie Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	9	na	na	>10	14
Chloride (mg L^{-1})	12	9	0	0	8	8.3
Chlorophyll a (µg L^{-1})	12	31	0	0	7	2.5
Color (Pt-Co units)	15	12	3	25	na	na
Dissolved organic carbon (mg L^{-1})[2]	4	92	10	11	3	2.8
Fecal coliforms (coliform 100mL^{-1})	20	92	18	20	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	68	0	0	0.3	<u>0.13</u>
pH (units)	6.5-8.5	80	2	3	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	2018 Mean[1]
Sodium, undig., filt. (mg L^{-1})	16	9	9	100	3	5.6
Soluble reactive phosphorus (µg L^{-1})	15	68	0	0	na	na
Sulfate (mg L^{-1})	15	9	0	0	10	2.9
Total ammonia-N (mg L^{-1})	0.1	68	0	0	0.05	0.01
Total dissolved phosphorus (µg L^{-1})	15	68	4	6	na	na
Total dissolved solids (mg L^{-1})[3]	50	92	32	35	40	47
Total phosphorus (µg L^{-1})	15	92	48	52	na	na
Total phytoplankton (ASU mL^{-1})	2000	31	0	0	na	na
Primary genus (ASU mL^{-1})	1000	31	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	31	0	0	na	na
Total suspended solids (mg L^{-1})	8	92	28	30	5	9.4
Turbidity (NTU)	5	92	68	74	na	na
Delaware System						
Cannonsville Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	18	na	na	>10	16
Chloride (mg L^{-1})	12	18	6	33	8	11.1
Chlorophyll a (µg L^{-1})	12	40	3	8	7	7.2
Color (Pt-Co units)	15	15	15	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	4	120	0	0	3	2.0
Fecal coliforms (coliform 100mL^{-1})	20	120	10	8	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	120	6	5	0.3	0.31
pH (units)	6.5-8.5	120	14	12	na	na
Sodium, undig., filt. (mg L^{-1})	16	18	18	100	3	7.3
Soluble reactive phosphorus (µg L^{-1})	15	120	0	0	na	na
Sulfate (mg L^{-1})	15	18	0	0	10	3.9
Total ammonia-N (mg L^{-1})	0.1	120	4	3	0.05	0.02
Total dissolved phosphorus (µg L^{-1})	15	120	7	6	na	na
Total dissolved solids (mg L^{-1})[3]	50	120	119	99	40	58
Total phosphorus (µg L^{-1})	15	120	70	58	na	na
Total phytoplankton (ASU mL^{-1})	2000	41	5	12	na	na
Primary genus (ASU mL^{-1})	1000	41	5	12	na	na
Secondary genus (ASU mL^{-1})	1000	41	0	0	na	na
Total suspended solids (mg L^{-1})	8	48	0	0	5	1.8
Turbidity (NTU)	5	120	11	9	na	na
Neversink Reservoir						

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	2018 Mean[1]
Alkalinity (mg $CaCO_3$ L^{-1})	na	12	na	na	>10	3
Chloride (mg L^{-1})	12	12	0	0	8	4.1
Chlorophyll a (µg L^{-1})	12	24	0	0	7	3.6
Color (Pt-Co units)	15	0			na	na
Dissolved organic carbon (mg L^{-1})[2]	4	79	0	0	3	2.1
Fecal coliforms (coliform 100mL^{-1})	20	80	3	4	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	80	0	0	0.3	0.13
pH (units)	6.5-8.5	80	68	85	na	na
Sodium, undig., filt. (mg L^{-1})	16	12	0	0	3	2.4
Soluble reactive phosphorus (µg L^{-1})	15	80	0	0	na	na
Sulfate (mg L^{-1})	15	12	0	0	10	2.4
Total ammonia-N (mg L^{-1})	0.1	80	0	0	0.05	0.01
Total dissolved phosphorus (µg L^{-1})	15	80	1	1	na	na
Total dissolved solids (mg L^{-1})[3]	50	79	0	0	40	20
Total phosphorus (µg L^{-1})	15	80	0	0	na	na
Total phytoplankton (ASU mL^{-1})	2000	32	0	0	na	na
Primary genus (ASU mL^{-1})	1000	32	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	32	0	0	na	na
Total suspended solids (mg L^{-1})	8	24	0	0	5	0.8
Turbidity (NTU)	5	79	1	1	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	8.3
Chlorophyll a (µg L^{-1})	12	39	1	3	7	4.9
Color (Pt-Co units)	15	16	6	38	na	na
Dissolved organic carbon (mg L^{-1})[2]	4	128	7	5	3	1.9
Fecal coliforms (coliform 100mL^{-1})	20	128	8	6	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	128	0	0	0.3	0.16
pH (units)	6.5-8.5	128	3	2	na	na
Sodium, undig., filt. (mg L^{-1})	16	21	21	100	3	5.0
Soluble reactive phosphorus (µg L^{-1})	15	128	0	0	na	na
Sulfate (mg L^{-1})	15	21	0	0	10	3.2
Total ammonia-N (mg L^{-1})	0.1	127	0	0	0.05	<0.02
Total dissolved phosphorus (µg L^{-1})	15	128	1	1	na	na
Total dissolved solids (mg L^{-1})[3]	50	128	3	2	40	45

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	2018 Mean[1]
Total phosphorus (µg L^{-1})	15	128	22	17	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	64	0	0	5	0.9
Turbidity (NTU)	5	128	10	8	na	na
Rondout Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	12	na	na	>10	10
Chloride (mg L^{-1})	12	12	0	0	8	8.6
Chlorophyll a (µg L^{-1})	12	24	0	0	7	4.2
Color (Pt-Co units)	15	10	0	0	na	na
Dissolved organic carbon (mg L^{-1})[2]	4	56	0	0	3	1.9
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	7	9	na	na
Sodium, undig., filt. (mg L^{-1})	16	12	12	100	3	5.0
Soluble reactive phosphorus (µg L^{-1})	15	56	0	0	na	na
Sulfate (mg L^{-1})	15	12	0	0	10	3.3
Total ammonia-N (mg L^{-1})	0.1	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	41
Total phosphorus (µg L^{-1})	15	80	0	0	na	na
Total phytoplankton (ASU mL^{-1})	2000	24	0	0	na	na
Primary genus (ASU mL^{-1})	1000	24	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	24	0	0	na	na
Total suspended solids (mg L^{-1})	8	32	0	0	5	<1.0
Turbidity (NTU)	5	80	0	0	na	na
West Branch Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	15	na	na	>10	27
Chloride (mg L^{-1})	12	15	15	100	8	34.7
Chlorophyll a (µg L^{-1})	12	32	1	3	7	5.4
Color (Pt-Co units)	15	9	9	100	na	na
Dissolved organic carbon (mg L^{-1})[2]	4	72	1	1	3	2.7
Fecal coliforms (coliform 100mL^{-1})	20	72	6	8	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	72	0	0	0.3	0.06

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**	**2018 Mean[1]**
pH (units)	6.5-8.5	72	5	7	na	na
Sodium, undig., filt. (mg L^{-1})	16	15	15	100	3	19.2
Soluble reactive phosphorus (µg L^{-1})	15	72	1	1	na	na
Sulfate (mg L^{-1})	15	15	0	0	10	5.8
Total ammonia-N (mg L^{-1})	0.1	72	3	4	0.05	0.02
Total dissolved phosphorus (µg L^{-1})	15	72	1	1	na	na
Total dissolved solids (mg L^{-1})[3]	50	72	72	100	40	124
Total phosphorus (µg L^{-1})	15	72	13	18	na	na
Total phytoplankton (ASU mL^{-1})	2000	32	0	0	na	na
Primary genus (ASU mL^{-1})	1000	32	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	32	0	0	na	na
Total suspended solids (mg L^{-1})	8	9	0	0	5	1.6
Turbidity (NTU)	5	72	0	0	na	na
Terminal Reservoir for Catskill/Delaware System						
Kensico Reservoir						
Alkalinity (mg $CaCO_3$ L^{-1})	na	24	na	na	>10	14
Chloride (mg L^{-1})	12	24	20	83	8	14.2
Chlorophyll a (µg L^{-1})	12	64	0	0	7	3.4
Color (Pt-Co units)	15	25	1	4	na	na
Dissolved organic carbon (mg L^{-1})[2]	4	200	0	0	3	1.8
Fecal coliforms (coliform 100mL^{-1})	20	200	1	1	na	na
Nitrate+Nitrite-N (mg L^{-1})	0.5	200	0	0	0.3	0.12
pH (units)	6.5-8.5	200	11	6	na	na
Sodium, undig., filt. (mg L^{-1})	16	24	24	100	3	7.9
Soluble reactive phosphorus (µg L^{-1})	15	200	0	0	na	na
Sulfate (mg L^{-1})	15	24	0	0	10	4.2
Total ammonia-N (mg L^{-1})	0.1	200	0	0	0.05	0.02
Total dissolved phosphorus (µg L^{-1})	15	200	3	2	na	na
Total dissolved solids (mg L^{-1})[3]	50	200	140	70	40	55
Total phosphorus (µg L^{-1})	15	200	3	2	na	na
Total phytoplankton (ASU mL^{-1})	2000	64	0	0	na	na
Primary genus (ASU mL^{-1})	1000	64	0	0	na	na
Secondary genus (ASU mL^{-1})	1000	64	0	0	na	na
Total suspended solids (mg L^{-1})	8	79	0	0	5	0.9
Turbidity (NTU)	5	200	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	2018 Mean[1]

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	2018 Mean[1]
Ashokan Watershed						
E10I (Bushkill at West Shokan)						
Alkalinity (mg L^{-1})	≥10.0	12	11	92	na	6.9
Chloride (mg L^{-1})	50	12	0	0	10	3.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	0.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	<u>0.08</u>
Sulfate (mg L^{-1})	15	4	0	0	10	3.0
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	24
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.3
E16i (Esopus Brook at Coldbrook)						
Alkalinity (mg L^{-1})	≥10.0	12	5	42	na	11.7
Chloride (mg L^{-1})	50	12	0	0	10	8.2
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.7
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	<u>0.14</u>
Sulfate (mg L^{-1})	15	4	0	0	10	3.0
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	4	33	40	41
Dissolved sodium (mg L^{-1})	10	4	0	0	5	5.2
E5 (Esopus Creek at Allaben)						
Alkalinity (mg L^{-1})	≥10.0	12	6	50	na	11.7
Chloride (mg L^{-1})	50	12	0	0	10	8.7
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	<u>0.13</u>
Sulfate (mg L^{-1})	15	4	0	0	10	3.0
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	2	17	40	41
Dissolved sodium (mg L^{-1})	10	4	0	0	5	4.5

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	2018 Mean[1]
Schoharie Watershed						
S5I (Schoharie Creek at Prattsville)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	19.5
Chloride (mg L^{-1})	50	12	0	0	10	12.3
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	<ins>0.16</ins>
Sulfate (mg L^{-1})	15	4	0	0	10	3.1
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	8	67	40	60
Dissolved sodium (mg L^{-1})	10	4	1	25	5	7.1
S6I (Bear Kill at Hardenburgh Falls)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	26.9
Chloride (mg L^{-1})	50	12	0	0	10	21.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.7
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.36
Sulfate (mg L^{-1})	15	4	0	0	10	3.9
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	12	100	40	92
Dissolved sodium (mg L^{-1})	10	4	3	75	5	11.0
S7I (Manor Kill)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	24.0
Chloride (mg L^{-1})	50	12	0	0	10	10.7
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.8
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	<ins>0.09</ins>
Sulfate (mg L^{-1})	15	4	0	0	10	3.6
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	8	67	40	63
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	2018 Mean[1]
SRR2CM (Schoharie Reservoir Diversion) [3]						
Alkalinity (mg L^{-1})	≥10.0	12	2	17	na	13.5
Chloride (mg L^{-1})	50	12	0	0	10	6.4
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.14
Sulfate (mg L^{-1})	15	4	0	0	10	3.1
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	4	33	40	40
Dissolved sodium (mg L^{-1})	10	4	0	0	5	3.8
Cannonsville Watershed						
C-7 (Trout Creek above Cannonsville Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	1	8	na	16.0
Chloride (mg L^{-1})	50	12	0	0	10	13.0
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.31
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	9	75	40	61
Dissolved sodium (mg L^{-1})	10	4	0	0	5	8.0
C-8 (Loomis Brook above Cannonsville Reservoir						
Alkalinity (mg L^{-1})	≥10.0	12	2	17	na	14.6
Chloride (mg L^{-1})	50	12	0	0	10	13.0
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.4
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.29
Sulfate (mg L^{-1})	15	4	0	0	10	4.6
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	9	75	40	59
Dissolved sodium (mg L^{-1})	10	4	1	25	5	8.4

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	2018 Mean[1]
CBS (formerly WDBN, West Branch Delaware River at Beerston Bridge)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	19.4
Chloride (mg L^{-1})	50	12	0	0	10	12.6
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.50
Sulfate (mg L^{-1})	15	4	0	0	10	3.9
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	10	83	40	65
Dissolved sodium (mg L^{-1})	10	4	0	0	5	6.9
Neversink Watershed						
NCG (Neversink River near Claryville)						
Alkalinity (mg L^{-1})	≥10.0	12	12	100	na	3.6
Chloride (mg L^{-1})	50	12	0	0	10	4.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.16
Sulfate (mg L^{-1})	15	4	0	0	10	2.4
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	21
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.4
NK4 (Aden Brook above Neversink Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	11	92	na	5.8
Chloride (mg L^{-1})	50	12	0	0	10	4.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.19
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	12	0	0	40	26
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.9

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	2018 Mean[1]
NK6 (Kramer Brook above Neversink Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	8	67	na	9.9
Chloride (mg L^{-1})	50	12	2	17	10	46.6
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	3.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.39
Sulfate (mg L^{-1})	15	4	0	0	10	3.2
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<u>0.03</u>
Total dissolved solids (mg L^{-1})[2]	50	12	12	100	40	126
Dissolved sodium (mg L^{-1})	10	4	4	100	5	33.3
Pepacton Watershed						
P-13 (Tremper Kill above Pepacton Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	1	8	na	16.7
Chloride (mg L^{-1})	50	12	0	0	10	11.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.30
Sulfate (mg L^{-1})	15	4	0	0	10	3.4
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	8	67	40	59
Dissolved sodium (mg L^{-1})	10	4	0	0	5	5.7
P-21 (Platte Kill at Dunraven)						
Alkalinity (mg L^{-1})	≥10.0	12	1	8	na	18.0
Chloride (mg L^{-1})	50	12	0	0	10	10.0
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	<u>0.23</u>
Sulfate (mg L^{-1})	15	4	0	0	10	3.1
Total Ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	5	42	40	55
Dissolved sodium (mg L^{-1})	10	4	0	0	5	4.5

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	2018 Mean[1]
P-60 (Mill Brook near Dunraven)						
Alkalinity (mg L^{-1})	≥10.0	12	8	67	na	10.7
Chloride (mg L^{-1})	50	12	0	0	10	2.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.21
Sulfate (mg L^{-1})	15	4	0	0	10	3.0
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	27
Dissolved sodium (mg L^{-1})	10	4	0	0	5	1.2
P-7 (Terry Clove above Pepacton Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	3	25	na	13.9
Chloride (mg L^{-1})	50	12	0	0	10	1.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.30
Sulfate (mg L^{-1})	15	4	0	0	10	3.4
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	30
Dissolved sodium (mg L^{-1})	10	4	0	0	5	1.0
P-8 (Fall Clove above Pepacton Reservoir)						
Alkalinity (mg L^{-1})	≥10.0	12	3	25	na	13.0
Chloride (mg L^{-1})	50	12	0	0	10	2.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.4
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.38
Sulfate (mg L^{-1})	15	4	0	0	10	3.5
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	33
Dissolved sodium (mg L^{-1})	10	4	0	0	5	1.8

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	2018 Mean[1]
PMSB (East Branch Delaware River near Margaretville)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	18.6
Chloride (mg L^{-1})	50	12	0	0	10	13.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.33
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	10	83	40	64
Dissolved sodium (mg L^{-1})	10	4	0	0	5	7.2
Rondout Reservoir						
RD1 (Sugarloaf Brook near Lowes Corners)						
Alkalinity (mg L^{-1})	≥10.0	12	12	100	na	4.7
Chloride (mg L^{-1})	50	12	0	0	10	7.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.3
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.12
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	12	0	0	40	31
Dissolved sodium (mg L^{-1})	10	4	0	0	5	4.3
RD4 (Sawkill Brook near Yagerville)						
Alkalinity (mg L^{-1})	≥10.0	12	12	100	na	5.1
Chloride (mg L^{-1})	50	12	0	0	10	6.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.10
Sulfate (mg L^{-1})	15	4	0	0	10	3.6
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	31
Dissolved sodium (mg L^{-1})	10	4	0	0	5	3.7

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	2018 Mean[1]
RDOA (Rondout Creek near Lowes Corners)						
Alkalinity (mg L^{-1})	≥10.0	12	12	100	na	3.6
Chloride (mg L^{-1})	50	12	0	0	10	4.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	1.2
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.13
Sulfate (mg L^{-1})	15	4	0	0	10	2.9
Total ammonia-N (mg L^{-1})	0.25	12	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	0	0	40	21
Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.2
RGB (Chestnut Creek below Grahamsville STP)						
Alkalinity (mg L^{-1})	≥10.0	12	11	92	na	7.6
Chloride (mg L^{-1})	50	12	0	0	10	17.2
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	0.30
Sulfate (mg L^{-1})	15	4	0	0	10	3.3
Total ammonia-N (mg L^{-1})	0.25	11	0	0	0.05	<0.02
Total dissolved solids (mg L^{-1})[2]	50	12	9	75	40	59
Dissolved sodium (mg L^{-1})	10	4	2	50	5	9.4

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	2018 Mean[1]
East of Hudson						
AMAWALKR (Amawalk Reservoir Release)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	78.5
Chloride (mg L^{-1})	100	12	12	100	35	140.6
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.25
Sulfate (mg L^{-1})	25	4	0	0	15	10.2
Total ammonia-N (mg L^{-1})	0.2	12	1	8	0.1	<u>0.10</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	416
Dissolved sodium (mg L^{-1})	20	4	4	100	15	74.0
BOGEASTBRR (Combined release for Bog Brook and East Branch Reservoirs)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	82.9
Chloride (mg L^{-1})	100	12	0	0	35	63.4
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.13
Sulfate (mg L^{-1})	25	4	0	0	15	8.5
Total ammonia-N (mg L^{-1})	0.2	12	0	0	0.1	<u>0.04</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	257
Dissolved sodium (mg L^{-1})	20	4	4	100	15	31.5
BOYDR (Boyd's Corners Release)[3]						
Alkalinity (mg L^{-1})	≥40.0	12	9	75	na	35.8
Chloride (mg L^{-1})	100	12	0	0	35	45.0
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.08
Sulfate (mg L^{-1})	25	4	0	0	15	6.1
Total ammonia-N (mg L^{-1})	0.2	12	0	0	0.1	<u>0.05</u>
Total dissolved solids (mg L^{-1})[2]	175	12	0	0	150	153
Dissolved sodium (mg L^{-1})	20	4	4	100	15	25.9

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	2018 Mean[1]
CROFALLSVC (Croton Falls Reservoir Release)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	69.6
Chloride (mg L^{-1})	100	12	1	8	35	96.3
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	3.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.30
Sulfate (mg L^{-1})	25	4	0	0	15	10.9
Total ammonia-N (mg L^{-1})	0.2	12	1	8	0.1	0.10
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	311
Dissolved sodium (mg L^{-1})	20	4	4	100	15	53.1
CROSS2 (Cross River above Cross River Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	1	8	na	54.4
Chloride (mg L^{-1})	100	12	0	0	35	51.4
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	5.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.18
Sulfate (mg L^{-1})	25	4	0	0	15	7.0
Total ammonia-N (mg L^{-1})	0.2	12	0	0	0.1	<u>0.03</u>
Total dissolved solids (mg L^{-1})[2]	175	12	10	83	150	192
Dissolved sodium (mg L^{-1})	20	4	3	75	15	25.0
CROSSRVVC (Cross River Reservoir Release)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	49.5
Chloride (mg L^{-1})	100	11	0	0	35	51.4
Dissolved organic carbon (mg L^{-1})	25	11	0	0	9	3.7
Nitrate+Nitrite-N (mg L^{-1})	1.5	11	0	0	0.35	<u>0.12</u>
Sulfate (mg L^{-1})	25	4	0	0	15	8.4
Total ammonia-N (mg L^{-1})	0.2	11	2	18	0.1	0.15
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	188
Dissolved sodium (mg L^{-1})	20	4	4	100	15	25.4

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	2018 Mean[1]
DIVERTR (Diverting Reservoir Release)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	81.9
Chloride (mg L^{-1})	100	12	0	0	35	75.8
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.5
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.20
Sulfate (mg L^{-1})	25	4	0	0	15	9.4
Total ammonia-N (mg L^{-1})	0.2	12	0	0	0.1	<u>0.04</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	282
Dissolved sodium (mg L^{-1})	20	4	4	100	15	40.5
EASTBR (East Branch Croton River above East Branch River)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	91.0
Chloride (mg L^{-1})	100	12	0	0	35	56.6
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.7
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.11
Sulfate (mg L^{-1})	25	4	0	0	15	7.3
Total ammonia-N (mg L^{-1})	0.2	11	0	0	0.1	<u>0.05</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	248
Dissolved sodium (mg L^{-1})	20	4	3	75	15	25.8
GYPSYTRL1 (Gypsy Trail Brook above West Branch Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	8	67	na	32.2
Chloride (mg L^{-1})	100	12	0	0	35	33.5
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	5.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	<u>0.04</u>
Sulfate (mg L^{-1})	25	4	0	0	15	5.3
Total ammonia-N (mg L^{-1})	0.2	12	0	0	0.1	<0.02
Total dissolved solids (mg L^{-1})[2]	175	12	2	17	150	123
Dissolved sodium (mg L^{-1})	20	4	2	50	15	17.4

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	2018 Mean[1]
HORSEPD12 (Horse Pound Brook above West Branch Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	7	58	na	42.1
Chloride (mg L^{-1})	100	12	0	0	35	53.2
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.8
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.32
Sulfate (mg L^{-1})	25	4	0	0	15	7.0
Total Ammonia-N (mg L^{-1})	0.2	12	0	0	0.1	<0.02
Total dissolved solids (mg L^{-1})[2]	175	12	7	58	150	182
Dissolved sodium (mg L^{-1})	20	4	4	100	15	28.9
KISCO3 (Kisco River above New Croton Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	76.0
Chloride (mg L^{-1})	100	12	7	58	35	140.4
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.0
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.73
Sulfate (mg L^{-1})	25	4	0	0	15	12.9
Total ammonia-N (mg L^{-1})	0.2	12	0	0	0.1	0.01
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	360
Dissolved sodium (mg L^{-1})	20	4	4	100	15	50.0
LONGPD1 (Long Pond outflow above West Branch Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	1	8	na	54.2
Chloride (mg L^{-1})	100	12	2	17	35	83.1
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	5.1
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.21
Sulfate (mg L^{-1})	25	4	0	0	15	7.2
Total ammonia-N (mg L^{-1})	0.2	12	0	0	0.1	0.02
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	260
Dissolved sodium (mg L^{-1})	20	4	4	100	15	41.8

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	2018 Mean[1]
MIKE2 (Michael Brook above Croton Falls Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	84.6
Chloride (mg L^{-1})	100	12	12	100	35	172.8
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	4.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	9	75	0.35	2.49
Sulfate (mg L^{-1})	25	4	0	0	15	15.2
Total ammonia-N (mg L^{-1})	0.2	12	1	8	0.1	<u>0.06</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	493
Dissolved sodium (mg L^{-1})	20	4	4	100	15	86.1
MUSCOOT10 (Muscoot River above Amawalk Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	78.9
Chloride (mg L^{-1})	100	12	12	100	35	150.8
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	5.6
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.36
Sulfate (mg L^{-1})	25	4	0	0	15	9.2
Total ammonia-N (mg L^{-1})	0.2	12	0	0	0.1	<u>0.03</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	435
Dissolved sodium (mg L^{-1})	20	4	4	100	15	80.5
TITICUSR (Titicus Reservoir Release)						
Alkalinity (mg L^{-1})	≥40.0	12	0	0	na	76.1
Chloride (mg L^{-1})	100	12	0	0	35	56.3
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	3.9
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	0.15
Sulfate (mg L^{-1})	25	4	0	0	15	8.8
Total ammonia-N (mg L^{-1})	0.2	12	0	0	0.1	<u>0.06</u>
Total dissolved solids (mg L^{-1})[2]	175	12	12	100	150	228
Dissolved sodium (mg L^{-1})	20	4	4	100	15	26.2

Comparison of stream water quality results to benchmarks.

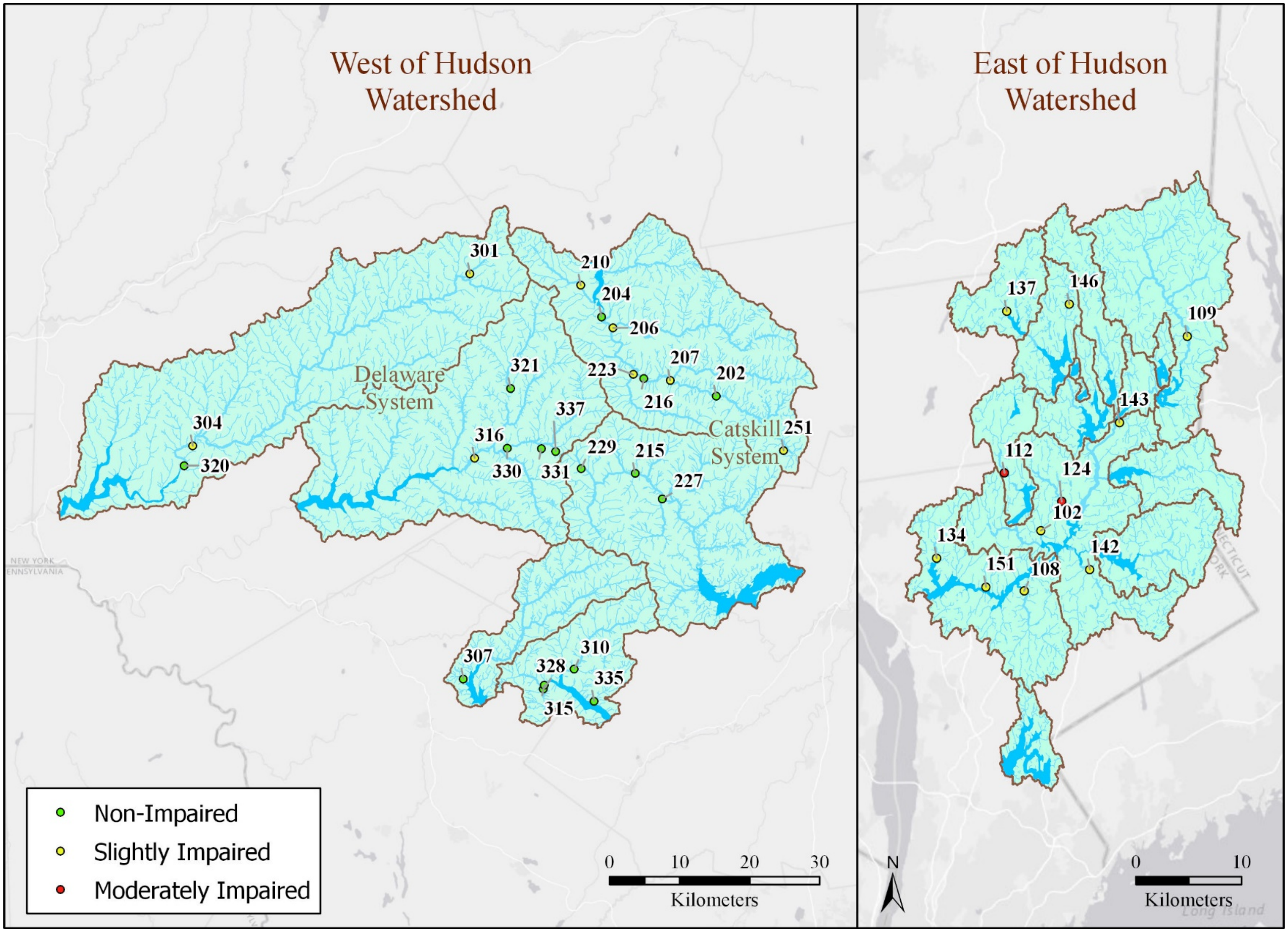
Site/Analyte	Single Sample Maximum (SSM)	Number samples	Number exceeding SSM	Percent exceeding SSM	Annual Mean Standard	2018 Mean[1]
WESTBR7 (West Branch Croton River above Boyd's Corners Reservoir)						
Alkalinity (mg L^{-1})	≥40.0	12	10	83	na	32.9
Chloride (mg L^{-1})	100	12	0	0	35	38.7
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	6.2
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.35	<u>0.04</u>
Sulfate (mg L^{-1})	25	4	0	0	15	4.6
Total ammonia-N (mg L^{-1})	0.2	12	0	0	0.1	<u>0.02</u>
Total dissolved solids (mg L^{-1})[2]	175	12	0	0	150	134
Dissolved sodium (mg L^{-1})	20	4	3	75	15	22.1
WESTBRR (West Branch Reservoir Release)						
Alkalinity (mg L^{-1})	≥10.0	12	0	0	na	27.8
Chloride (mg L^{-1})	50	12	0	0	10	32.9
Dissolved organic carbon (mg L^{-1})	25	12	0	0	9	2.8
Nitrate+Nitrite-N (mg L^{-1})	1.5	12	0	0	0.4	<u>0.07</u>
Sulfate (mg L^{-1})	15	4	0	0	10	5.5
Total ammonia-N (mg L^{-1})	0.2	12	1	8	0.05	0.07
Total dissolved solids (mg L^{-1})[2]	50	12	12	100	40	116
Dissolved sodium (mg L^{-1})	10	4	4	100	5	18.6

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).

Appendix H. Biomonitoring Sampling Sites



2018 Biomonitoring Sites and their Water Quality (WQ) Status

SYSTEM	SITE	WQ STATUS	WQ SITE	STREAM
EOH	102	Slight	ANGLE3	Angle Fly Brook
EOH	108	Slight	Kisco River 3	Kisco River
EOH	109	Slight	EASTBR	East Br. Croton R.
EOH	112	Moderate	MUSCOOT9	Muscoot River
EOH	124	Moderate	PLUM2	Plum Brook
EOH	134	Slight	HUNTER1	Hunter Brook
EOH	137	Slight	WESTBR7	West Br. Croton R.
EOH	142	Slight	STONE5	Stone Hill River
EOH	143	Slight		Holly Stream
EOH	146	Slight	HORSEPD12	Horse Pound Brook
EOH	151	Slight	SAWMILL1	Saw Mill Brook
Catskill	202	Non	S3	Schoharie Creek
Catskill	204	Non	S5I	Schoharie Creek
Catskill	206	Slight	S10	Batavia Kill
Catskill	207	Slight	SEK	East Kill
Catskill	210	Slight	S9	Bear Kill
Catskill	215	Non	E5	Esopus Creek
Catskill	216	Non	S4	Schoharie Creek
Catskill	223	Slight	SWK	West Kill
Catskill	227	Non	AEAWDL	Esopus Creek
Catskill	229	Non	BELLEGIG	Giggle Hollow
Catskill	251	Slight	SSHG	Sugarloaf Bk.
Delaware	301	Slight	WDHOA	W. Br. Delaware R.
Delaware	304	Slight	WSPB	W. Br. Delaware R.
Delaware	307	Non	NK4	Aden Brook
Delaware	310	Non	RDOA	Rondout Creek
Delaware	315	Non	RGB	Chestnut Creek
Delaware	316	Slight	PMSB	E. Br. Delaware R.
Delaware	320	Non	WDBN	W. Br. Delaware R.
Delaware	321	Non	EDRB	E. Br. Delaware R.
Delaware	328	Non	RK	Red Brook
Delaware	330	Non	PBKG	Bush Kill
Delaware	331	Non	BELLETOD	Tributary to Bush Kill
Delaware	335	Non	RD4	Sawkill Creek
Delaware	337	Non	BELLE5	Tributary to Emory Brook

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