New York City Department of Environmental Protection

2022 Watershed Water Quality Annual Report

July 2023

Environmental Protection

Rohit T. Aggarwala, Commissioner
Paul V. Rush, P.E., Deputy Commissioner
Bureau of Water Supply

Table of Contents

List of Figures

List of Tables

List of Acronyms

Acronym	Definition
abs cm^{-1}	absorbance per centimeter
ARC	Ashokan Release Channel
BAP	Biological Assessment Profile
BEPA	Bureau of Environmental Planning and Analysis
BIT	Bureau of Information Technology
BMP	Best Management Practice
BWS	Bureau of Water Supply
CATALUM	Catskill Alum Chamber Sampling Location
CATIC	Catskill Influent Chamber
CAT/DEL	Catskill/Delaware System
CATUEC	Catskill Upper Effluent Chamber
CCCLAB	Catskill Aqueduct Connection Chamber just prior to lower Catskill Aqueduct piped to a sample tap in the UV Plant Laboratory
CC-IFA	cell culture immunofluorescent assay
CDC	Center for Disease Control
CDUV	Catskill-Delaware Ultraviolet Disinfection Facility
CFR	Code of Federal Regulations
cfs	cubic feet per second
CONF	Confluent growth
CROGH	New Croton Reservoir Gatehouse; elevation 213 feet above sea level
CUNY-RF	City University of New York Research Foundation
DBP	Disinfection Byproducts
DBPFP	Disinfection Byproduct formation potential
DEL9	Delaware Aqueduct at entry to West Branch Reservoir
DEL17	Delaware Aqueduct Shaft Building 17 Sampling Location
DEL18DT	Delaware Aqueduct Shaft Building 18 Sampling Location
DEM	digital elevation model
DEP	New York City Department of Environmental Protection
DOC	Dissolved Organic Carbon
DOM	dissolved organic matter
DTO	Data and Technology Operations
DWG	Dividing Weir Gates
EARCM	Ashokan Reservoir effluent collected at Ashokan Reservoir pump house
EOH	East of Hudson
ET	evapotranspiration
EWRM	Early Warning Remote Monitoring

Acronym	Definition
FAD	Filtration Avoidance Determination
fDOM	Fluorescent Dissolved Organic Matter
GCM	Global Climate Model
GEFS	Global Ensemble Forecast System
GLEON	Global Lake Ecological Observatory Network
GSM	geosmin
GWLF	Generalized Watershed Loading Function
HAA5FP	formation potential for the sum of five haloacetic acids
HBI	Hilsenhoff Biotic Index
HEFS	Hydrologic Ensemble Forecast System
HEV	Human Enteric Virus
IAR	Inactivation Ratio
LAI	leaf area index
LT2	Long-Term 2 Enhanced Surface Water Treatment Rule
LULC	land cover land use
µg L^{-1}	microgram per liter
µmhos cm^{-1}	micromhos per centimeter
mg L^{-1}	milligram per liter
MIB	2-methylisoborneol
MOU	Memorandum of Understanding
MPN	Most Probable Number
MST	Microbial Source Tracking
NASEM	National Academies of Sciences, Engineering, and Medicine
NBI-P	Nutrient Biotic Index-Phosphorus
ND	Non-detect
nm	Nanometers
NOM	natural organic matter
NR2	Neversink Reservoir Elevation Tap 2; elevation 1350 feet above sea level
NSE	Nash-Sutcliffe efficiency statistic
NTU	Nephelometric Turbidity Units
NWS	National Weather Service
NYC	New York City
NYSDEC	New York State Department of Environmental Conservation
NYSDOH	New York State Department of Health
NYCWSS	New York City Water Supply System
OGP	Operational Guidance Plan
OST	Operational Support Tool

Acronym	Definition
PBIAS	percent bias
PCN	Pepacton, Cannonsville, Neversink
PFAS	Per- and polyfluoroalkyl substances
PFOA	Perfluorooctanoic Acid
PFOS	Perfluoroctanesulfonic acid
PMA	Percent Model Affinity
PR2	East Delaware Intake Chamber Tap 2; 1186 feet above sea level
RFP	Request for Proposals
RIBS	Rotating Integrated Basin Studies
RoboMon	Robotic Monitoring
ROS	Regression on order statistics
ROV	Remotely operated vehicle
RWBT	Rondout-West Branch Tunnel
Shaft 17	Delaware Aqueduct Shaft Building 17
Shaft 18	Delaware Aqueduct Shaft Building 18
SPDES	State Pollutant Discharge Elimination System
SRR2CM	Schoharie Reservoir Release, Shandaken tunnel outlet into Esopus Creek.
SSM	Single sample maximum
SVOC	Semivolatile Organic Compound
SWAT	Soil Water Assessment Tool
SWO	Source Water Operations
SWTR	Surface Water Treatment Rule
T&O	Taste and Odor
TDP	Total dissolved phosphorus
TDS	Total dissolved solids
THAA	Trihaloacetic acids
TMDL	Total Maximum Daily Load
TP	Total Phosphorus
TSI	Trophic State Index
TTHMFP	Total trihalomethane formation potential
TWI	Topographic wetness index
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	United States Geological Survey
UV254	Absorbance reading at 254 nm
VOC	Volatile Organic Compound
VSA	Variable Source Area

Acronym	Definition
W2	CE-QUAL-W2, a two-dimensional hydrothermal and water quality model
WISKI	Water Information Systems KISTERS
WMP	Waterfowl Management Program
WOH	West of Hudson
WPP	Watershed Protection Programs
WQI	Water Quality & Innovation Directorate
WQSP	Water Quality Science and Planning
WR&R	New York City Watershed Rules and Regulations
WRF	Water Research Foundation
WRRF	Water Resource Recovery Facility
WTO	Water Treatment Operations
WUCA	Water Utility Climate Alliance
WWQMP	Watershed Water Quality Monitoring Plan
WWQO	Watershed Water Quality Operations
WWTP	Wastewater Treatment Plant

Acknowledgements

This report provides a summary of the scientific work conducted in 2022 to manage the water quality of the New York City water supply and to provide information for regulatory agencies and the public. New York City Department of Environmental Protection (DEP) Commissioner Rohit Aggarwala provided oversight of the department throughout 2022. Paul Rush, P.E., Deputy Commissioner, and Lori Emery, MPA, Director of Water Quality & Innovation provided direction for the many activities of the Bureau of Water Supply and the Water Quality & Innovation Directorate (WQI).

Authors, contributors, and reviewers include:

James Alair
Kerri Alderisio
James Broderick
Dana Bucci
John Canning
Anita DeKoskie
Ken DeRose
Allison Dewan
Lori Emery
Jennifer Farmwald
Salome Freud
Allan Frei, CUNY
Kurt Gabel
Jennifer Garigliano
Jordan Gass
Rakesh Gelda
Theresa Kelly
Richard Kowalczyk
Alessandro Maestri
Meredith Mathewson
Adao Matonse
Lisa McDonald
Jerry Mead
Mahrokh Moknatian
Karen Moore
Rajith Mukundan
Chris Nadareski
Brian O'Malley
Christian Pace
David Quentin
Jason Railing
David Reckhow, UMass
Kristin Rendler
Michael Risinit
David Robinson
Michael Spada
Michael Usai
Rich VanDreason
Dave Van Valkenburg
Lyndsay Vlaovich
Kezhen Wang
Kyle Winslow

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

Executive Summary

Chapter 1 Introduction

This report provides summary information about the watersheds, streams, and reservoirs that are the sources of New York City's drinking water. It is an annual report that provides a detailed description of the City's water resources, their condition during 2022, and compliance with regulatory standards. It is complementary to the New York City 2022 Drinking Water Supply and Quality Report (2022 Drinking Water Supply Quality Report), which is distributed to consumers annually to provide information about the quality of the City's tap water. Thus, the two reports together document water quality from its source to the tap.

The New York City Water Supply System provides drinking water to almost half the state's population, which includes over 8.5 million people in New York City and 1 million people in upstate counties. The City's water is supplied from a network of 19 reservoirs and three controlled lakes. A summary of the number of sites, samples, and analyses that were processed in 2022 by the three upstate laboratories is provided. Grab sampling, robotic monitoring, and an early warning system are all employed. These data are used to guide system operations to provide high quality drinking water to the City.

Chapter 2 Water Quantity

In New York's Climate Division 2, which includes the West of Hudson (WOH) reservoirs, the 2022 precipitation total was 2.99 inches (76 mm) above the 20th-century mean. In New York's Climate Division 5, which includes the East of Hudson (EOH) reservoirs, precipitation was 1.83 inches (46.5 mm) above the 20th-century mean. In general, wetter than average conditions occurred in the water supply in February, April, September, and December while drier than average conditions were often observed from late spring through summer, from May-August. Usable storage of the water supply was mostly above normal through April, then fell below normal until mid-December before ending the year about 4% above normal.

Chapter 3 Water Quality

Turbidity in all monitored reservoirs was close to historic annual median levels in 2022. All WOH streams, except for those inflows in predominantly forested watersheds, exceeded their historical 75th percentiles for turbidity on at least one occasion between February and April but were mostly low during the remainder of the year due to low rainfall. Streams in EOH were occasionally above the 75th percentile of historical turbidity within three days of a rain event.

Fecal and total coliforms were generally close to historic median 75th percentile levels in most of the NYC Water Supply reservoirs and controlled lakes. Although higher coliform counts were associated with a September storm event in the Catskill/Delaware System, coliform counts remained low in the Ashokan West Basin. Mostly low coliform counts were observed in the Croton System and low rainfall likely accounts for this although elevated fecal coliform levels were observed in Middle Branch, Croton Falls, and New Croton reservoirs. All terminal reservoir basins remained "non-restricted" for coliform-restricted assessments in 2022. For non-terminal reservoir coliform-restricted evaluations based on total coliforms, seven of the 17 reservoirs evaluated had no exceedances of the total coliform standard. Routine stream samples for WOH main inflows exceeded their historical monthly ranges for fecal coliforms on several occasions in 2022 during the period from January to May. Streamflow declined through August and was accompanied by fecal coliform counts that were lower or within historical ranges. Fecal coliform results were usually lower or within historical monthly ranges in EOH streams except for increases seen after rain events in September, October, and December.

Phosphorus-restricted status for all WOH and EOH reservoirs remained the same as in the previous assessment except Bog Brook Reservoir, which shifted into the non-restricted category. When comparing total phosphorus (TP) sample results to benchmark values, annual median total phosphorous (TP) levels were slightly elevated in seven of nine Catskill/Delaware System reservoirs after rain events. In the Delaware System, Cannonsville had the greatest number of TP single sample maximum exceedances of 15 $\mu g\ L^{-1}$ (60% of all samples, all depths, and 65% of samples collected in the epilimnion at a depth of 3 m), Pepacton had fewer exceedances (14% overall with 25% in the epilimnion), and Neversink had no exceedances of the TP benchmark value. In the Catskill System, Ashokan East Basin had few exceedances (5% for all samples, with no exceedances in the epilimnion), Ashokan West Basin had 10% exceedances (all samples, with 8% in the epilimnion). In the Croton System, TP exceedances were high throughout, with the lowest number of exceedances in Boyd Corners (45%) and Lake Gleneida (44%). West Branch, with influences from the local watershed and the Delaware System, had few exceedances (19%).

Trophic state indices (TSI) are used to describe algal productivity of lakes and reservoirs. In 2022, TSI was close to historic median levels in Schoharie Reservoir, higher than historic levels at Ashokan West, but lower levels in the Ashokan East Basin. TSI levels in the Delaware System source water reservoirs were generally within their historical interquartile ranges but higher than their historical medians or were much lower (i.e., West Branch and Kensico). TSI trends varied in the Croton System. TSI was lower than historic levels at EOH FAD basins Boyd Corners, Croton Falls, and Cross River. Productivity reflected in the TSI was elevated at New Croton Reservoir in 2022, especially in the spring.

The New York State Department of Environmental Conservation (DEC) and the New York City Department of Environmental Protection (DEP) finalized a memorandum of understanding (MOU) in 1997 governing several aspects of enforcement protocols in the New York City water supply watersheds. This report includes the information needed to satisfy the MOU requirement of the Addendum E report. In 2022, 522 samples were collected at 75 sites, analyzed, and later compared to water quality guidance values. There were 14 sites at which the mean value contravened the guidance values, and there were no exceedances of the spike threshold.

DEP continued to monitor Amawalk, Muscoot, and New Croton reservoirs in 2022 for the presence of zebra mussels (*Dreissena polymorpha*) using multiplate settlement substrates. A significant advancement of the infestation was observed in Amawalk Reservoir, with most nearshore substrate colonized by several year classes of zebra mussels. Surveys of New Croton Reservoir revealed the presence of settled adults on naturally occurring substrate near the weir separating Muscoot from New Croton Reservoir, indicating successful downstream transport, as well as low densities of attached adults and low concentrations of veligers in plankton samples throughout the New Croton Reservoir. DEP is continuing to monitor this emerging infestation and a multi-directorate working group convened on a regular basis to develop management and impact mitigation plans.

Water quality assessments of watershed streams based on resident benthic macroinvertebrate assemblages continued in 2022, with samples from 36 sites in 23 streams throughout New York City’s watershed. In the Croton System, six sites ranked as slightly impaired, and five sites were moderately impaired. Among the 12 Catskill System sites assessed, four were non-impaired, seven slightly impaired, and one site was on the line between the two categories. Of the 13 Delaware System sites assessed, five were considered slightly impaired and the remainder were assessed as non-impaired.

To supplement required distribution system monitoring, DEP collects one sample at key sites throughout the upstate watersheds during the last quarter of the year to test for many volatile and semi-volatile organic compounds as well as the herbicide glyphosate. In 2022, only one compound was above its detection limit at one site but was below the detection limit in a follow-up sample. Additionally, supplemental, noncompliance sampling is conducted to determine background concentrations for a variety of metals. Most metal sample results were well below state and federal benchmarks. Antimony, arsenic, beryllium, cadmium, chromium, lead, mercury, selenium silver, and thallium were not detected at any monitored site in 2022.

Special studies were initiated when a water quality concern was raised or to better understand monitoring and management alternatives. The four investigations reported here include: a pilot study to test a concept recommended by a Water Research Foundation expert panel to study the effects of step-chlorination on disinfection byproduct formation; targeted monitoring to identify taste and odor sources; evaluation of copper sulfate treatment to mitigate algal blooms; and monitoring of emerging contaminants.

Chapter 4 Kensico Reservoir

Kensico Reservoir is the terminal reservoir for the unfiltered Catskill/Delaware water supply and routine monitoring within the watershed returned to pre-pandemic levels in 2022. Monitoring of the outflow from Kensico takes place at DEL18DT. The City's high-frequency monitoring ensures that every effort is taken at this location to meet strict requirements for turbidity and fecal coliform concentrations set forth in the federal Surface Water Treatment Rule (SWTR). The SWTR establishes a 5 NTU limit for turbidity and the requirement that no more than 10 percent of fecal coliform samples over the previous six months exceed 20 fecal coliforms 100mL^{-1}. During 2022, all DEL18DT samples met the SWTR criteria. The Waterfowl Management Program and operational decisions continued to be instrumental in keeping coliform bacteria concentrations well below the limits set by the SWTR. Turbidity curtain inspections were permanently transferred to BWS Operations staff to perform the visual observations and provide Water Quality staff with inspection reports that contain information on condition, position, and suggested maintenance that Operations staff would perform. Overall, water quality from Kensico continued to be excellent during 2022.

In addition to DEP's routine monitoring, there was one ongoing project and one special investigation conducted in the Kensico watershed: (1) Kensico Shoreline Stabilization Project and (2) September 2022 storm event. The second phase to stabilize the Kensico Reservoir shoreline near the Delaware Shaft 18 facility was completed and neither automated monitoring buoys nor routine grab sampling monitoring detected any contraventions outside of the construction zone. The September storm event measured fecal coliform and UV254 two to four orders of magnitude greater than DEL18DT and there appeared to be no influence of elevated results at DEL18DT.

Chapter 5 Pathogen Monitoring and Research

DEP collected 364 samples for protozoan analysis and 52 samples for *Cryptosporidium* infectivity testing in 2022. Of these samples, 35% were collected from Kensico and New Croton reservoir inflows and outflows, 23% from EOH streams, and 30% from the outflows of the Catskill-Delaware Ultraviolet Disinfection Facility and Hillview Reservoir. Additional samples were collected for special investigations at upstate reservoir streams, effluents, and water resource recovery facilities (WRRFs) and wastewater treatment plants (WWTPs) as needed (12% of samples collected).

For the two-year period from January 1, 2021, to December 31, 2022, DEP Catskill/Delaware source water results continued to be below the Long Term 2 Enhanced Surface Water Treatment Rule (LT2) *Cryptosporidium* threshold for additional treatment (0.010 oocysts L^{-1}). The calculation for 2021-2022 resulted in a mean of 0.0015 oocysts L^{-1} at the Delaware outflow – which is comparable to the LT2 means of the past few years.

Based on historical data, protozoan concentrations leaving the upstate reservoirs and Kensico Reservoir were generally lower than levels at the stream sites that feed these reservoirs, noting that fewer stream samples were collected in 2022, when compared to 2021 and prior. As per the Hillview Consent Decree and Judgment, DEP continued weekly protozoan monitoring at the Hillview Reservoir outflow (Site 3) through 2022, with 52 routine samples collected. Of the 52 samples, 12 were positive for *Giardia,* representing four less detections than 2021. Three samples were positive for *Cryptosporidium* (one less than in 2021). All 52 Hillview samples tested for infectious *Cryptosporidium* by cell-culture immunofluorescent assay were negative.

Chapter 6 Water Quality Modeling

DEP's Water Quality Modeling Program uses models to quantify the impact of climate change, changes in land use, individual and grouped components of the watershed protection program, operation of the water supply system, and water demand on the quantity and quality of water delivered to the City.

In 2022, DEP developed an aggregated index to describe the degree of extreme conditions for a given year relative to the reference period of 1970-2000. The index combined several extreme climate indicators. DEP also developed a bias correction method for multi-year precipitation extremes. Such a correction was necessary because of the underestimation of the magnitudes of multi-year precipitation extremes by GCMs, resulting in an inaccurate estimation of the magnitudes of extremes in future scenarios. In 2022, DEP initiated a SWAT model application to develop dissolved organic carbon (DOC) simulation capability in streams of WOH watersheds. Initial testing of the SWAT-Carbon (C) model was done for the Neversink watershed. DEP also started SWAT model setups for the five EOH watersheds – Amawalk, Boyd Corners, Cross River, Titicus, and East Branch, which have natural inflow.

DEP also completed the development and testing of a turbidity model for West Branch Reservoir. During 2022, DEP proposed and validated a two-component, simple statistical approach to predict the formation potentials of the sum of five haloacetic acids (HAA5FP) and total trihalomethanes (TTHMFP) in inflows to Cannonsville and Neversink reservoirs using environmental variables (streamflow, total phosphorus, and soil temperature) and UV254 as a surrogate for DBP precursors. DEP also began testing of a two-dimensional hydrothermal and water quality model CE-QUAL-W2 (W2) for predicting UV254 in Cannonsville and Neversink reservoirs.

DEP performed 615 OST simulations, supporting daily reservoir operations as well as long-term planning activities in 2022. We continued enhancing OST so that it better reflected current system rules, infrastructure status, and provided guidance for various infrastructure outage applications, e.g., the planned 2023 Rondout-West Branch Tunnel outage. The modeling group also published one paper and presented seven papers at conferences during 2022.

Chapter 7 Further Research

BWS remains at the forefront of the industry through a complimentary array of programs including research undertaken within the bureau, participation in the Water Research Foundation (WRF), and interactions with national and international groups and universities such as the Water Utility Climate Alliance (WUCA), the Global Lake Ecological Observation Network (GLEON), the Cary Institute of Ecosystem Studies, Cardiff University in Wales, and Virginia Tech. In 2022, internal research initiatives included data modernization, an enhanced treatment working group, a salinity task force, and a monthly training for R statistical software to conduct statistical analysis and perform data visualizations. In 2022, research efforts on taste and odor included an international partnership with Cardiff University and an expert panel workshop hosted by WRF.

Emerging and ongoing research is disseminated throughout the bureau in several ways. BWS developed and maintains the research inventory, a repository of all proposed, active, and completed research, with the assistance of the Research Advisory Council (RAC). In addition, BWS holds an annual internal conference, inviting staff to present on critical research underway within the bureau. In 2022, the conference theme was “Adaptation: What Comes Next?” with more than 140 BWS staff participating in the virtual conference. In addition to the annual conference, BWS also highlights ongoing research or related activities with monthly “Thirsty Thursday” webinars. In 2022, 438 staff participated in five webinars.

1. Introduction

1.1 Water Quality Monitoring in the Watershed

This report provides information on 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 2022, and compliance with regulatory standards. It also provides an overview of operations and the use of field, laboratory, robotic, and continuous water quality monitoring data and models for the management of the water supply. This summary is complementary to the New York City 2022 Drinking Water Supply and Quality Report (available at: [2022-drinking-water-supply-quality-report.pdf (nyc.gov))](2022-drinking-water-supply-quality-report.pdf), which is distributed to consumers annually to provide information about the quality of the City's tap water. These two reports together document water quality from its source to the tap.

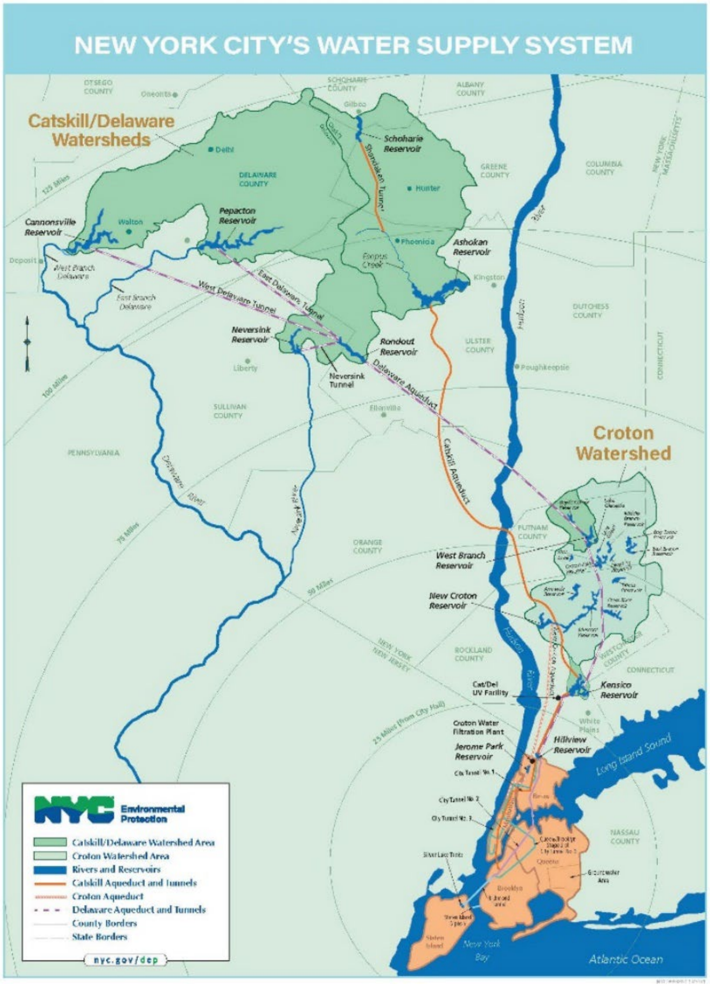


Figure 1.1 New York City Water Supply System.

The New York City Water Supply System (Figure 1.1) provides drinking water to almost half the state's population, which includes over 8.5 million people in New York City and 1 million people in upstate counties, plus millions of commuters and tourists. New York City's Catskill/Delaware (CAT/DEL) 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. The total watershed area for the system is approximately 5,100 square kilometers (1,972 square miles), extending over 200 kilometers (125 miles) north and west of New York City. This resource is essential for the health and well-being of millions and must be monitored, managed, and protected for the future. The mission of the Bureau of Water Supply (BWS) is to deliver a reliable and sufficient quantity of high-quality drinking water to protect public health and the quality of life for the City of New York. To gather and process the information needed to meet these goals, there is an ongoing program of water quality monitoring and modeling. Monitoring of the watershed is accomplished by the Directorate of Water Quality & Innovation's (WQI) Division of Watershed Water Quality Operations based primarily at three upstate New York locations: Grahamsville, Kingston, and Hawthorne. Much of the information generated by field, laboratory, automated monitoring, and data analysis activities is presented here to provide an overview of watershed water quality in 2022, and to show how high-quality source water is reliably maintained through constant vigilance and operational changes. In addition to the work of WQI, DEP supplements its capabilities through contracts and interactions with other organizations (see Chapter 7 Innovation and Research).

1.1.1 Grab Sample Monitoring

Water quality of the reservoirs, streams, and aqueduct keypoints is monitored throughout the watershed to meet several objectives including regulatory compliance, water supply operations, and to demonstrate the effectiveness of watershed protection measures. The Watershed Water Quality Monitoring Plan (WWQMP; DEP 2018) is DEP's comprehensive plan that describes the water quality monitoring conducted throughout the watershed. The sampling effort is continuously evaluated and tailored to meet specific DEP objectives. In 2022, DEP collected 11,600 samples from 365 watershed locations and performed over 206,100 analyses to support various water quality objectives.

1.1.2 Robotic Monitoring (RoboMon) Network

DEP's Robotic Monitoring (RoboMon) network provides high frequency, near real-time data that are essential for guiding water supply operations and supporting water quality modeling. The data are of particular importance when water quality conditions are changing rapidly and operational responses may be required. In addition to water quality surveillance, these data are used to run the Operations Support Tool (OST), and reservoir and watershed models. The data generated by the RoboMon network have proven to be invaluable for the protection of the water supply during storm events, water quality special investigations, and the construction phase of water supply infrastructure projects that can potentially affect water quality. In 2022, over 2.7 million measurements were recorded from 31 sites (22 buoys and 9 stream sites). These automated water quality monitoring systems have become critical in managing the day-to-day operation of the water supply as we strive to reliably deliver the highest quality drinking water. The sites and associated parameters are included in Appendix A.

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

Changes in the robotic monitoring program during 2022 coincided with the conclusion of the Kensico shoreline stabilization project.

1.1.3 Early Warning Remote Monitoring

The Early Warning Remote Monitoring (EWRM) team continued to operate a network of real-time, continuous, water quality monitoring stations at critical aqueduct monitoring locations. Instrumentation and sensors vary by site and are outlined in Appendix B. The data generated by this program are critical for water supply operations, for fluoride residual monitoring, State Pollutant Discharge Elimination System (SPDES) monitoring, and for regulatory compliance including calculation of the inactivation ratios (IAR) for pathogens and viruses. Data from reservoir effluent chambers and gatehouses are also critical for making decisions about diversions, releases, and treatment operations. In addition to the instrumentation and parameters listed in Appendix B, the ToxProtect 64 fish biomonitoring systems were operated at DEL18DT and CROGH sites in 2022 to provide rapid detection of contaminants that may not be detected by standard instrumentation. Neither site produced a water quality alarm signal in 2022.

In 2022, work on the new alum treatment facility at Pleasantville, NY (CATALUM) entered the final construction phase. Plumbing and electrical work were completed to prepare to install continuous monitoring sensors to measure turbidity, dissolved oxygen, pH, chlorine dioxide, and total chlorine residual as shown in Figure 1.2. Testing and final calibration will be done once the new facility has been completed, which is expected in 2023.

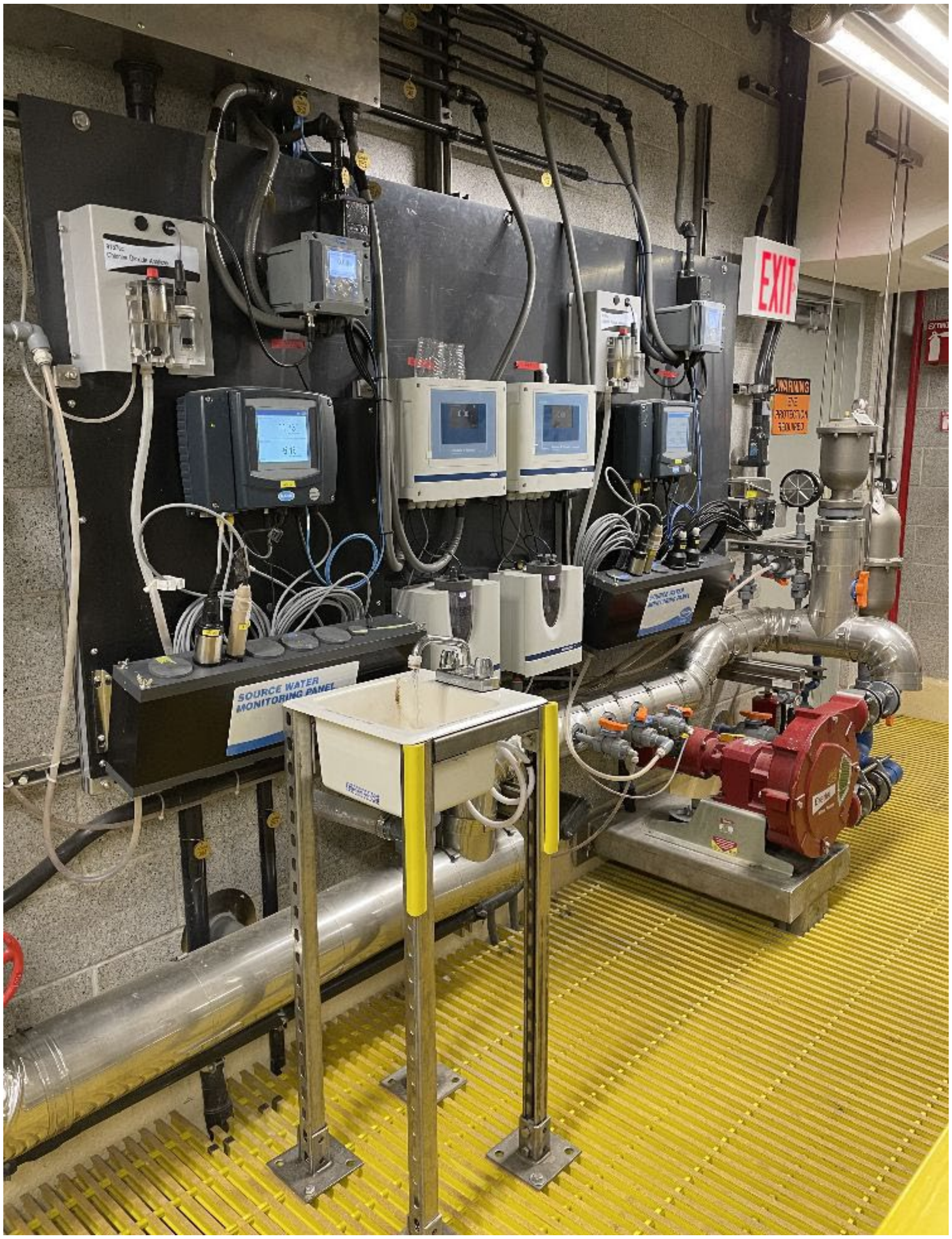
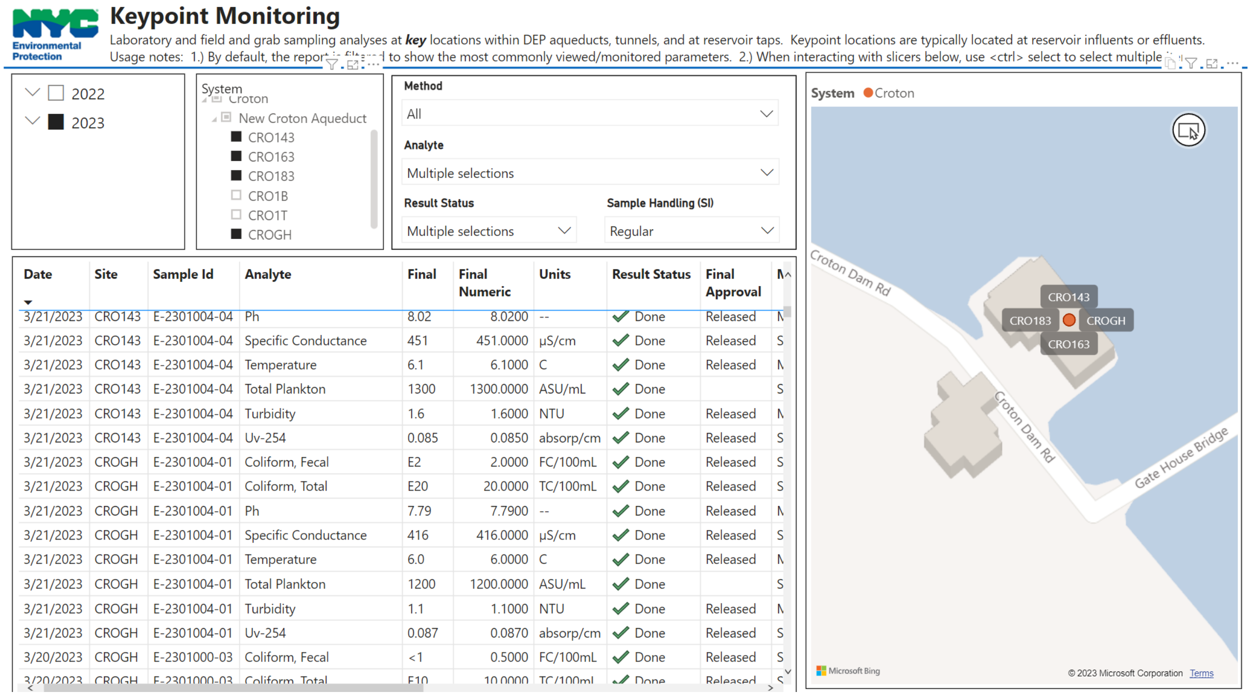


Figure 1.2 Continuous Monitoring Panel at CATALUM.

1.2 Tools for Optimizing Water Quality

1.2.1 Bureau of Water Supply Operational Reporting and Dashboards

WQI Data and Technology Operations (DTO) staff have continued a collaborative effort with DEP's Bureau of Information Technology (BIT), BWS Source Water Operations (SWO), and BWS Water Treatment Operations (WTO) to develop a modern cloud-based data warehouse to support consolidation of a variety of data-driven dashboards and reports using Microsoft's enterprise business intelligence package called Power BI. Examples from the Power BI dashboard are provided in Figure 1.3 and Figure 1.4. The goal of the project is to develop a shared data repository that will allow data users easier access to reporting data as well as streamline integration activities between water quality and operations data. During 2022, significant steps were undertaken to successfully integrate watershed laboratory sample results, robotic monitoring data, reservoir operations data, and remaining work related to Early Warning and Remote Monitoring data. Late in 2022, WQI staff began planning and design work to include distribution laboratory data as well as kicking off discussions to add machine learning based anomaly detection to time series trends.



Keypoint Monitoring

Laboratory and field and grab sampling analyses at ***key*** locations within DEP aqueducts, tunnels, and at reservoir taps. Keypoint locations are typically located at reservoir influents or effluents.
Usage notes: 1.) By default, the report is filtered to show the most commonly viewed/monitored parameters. 2.) When interacting with slicers below, use <ctrl> select to select multiple

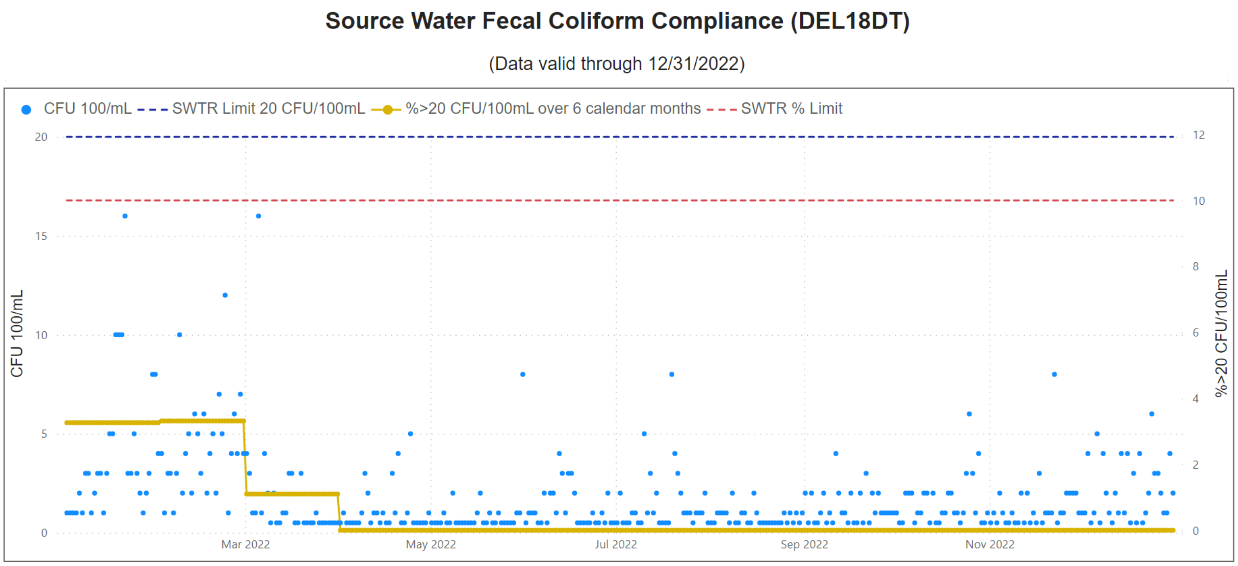
☐ 2022
■ 2023

System
Croton
New Croton Aqueduct
■ CRO143
■ CRO163
■ CRO183
☐ CRO1B
☐ CRO1T
■ CROGH

Method: All
Analyte: Multiple selections
Result Status: Multiple selections
Sample Handling (SI): Regular

Date	Site	Sample Id	Analyte	Final	Final Numeric	Units	Result Status	Final Approval	M
3/21/2023	CRO143	E-2301004-04	Ph	8.02	8.0200	--	✓ Done	Released	M
3/21/2023	CRO143	E-2301004-04	Specific Conductance	451	451.0000	µS/cm	✓ Done	Released	S
3/21/2023	CRO143	E-2301004-04	Temperature	6.1	6.1000	C	✓ Done	Released	M
3/21/2023	CRO143	E-2301004-04	Total Plankton	1300	1300.0000	ASU/mL	✓ Done		S
3/21/2023	CRO143	E-2301004-04	Turbidity	1.6	1.6000	NTU	✓ Done	Released	M
3/21/2023	CRO143	E-2301004-04	Uv-254	0.085	0.0850	absorp/cm	✓ Done	Released	S
3/21/2023	CROGH	E-2301004-01	Coliform, Fecal	E2	2.0000	FC/100mL	✓ Done	Released	S
3/21/2023	CROGH	E-2301004-01	Coliform, Total	E20	20.0000	TC/100mL	✓ Done	Released	S
3/21/2023	CROGH	E-2301004-01	Ph	7.79	7.7900	--	✓ Done	Released	M
3/21/2023	CROGH	E-2301004-01	Specific Conductance	416	416.0000	µS/cm	✓ Done	Released	S
3/21/2023	CROGH	E-2301004-01	Temperature	6.0	6.0000	C	✓ Done	Released	M
3/21/2023	CROGH	E-2301004-01	Total Plankton	1200	1200.0000	ASU/mL	✓ Done		S
3/21/2023	CROGH	E-2301004-01	Turbidity	1.1	1.1000	NTU	✓ Done	Released	M
3/21/2023	CROGH	E-2301004-01	Uv-254	0.087	0.0870	absorp/cm	✓ Done	Released	S
3/20/2023	CROGH	E-2301000-03	Coliform, Fecal	<1	0.5000	FC/100mL	✓ Done	Released	S
3/20/2023	CROGH	E-2301000-03	Coliform, Total	E10	10.0000	TC/100mL	✓ Done	Released	S

Figure 1.3 Laboratory keypoint monitoring report allows user to interactively find and locate data.


Source Water Fecal Coliform Compliance (DEL18DT)

(Data valid through 12/31/2022)

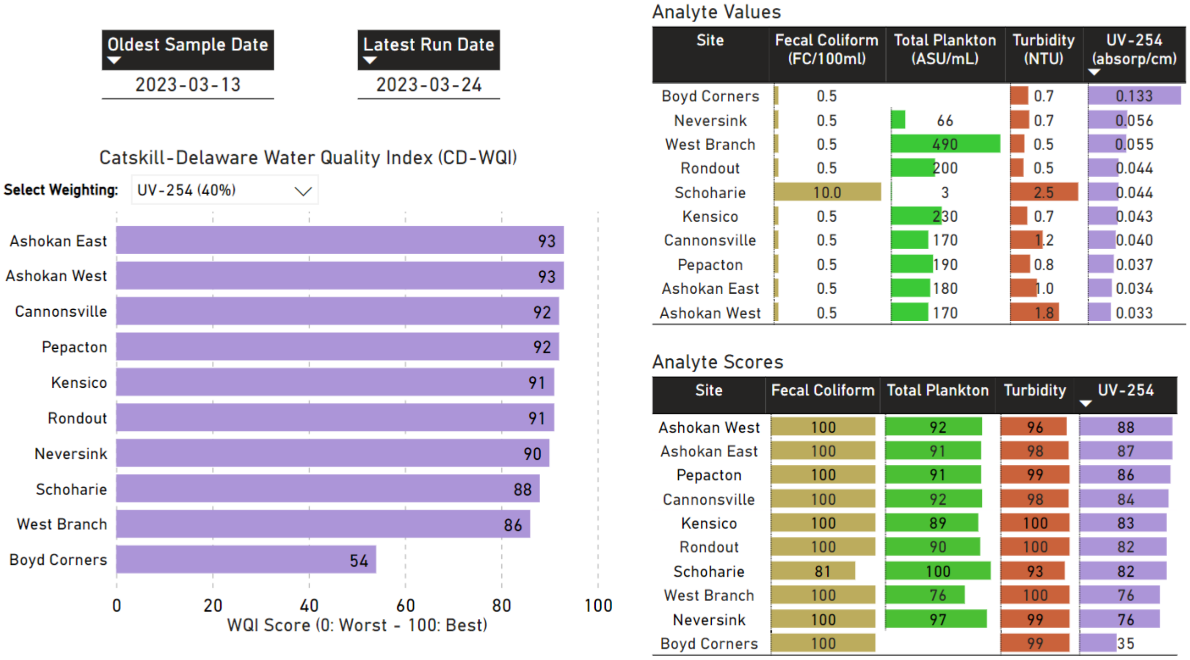
Figure 1.4 Surface Water Treatment Rule Fecal Coliform Monitoring report.

WQI staff will be expanding the storage period for data contained within the data warehouse to include the period of record for each of the WQI related datasets within the single database location. The combination of period of record and up to date current data in a single repository will continue to improve BWS's ability to react to changing water supply issues efficiently and rapidly. Additionally, having a robust data warehouse will allow for BWS scientists and modelers to have self-service access to expansive datasets.

1.2.2 Water Quality Index

In 2022, WQI, Water Treatment Operations (WTO), and Source Water Operations (SWO) staff continued to utilize the Water Quality Index to assist in routine operations to deliver the best quality water to Kensico Reservoir. The Water Quality Index underwent a significant upgrade that included moving the stored data to a server location, harmonizing the scoring of the CAT/DEL System index with a newly developed New Croton System index, and changing the reporting mechanism to Microsoft Power BI to make both indices more readily available and updated more frequently (daily vs weekly).

The CAT/DEL Water Quality Index uses the most recent laboratory grab sample data available for turbidity, fecal coliform, UV254, and phytoplankton to calculate an index score for each of the nine reservoirs in the Catskill and Delaware systems. The reservoirs are then ranked in a report according to their index scores. Under default conditions, the four parameters are equally weighted by the calculation to determine the final index score. During 2022, however, UV254 weighting was adjusted to 40 percent by WQI management to closely track disinfection byproduct formation potential. End users also have the option to view different weighting, if desired, via selection in the new report format. An example of Power BI output for the CAT/DEL Water Quality Index is provided in Figure 1.5.



Oldest Sample Date: 2023-03-13

Latest Run Date: 2023-03-24

Select Weighting: UV-254 (40%)

Analyte Values

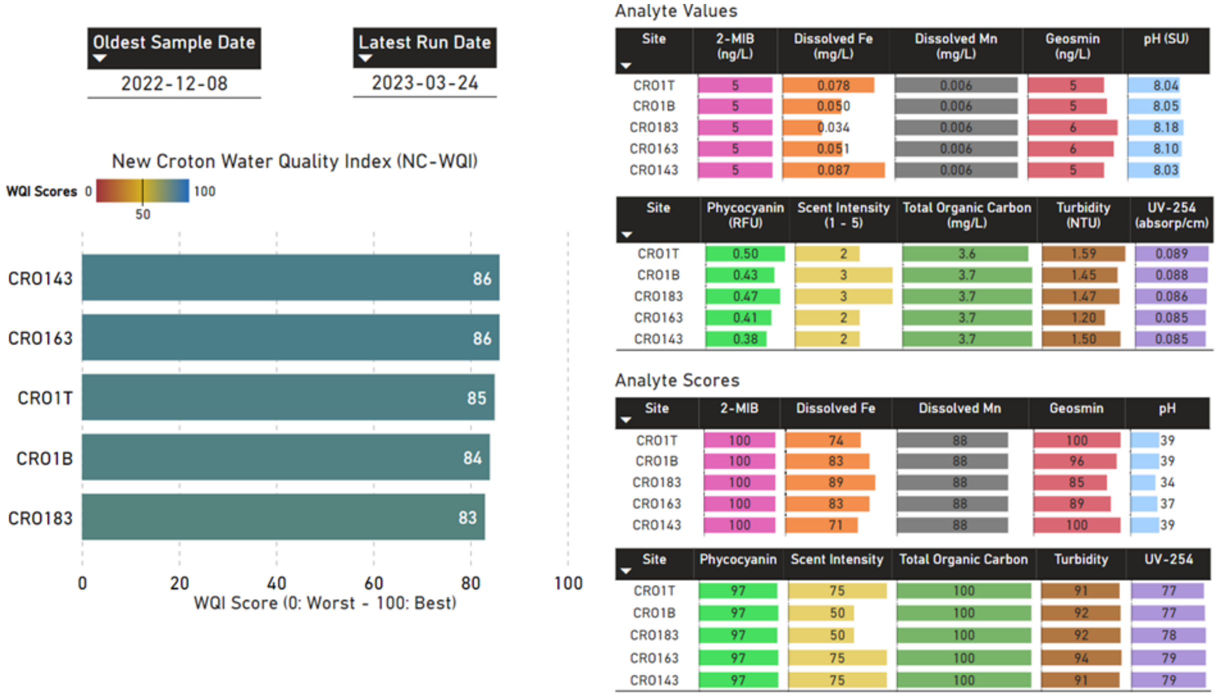
Site	Fecal Coliform (FC/100ml)	Total Plankton (ASU/mL)	Turbidity (NTU)	UV-254 (absorp/cm)
Boyd Corners	0.5		0.7	0.133
Neversink	0.5	66	0.7	0.056
West Branch	0.5	490	0.5	0.055
Rondout	0.5	200	0.5	0.044
Schoharie	10.0	3	2.5	0.044
Kensico	0.5	230	0.7	0.043
Cannonsville	0.5	170	1.2	0.040
Pepacton	0.5	190	0.8	0.037
Ashokan East	0.5	180	1.0	0.034
Ashokan West	0.5	170	1.8	0.033

Analyte Scores

Site	Fecal Coliform	Total Plankton	Turbidity	UV-254
Ashokan West	100	92	96	88
Ashokan East	100	91	98	87
Pepacton	100	91	99	86
Cannonsville	100	92	98	84
Kensico	100	89	100	83
Rondout	100	90	100	82
Schoharie	81	100	93	82
West Branch	100	76	100	76
Neversink	100	97	99	76
Boyd Corners	100		99	35

Figure 1.5 Catskill - Delaware Water Quality Index.

The Croton Water Quality Index uses the most recent data from a combination of laboratory grab sample data and in-situ data. The purpose of the Croton Water Quality Index is to calculate an index score for the five New Croton Reservoir draw locations based on 10 parameters that inform operation at the Croton Water Filtration Plant. All 10 parameters: 2-MIB, Geosmin, dissolved iron, dissolved manganese, pH, phycocyanin, scent intensity, TOC, turbidity, and UV254 are equally weighted. An example of Power BI output for the Croton Water Quality Index is provided in Figure 1.6.



Oldest Sample Date
2022-12-08

Latest Run Date
2023-03-24

Analyte Values

Site	2-MIB (ng/L)	Dissolved Fe (mg/L)	Dissolved Mn (mg/L)	Geosmin (ng/L)	pH (SU)
CRO1T	5	0.078	0.006	5	8.04
CRO1B	5	0.050	0.006	5	8.05
CRO183	5	0.034	0.006	6	8.18
CRO163	5	0.051	0.006	6	8.10
CRO143	5	0.087	0.006	5	8.03

Site	Phycocyanin (RFU)	Scent Intensity (1 - 5)	Total Organic Carbon (mg/L)	Turbidity (NTU)	UV-254 (absorp/cm)
CRO1T	0.50	2	3.6	1.59	0.089
CRO1B	0.43	3	3.7	1.45	0.088
CRO183	0.47	3	3.7	1.47	0.086
CRO163	0.41	2	3.7	1.20	0.085
CRO143	0.38	2	3.7	1.50	0.085

Analyte Scores

Site	2-MIB	Dissolved Fe	Dissolved Mn	Geosmin	pH
CRO1T	100	74	88	100	39
CRO1B	100	83	88	96	39
CRO183	100	89	88	85	34
CRO163	100	83	88	89	37
CRO143	100	71	88	100	39

Site	Phycocyanin	Scent Intensity	Total Organic Carbon	Turbidity	UV-254
CRO1T	97	75	100	91	77
CRO1B	97	50	100	92	77
CRO183	97	50	100	92	78
CRO163	97	75	100	94	79
CRO143	97	75	100	91	79

Figure 1.6 Croton System Water Quality Index.

1.3 Operational Strategies

Catskill West of Hudson

In 2022, water quality in the Catskill System was excellent throughout the year. Like previous years, the elevation and location (East Basin/West Basin) of withdrawal and dividing weir operations at Ashokan Reservoir were adjusted as needed to divert the best quality water from the reservoir. These changes were also made to meet operational needs (e.g., lowering the West Basin to create a void to accept more runoff during large storm events). The combination of a dry summer period, use of the dividing weir, and West Basin withdrawal maintained a West Basin elevation well below spill level (Figure 1.7). The West Basin elevation increased near the end of the year due to rainfall and aqueduct shutdowns to support remotely operated vehicle (ROV) work in early December (Figure 1.7).

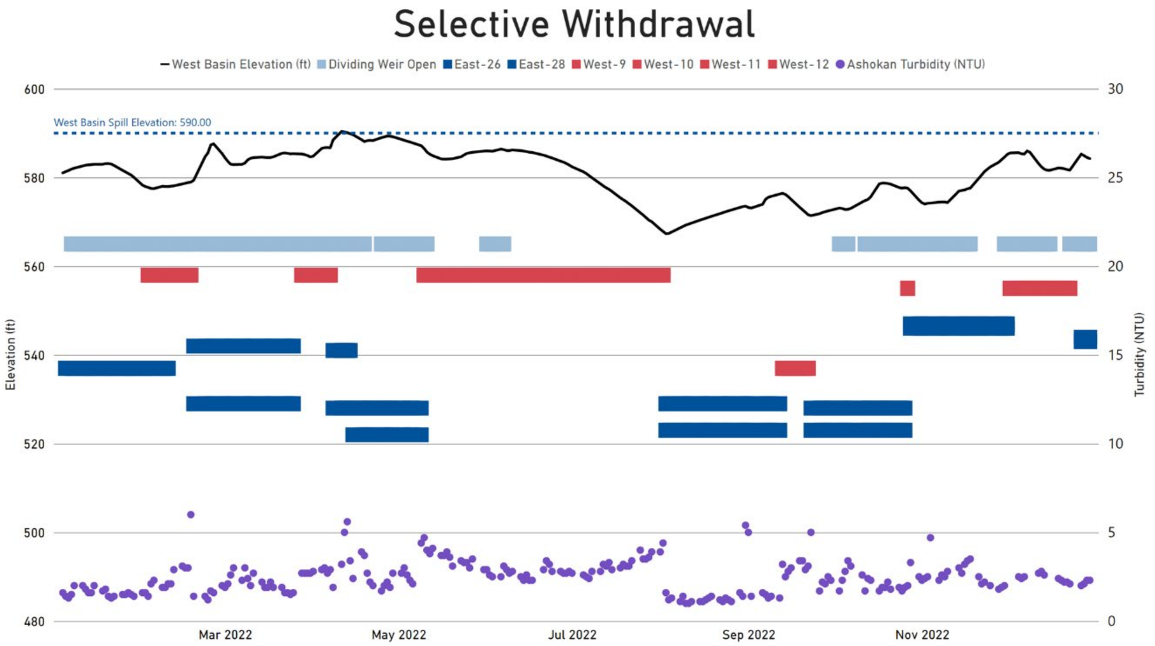


Figure 1.7 Ashokan diversion in relation to turbidity in 2022.

Delaware West of Hudson

After experiencing increased levels of UV254 in 2021, the Delaware System exhibited more typical levels of this disinfection byproduct formation potential (DBPFP) surrogate in 2022. UV254 in all four Delaware System reservoirs continued to decline after tropical storms Henri and Ida inundated the watershed on August 21 and September 1, 2021. Consistent with past large storms, it took several months for UV254 levels to return to what was considered pre-storm levels (Figure 1.8). Over that period, to decrease DBPFP in the system, DEP minimized the use of Neversink Reservoir which had the highest levels of UV254.

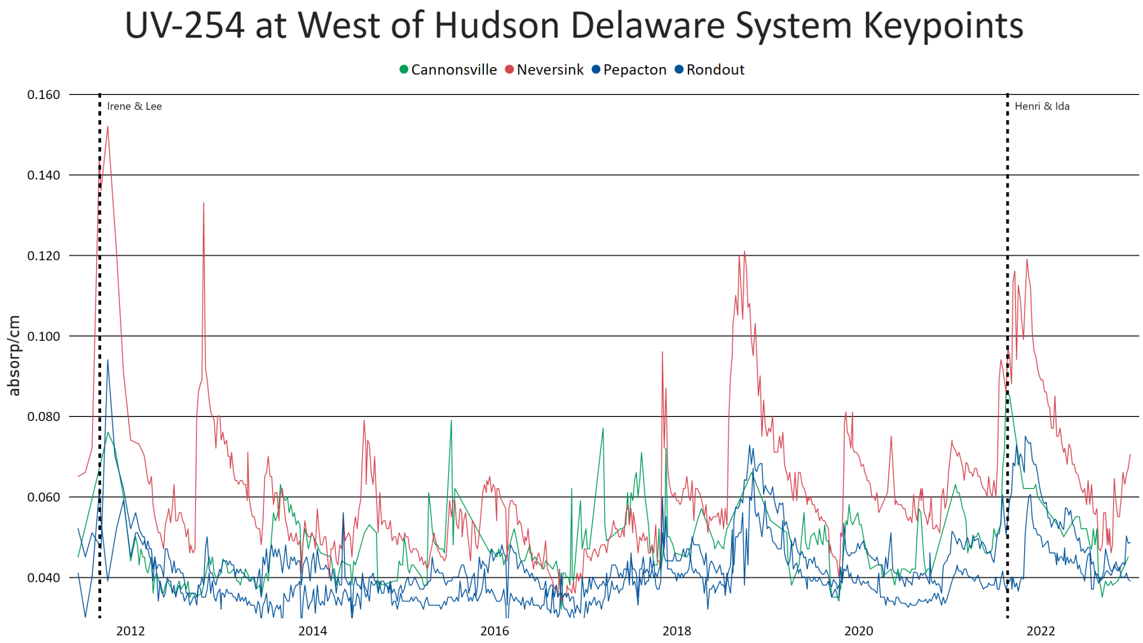


Figure 1.8 UV254 at Delaware System keypoints.

Catskill-Delaware East of Hudson

In preparation for the 2023 shutdown of the Rondout-West Branch Tunnel, work on the Kensico shoreline stabilization project continued in 2022. This project required ongoing monitoring of continuous, robotic, and laboratory water quality data to mitigate the impacts of storm-related increases in turbidity, fecal coliforms, and natural organic matter (NOM). With the Catskill Repair and Rehabilitation Project largely complete, DEP was able to divert more Ashokan water into Kensico Reservoir. This allowed DEP to reduce the DBPFP entering Kensico which ultimately contributed to the system regaining compliance with the Stage 2 Disinfection By-Product Rule in the second quarter of 2022.

1.3.1 Croton Water Filtration Plant

Water Treatment Operations staff at the Croton Water Filtration Plant (CWFP) provided distribution of filtered water from the start of 2022 through April 6. The CWFP successfully performed a pilot test for an alternative granular activated carbon (GAC), with filtered water going into distribution from May 27–June 12. The existing 8x30 bituminous coal GAC had an effective size of 0.8 mm and a uniformity coefficient of 2.1. The tested bituminous coal GAC, which had an effective size of 1.1 mm and a uniformity coefficient of 1.5, proved adequate at reducing geosmin/2-methylisoborneol (MIB) while providing improved production output. Based on these results, the original GAC was replaced with the alternative in half the CWFP and then commissioned to allow for the distribution of filtered water in October. GAC replacement in the other half of the plant was completed by the end of 2022 for commissioning in 2023.

2. Water Quantity

2.1 Introduction

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

2.2 2022 Watershed Precipitation

The average precipitation for each watershed was determined from daily readings collected from one precipitation gauge 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 2022 monthly precipitation total for each watershed is plotted along with the historical monthly average (1992-2021) (Figure 2.1).

In general, wetter than average conditions occurred in the water supply in February, April, September, and December while drier than average conditions were often observed from late spring through summer from May-August. Several notable rain events/periods affecting large portions of the water supply occurred in 2022. During a three-day period in early February, precipitation in the WOH watersheds ranged from 1.76 to 2.47 inches. On April 7, precipitation amounts exceeded 2 inches in all watersheds ranging from 2.19 inches at Cannonsville to 4.28 inches at Ashokan. Significant rainfall also occurred in early September where three-day totals from September 4-6 exceeded 5.24 inches at Ashokan, Rondout, Neversink, and Pepacton with lesser amounts at Cannonsville (4.3 inches) and Croton (3.67 inches). The National Climatic Data Center's (NCDC) climatological rankings (https://www.ncdc.noaa.gov/cag/) were queried to determine the 2022 rankings for New York. Overall total precipitation for New York State in 2022 was 42.86 inches (1,188 mm), which was 2.57 inches (65.3 mm) above the 20th-century mean (1901-2000) and the 40th wettest year in the last 128 years (1895-2022). In New York's Climate Division 2, which includes the WOH reservoirs, the 2022 precipitation total was 2.99 inches (76 mm) above the 20th-century mean. In New York's Climate Division 5, which includes the EOH reservoirs, precipitation was 1.83 inches (46.5 mm) below the 20th-century mean.

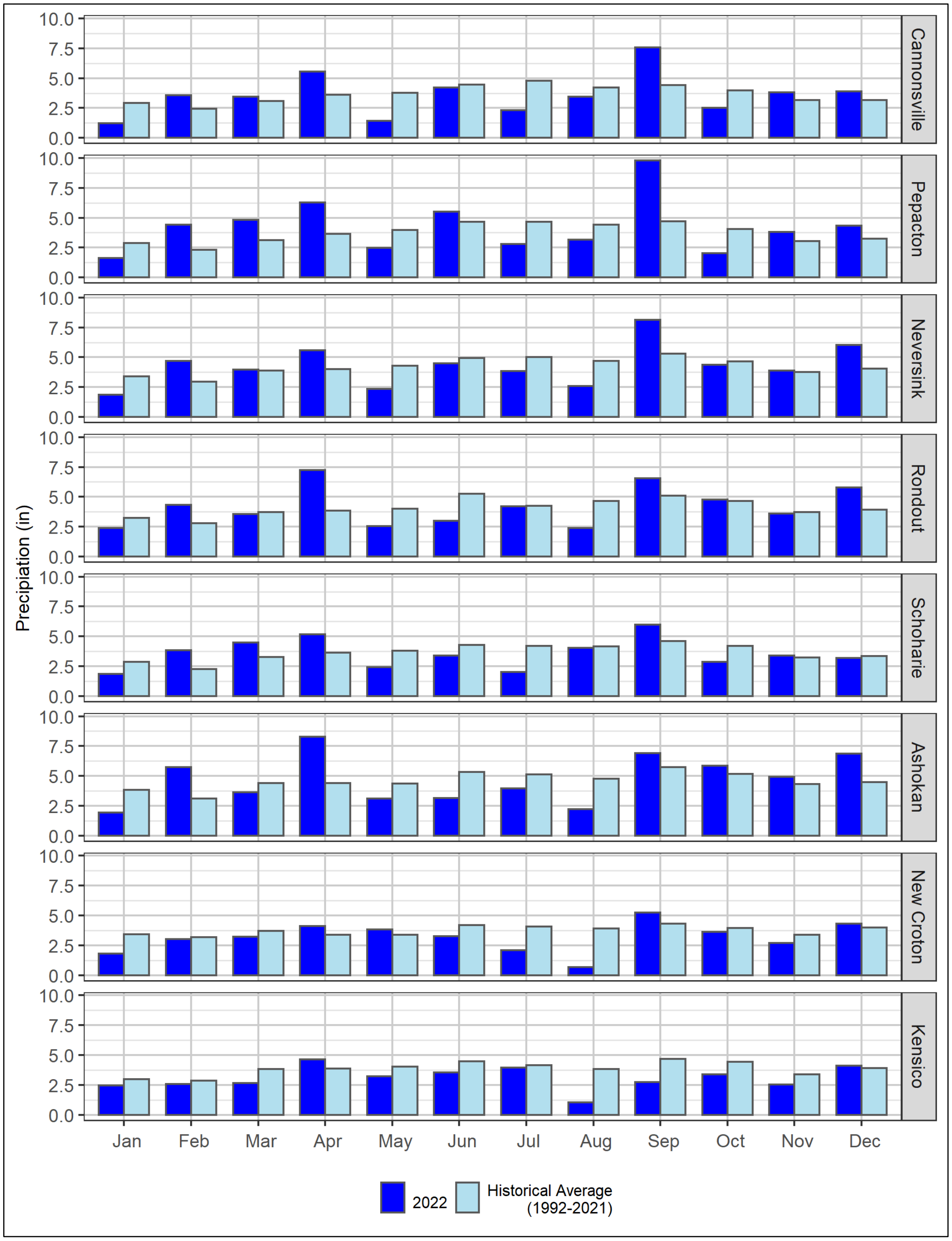


Figure 2.1 Monthly precipitation totals for New York City watersheds, 2022 and historical values (1992-2021).

2.3 2022 Watershed Streamflow

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

Selected United States Geological Survey (USGS) stations were used to characterize streamflow in the different NYC Water Supply watersheds. Wappinger Creek is not located in the EOH System but is included here because it is in nearby Dutchess County and its longer period of record is more comparable to those found in the WOH System (Figure 2.2). The 2022 total monthly streamflow for each of the stations is shown as blue-green dots; historical (1992-2021 for WOH and Wappingers Creek and 1995-2021 for the remaining EOH streams) streamflow data is provided in the boxplots. The 2022 streamflow values largely reflect the precipitation patterns. For WOH streams, monthly streamflow values were mostly at or above historic median flows from February-April and in September, October (except at CBS), and December. Flows were especially elevated in February, April, and December when all the streams were near or exceeded their historic 75th percentile flows. Drier conditions prevailed from May-August and in November when all streams were at or below their historic 25th percentile flows. With some exceptions, similar seasonal patterns were observed for EOH streams. In contrast to WOH streams, EOH streams also experienced low flows in October and low to normal flows in December.

Overall, New York State had relatively high computed runoff (streamflow per unit area) for the 2022 water year (October 1, 2021-September 30, 2022), ranking as the 34th highest annual runoff (72.36 percentile out of the last 121 years as determined by the USGS (http://waterwatch.usgs.gov/index.php?r=ny&m=statesum). Daily flow/runoff data from October 1-December 31, 2022, are provisional and subject to revision until final approval from the USGS.

Figure 2.3 shows the 2022 mean daily streamflow, along with the minimum, maximum, and median daily streamflow for the previous 30 years, for the same USGS stations used to characterize annual areal-normalized streamflow. While the patterns generally reflect the monthly precipitation patterns, the higher time resolution of these plots are useful in that they identify shorter-term wet and dry periods as well as individual storms. Throughout the water supply, peak flows were generally observed from February to April and after August. One notable exception occurred at Cross River when a local rain event caused stream flow to rise from a historic low to near a historic high flow in mid-July. The peak flows often followed dry periods which can be especially detrimental to water quality since contaminants can accumulate during dry periods and then be quickly transported to streams during the first large rain event.

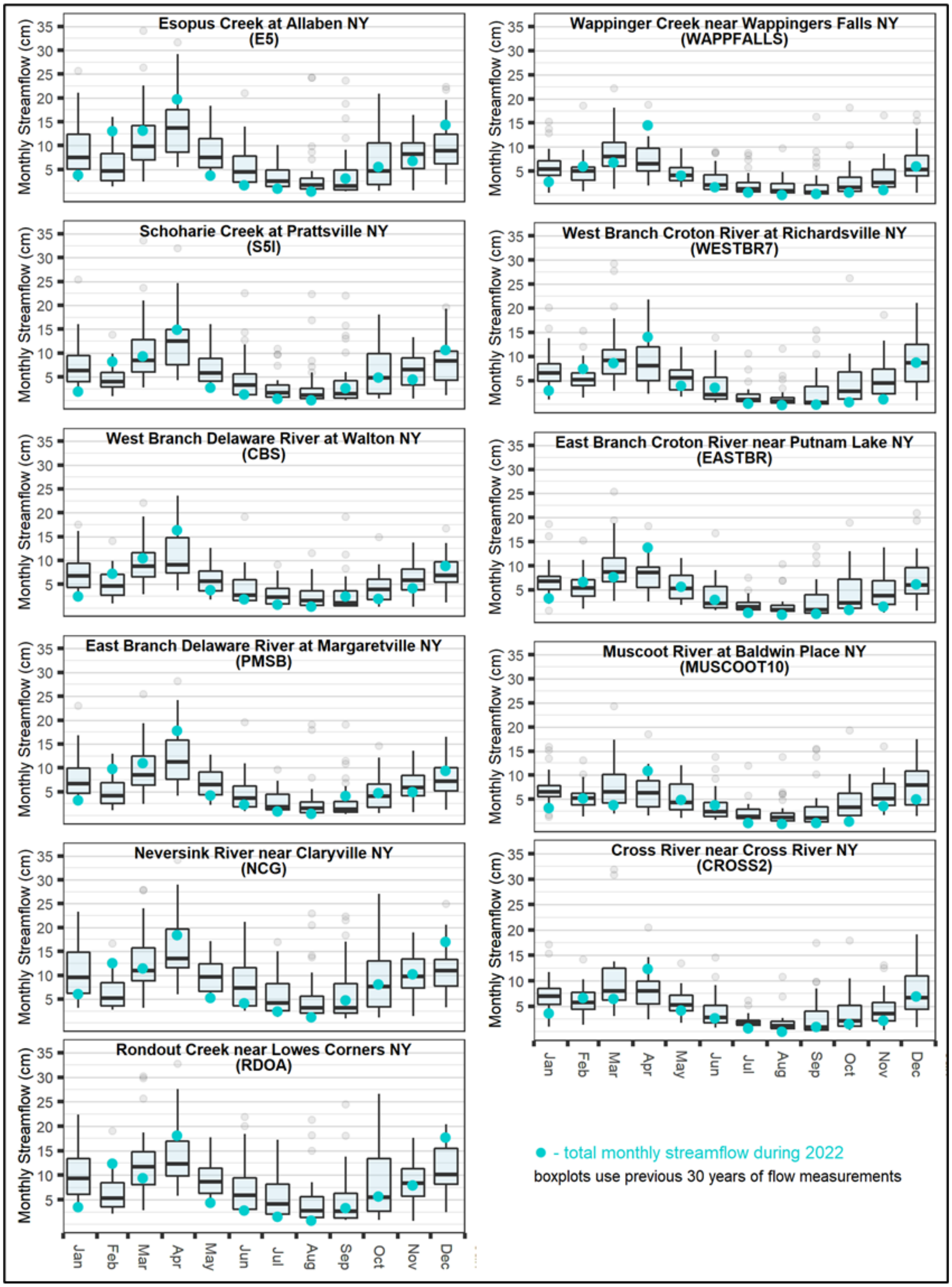


Figure 2.2 Historical areal-normalized streamflow vs. 2022 monthly areal-normalized streamflow with the historical data (1992-2021 for WOH and 1995-2021 for EOH) displayed as boxplots and the values for 2022 displayed as a solid blue dot. The gray circles indicate outliers (see Appendix C for a key to the boxplot).

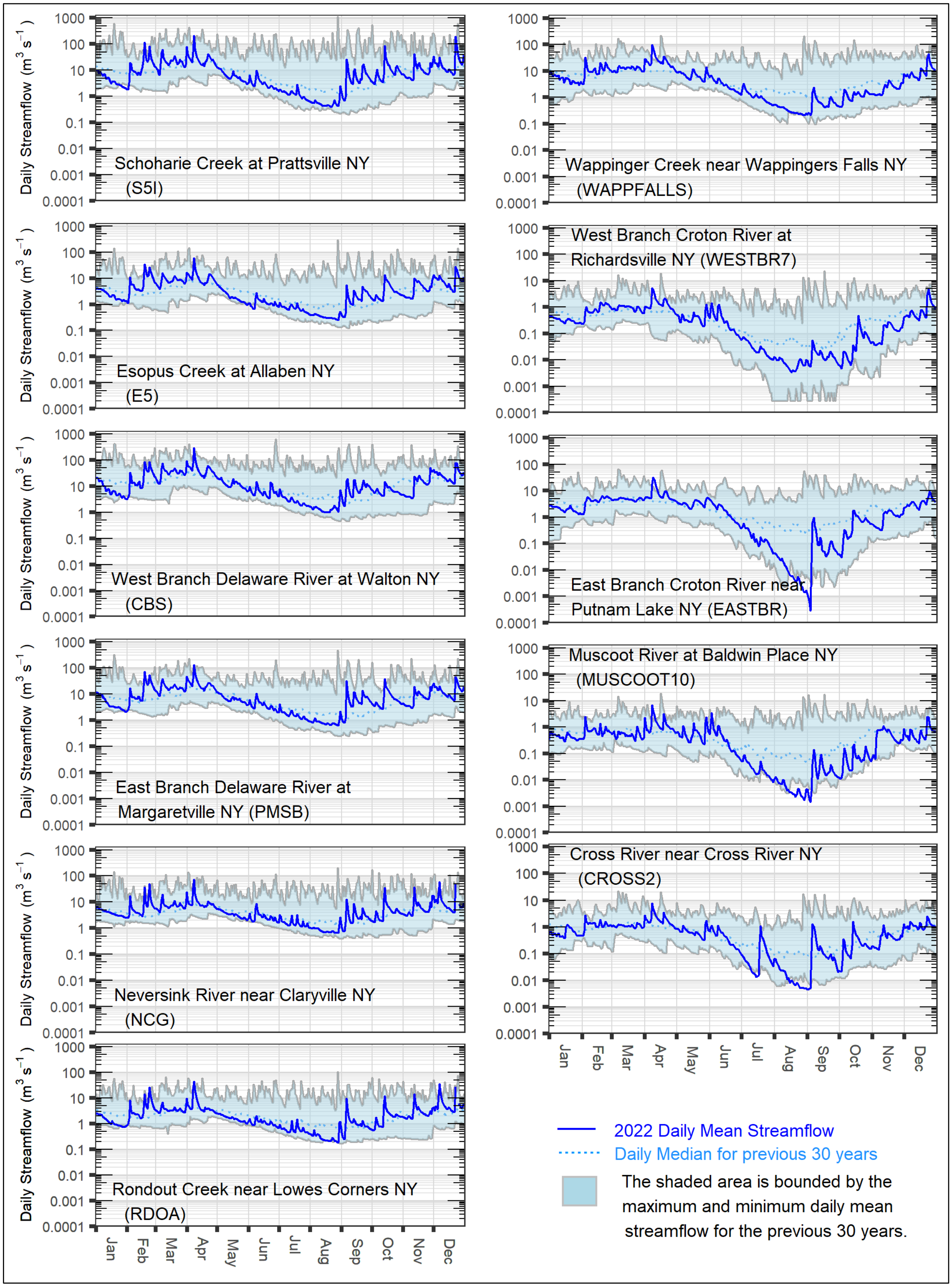


Figure 2.3 Daily mean streamflow for 2022 at selected USGS stations.

2.4 Reservoir Usable Storage in 2022

Ongoing daily monitoring of reservoir storage allowed DEP to compare the system-wide storage in 2022 (including Kensico Reservoir) against average historical values for 1991-2021 for any given day of the year Figure 2.4. Storage was above normal at the start of the year due to frequent small rain events in late December 2021 through early January 2022. From mid-February to the end of April storage levels were usually 5% above normal. Dry conditions then prevailed through November resulting in storage levels falling to approximately 10% below normal from late July to early November. Rain events and melting snow in December restored storage to above normal capacity by the end of the year.

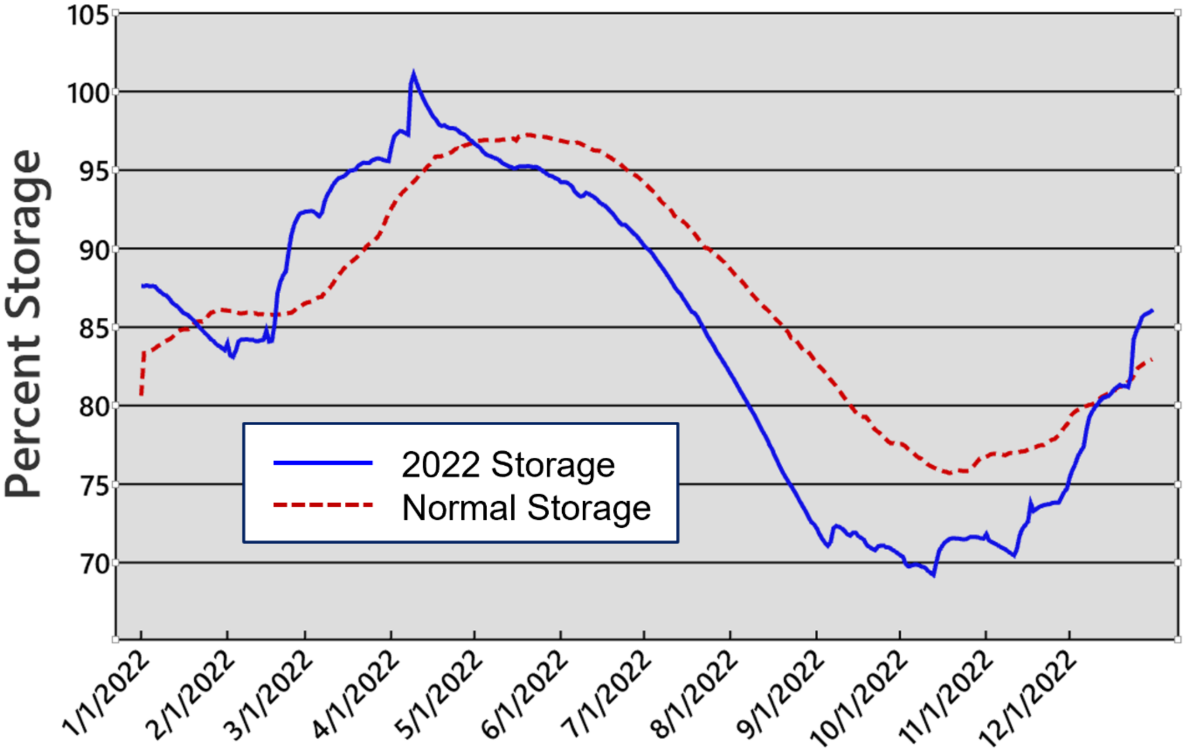


Figure 2.4 System-wide usable storage in 2022 compared to the average historical value (1991-2021). Storage greater than 100% occurs when the water surface elevation is greater than the spillway elevation and reservoirs are spilling.

3. Water Quality

3.1 Monitoring Overview

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

Historically, reservoir samples are obtained from multiple sites and multiple depths with routine sampling frequencies of once per month. In previous reports, the sample period is from April through November. In 2022, the typical historic schedule was followed for all reservoirs.

To ensure an impartial comparison with past data, reservoir historic data were adjusted to reflect the months and sites collected in 2022. If the historic data did not have adequate representation (75% of the 2022 sample load) that particular year was set to missing.

Aqueduct keypoint samples are collected year-round at frequencies that vary from daily, weekly, and monthly. While Kensico Reservoir is usually operated as a source water, the reservoir can currently be bypassed so that Rondout or West Branch can be operated as source waters. Regardless of reservoir operations, Delaware Shaft 18 (DEL18DT) remains the Surface Water Treatment Rule (SWTR) compliance sampling site since all water flows through this location prior to delivery to Hillview Reservoir.

3.2 Reservoir Turbidity Patterns in 2022

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

In 2022, turbidity levels in the CAT/DEL reservoirs were close to their median historic levels (Figure 3.1). A key to boxplots is provided in Appendix C. Turbidity was slightly above normal at Schoharie due primarily to snowmelt in February and multiple rain events from mid-February through April. Although the West Basin of Ashokan was affected by these same events, less impact was observed as median 2022 turbidity levels were equivalent to historic levels. In part, this was due to the shutdown of the Schoharie diversion from mid-February through April and use of the release channel in April. Turbidity levels were also equivalent to historic median concentrations in the East Basin of Ashokan. Turbidity levels were controlled here by closing the dividing weir gate to prevent transfer of turbid water to the East Basin. Maintaining a low elevation in the West Basin for flood control also helped control turbidity by preventing West Basin water from spilling over the dividing weir to the East Basin. Except for April, all Delaware System reservoirs including West Branch, which typically receives >95% of its water from the Delaware System, maintained low turbidity levels throughout the year. The watersheds of the Delaware System lack the easily erodible clays of the Catskill watersheds. Hence, while 2022 rainfall amounts were above average to nearly average in both the Catskill and Delaware watersheds, stream turbidity levels in the Delaware System remained comparatively low in 2022. Consequently, low turbidity inputs from the Rondout and Ashokan basins account for the low turbidity levels observed at Kensico, the terminal reservoir of the Catskill/Delaware System. Turbidity in all monitored Croton System reservoirs was close to historic annual median levels (Figure 3.1). Turbidity levels in the Croton System were low to normal throughout the year in large part due to below average rainfall in 2022.

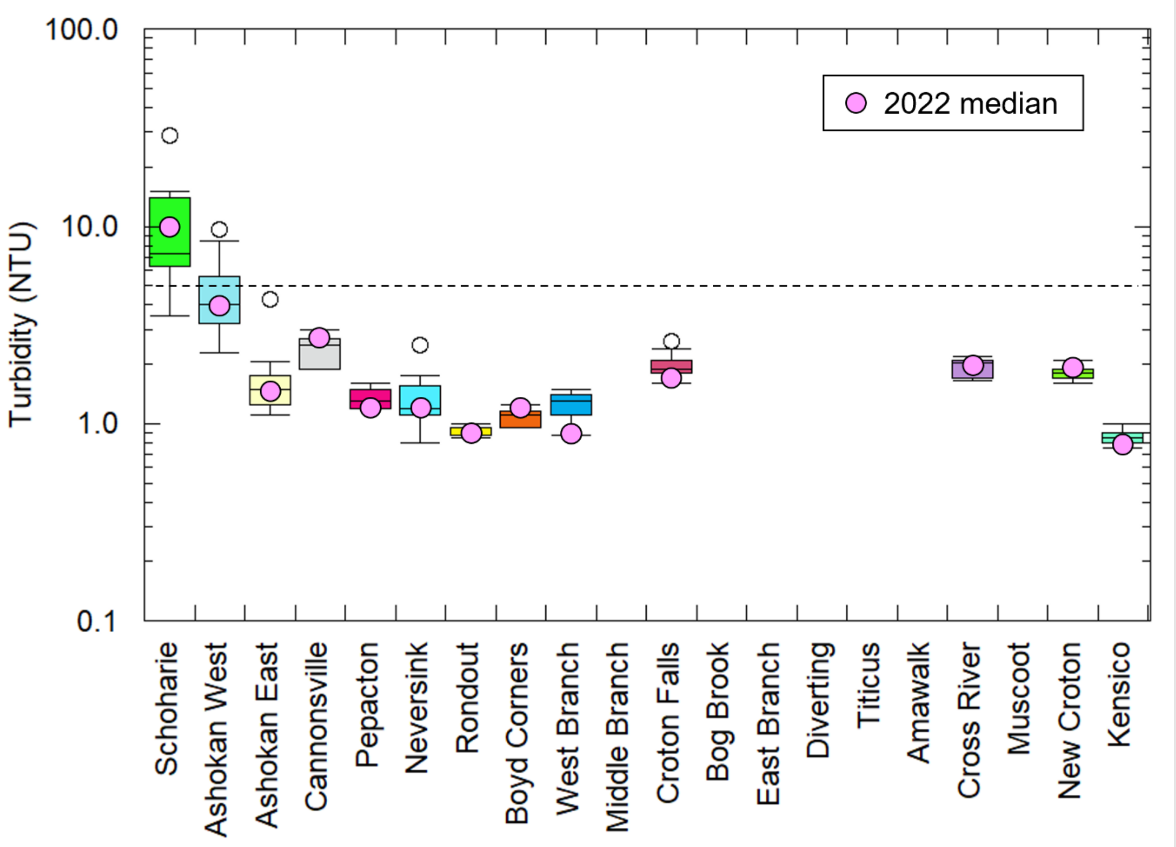


Figure 3.1 Annual median turbidity in NYC water supply reservoirs (2022 vs. 2012-2021), with the 2022 values displayed as a solid dot and outliers as open circles. The dashed line at 5 NTU represents the SWTR standard for source water as a reference.

3.3 Coliform-Restricted Basin Assessments in 2022

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

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

3.3.1 Terminal Basin Assessments

Table 3.1 provides coliform-restricted assessments for the five terminal reservoir basins. The results are based on 2022 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 2022.

Table 3.1 Coliform-restricted basin status as per Section18-48(c)(1) for terminal reservoirs in 2022.

Reservoir basin	Effluent keypoint	2022 assessment
Kensico	DEL18DT	Non-restricted
New Croton	CROGH[1,2]	Non-restricted
Ashokan	EARCM[2]	Non-restricted
Rondout	RDRRCM[2]	Non-restricted
West Branch	CWB1.5	Non-restricted

[1] Data from the corresponding alternate site used when the sample could not be collected at the primary site listed.

[2] Data from the elevation tap that corresponds to the level of withdrawal are included one day per week, and all other samples are collected at the specified effluent keypoint.

3.3.2 Non-Terminal Basin Assessments

Section 18-48(a)(1) of the WR&R requires that non-terminal basins be assessed according to 6 NYCRR Part 703 for total coliform. These New York State regulations are specific to the class of the reservoir. A minimum of five samples per month are required in each basin to be included in the assessment. If both the median value and more than 20% of the total coliform counts for a given month exceed the values ascribed to the reservoir class, then the results exceed the reservoir class standard, and the non-terminal reservoir is designated as restricted. Table 3.2 provides a summary of the 2022 coliform-restricted calculation results for the non-terminal reservoirs and Appendix E includes the details for coliform monthly medians and the percentage of values exceeding the relevant standard.

In 2022, eight reservoirs had no exceedances for the Part 703 total coliform standard for the 14 reservoirs and 3 controlled lakes evaluated (Table 3.2). The highest number of exceedances occurred in Croton Falls Reservoir.

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

Table 3.2 Coliform-restricted calculations for total coliform counts on non-terminal reservoirs in 2022.

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

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

3.4 Reservoir Fecal and Total Coliform Patterns in 2022

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

Reservoir fecal coliform results are presented in Figure 3.2 and reservoir total coliform results in Figure 3.3. According to the filtration avoidance criteria of the SWTR, fecal coliform concentrations must be ≤ 20 fecal coliforms $100mL^{-1}$ or total coliform concentrations must be ≤ 100 total coliforms $100mL^{-1}$ in at least 90% of the measurements from the last six months at the sample point immediately prior to the first point of disinfectant application. While this criterion does not apply to other sampling locations, lines at 20 fecal coliforms $100mL^{-1}$ and 100 total coliforms $100mL^{-1}$ are provided on the plots in this section as a point of reference. The centerline in the boxplot represents the median of the 75th percentile values rather than the 50th percentile or median of annual values. If a calculated annual 75th percentile results in a censored value or zero, it was estimated using the robust regression on statistics method (ROS) of Helsel and Cohn (1988).

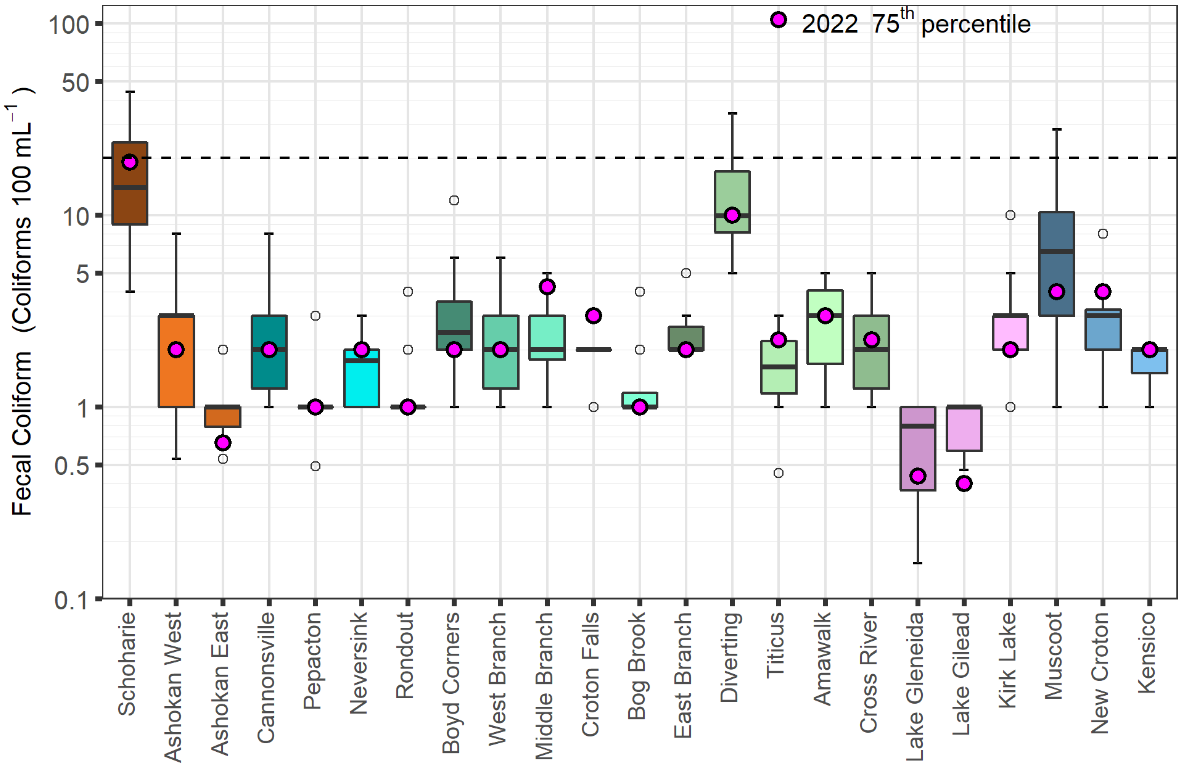


Figure 3.2 Annual 75th percentile of fecal coliforms in NYC water supply reservoirs (2022 vs. 2012-2021), with the 2022 values displayed as a solid dot and outliers as open circles. The dashed line represents the SWTR standard for source water as a reference benchmark.

In 2022, fecal and total coliform were generally similar to historic median 75th percentile levels in most of the NYC water supply reservoirs and controlled lakes (Figure 3.2, Figure 3.3). However, high counts were observed in the CAT/DEL System following a three-day rain event starting on September 4. Schoharie also experienced rain related elevated counts in April, October, and November causing its 2022 75th fecal counts to exceed historic levels and approached the SWTR benchmark of 20 fecal coliforms $100mL^{-1}$. However, fecal and total coliform counts remained low in the Ashokan West Basin presumably because samples were not collected close enough to rain events in October and November and due to the shutdown of the Shandaken tunnel until May. Low coliform counts were also observed at the Ashokan East Basin due in part to operational changes (i.e., Shandaken tunnel shutdown, dividing weir and release operations) as well as natural processes such as predation, die-off, photolysis, and sedimentation as water moves through the West Basin to the east. These processes and the relatively low coliform inputs from the CAT/DEL System were the likely factors that helped to maintain the typically low fecal coliform levels in Kensico in 2022. Generally low fecal coliform counts were also observed in the Croton System. Below average rainfall is the likely reason although the effects of an early September rain event may have not been captured since sampling surveys occurred before or at least eleven days post storm. Elevated fecal coliforms beyond historic levels were only observed at Middle Branch, Croton Falls and New Croton reservoirs in 2022. The higher levels at New Croton may at least partially be explained by sampling within one to three days of rain events exceeding 1 inch in June and July. Higher than historic levels at Middle Branch and Croton Falls can also be explained by multiple sample collections after rainfall events

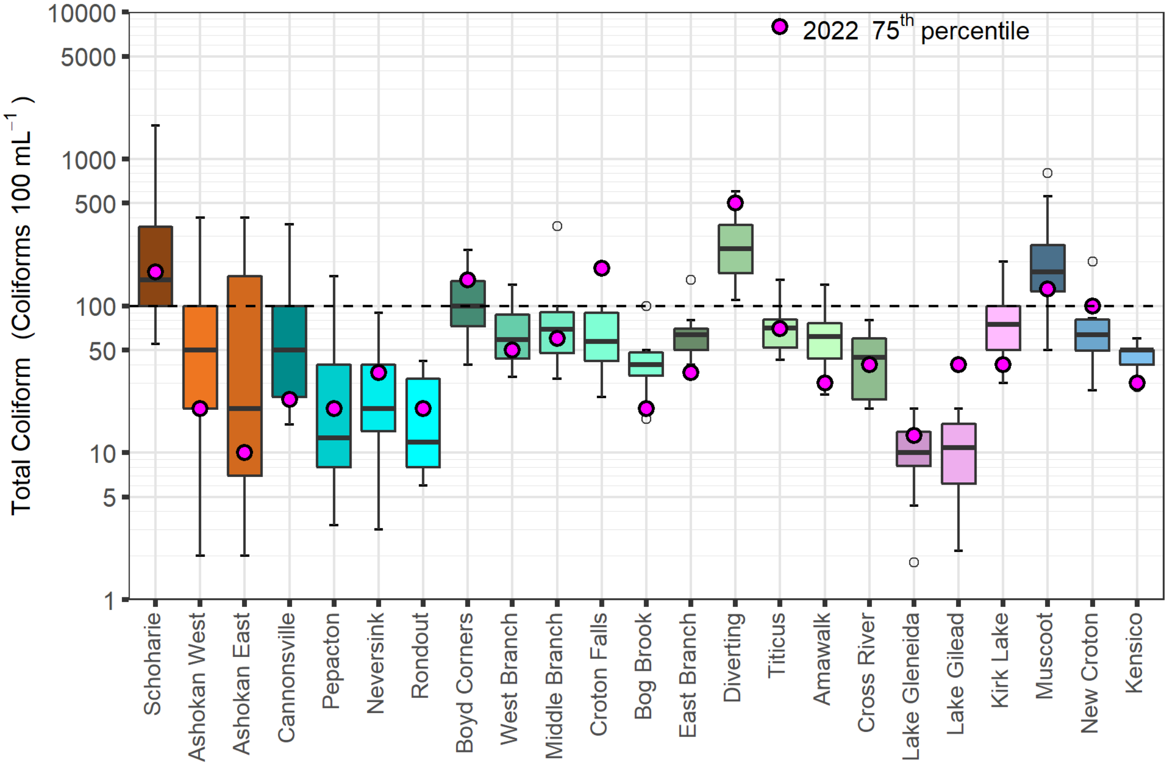


Figure 3.3 Annual 75th percentile of total coliforms in NYC water supply reservoirs (2022 vs. 2012-2021), with the 2022 75th percentile values displayed as a solid dot and outliers as open circles. The dashed line represents the SWTR standard for source water as a reference.

3.5 Phosphorus-Restricted Basin Assessments in 2022

The phosphorus-restricted basin status determination for 2022 is presented in Figure 3.4 and Table 3.3. Status is determined from two consecutive five-year assessments (2017-2021 and 2018-2022) using the methodology described in Appendix F. 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.

Phosphorus-restricted status for all West of Hudson and East of Hudson reservoirs remained the same as in the previous assessment (Table 3.3). Figure 3.4 graphically shows the phosphorus-restricted basin status of the City's reservoirs and controlled lakes. Geometric means for individual years that contributed to the assessments are shown in Appendix F. The influence of early-season sample reductions in the East of Hudson reservoirs in 2021 continued to affect the current assessment.

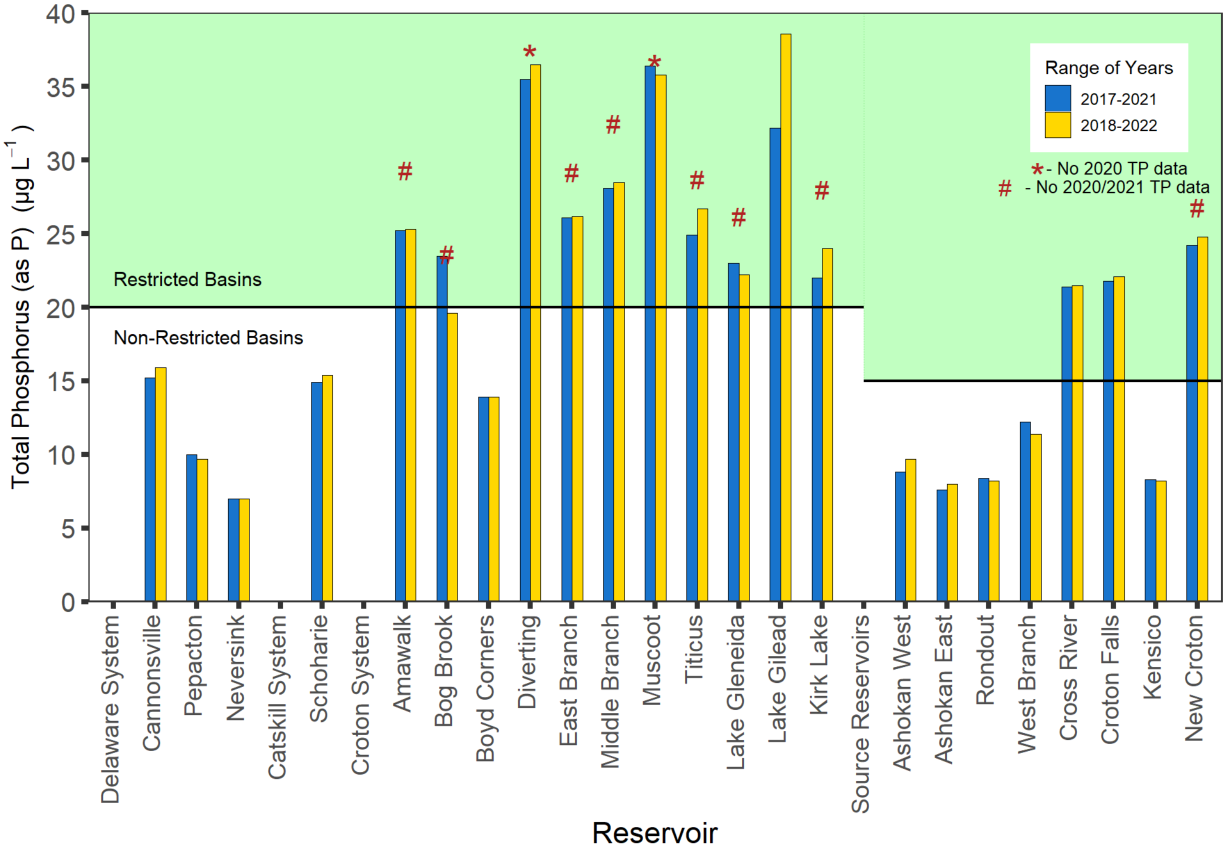


Figure 3.4 Phosphorus-restricted basin assessments. The horizontal solid lines at 20 µg L^{-1} and 15 µg L^{-1} represent the trophic guidance value for non-source and source waters, respectively.

Table 3.3 Phosphorus-restricted basin status for 2022.

Reservoir basin	2017-2021 Assessment[1,2] (µg L^{-1})	2018-2022 Assessment[1, 2] (µg L^{-1})	Phosphorus restricted status[3]
Non-Source Waters (Delaware System)			
Cannonsville	15.2	15.9	Non-restricted
Pepacton	10.0	9.7	Non-restricted
Neversink	7.0	7.0	Non-restricted
Non-Source Waters (Catskill System)			
Schoharie	14.9	15.4	Non-restricted
Non-Source Waters (Croton System)			
Amawalk	25.2	25.3	Restricted
Bog Brook	23.5	19.6	Restricted
Boyd Corners	13.9	13.9	Non-restricted
Diverting	35.5	36.5	Restricted
East Branch	26.1	26.2	Restricted
Middle Branch	28.1	28.5	Restricted
Muscoot	36.4	35.8	Restricted
Titicus	24.9	26.7	Restricted
Lake Gleneida	23.0	22.2	Restricted
Lake Gilead	32.2	38.6	Restricted
Kirk Lake	22.0	24.0	Restricted
Source Waters (all systems)			
Ashokan West	8.8	9.7	Non-restricted
Ashokan East	7.6	8.0	Non-restricted
Rondout	8.4	8.2	Non-restricted
West Branch	12.2	11.4	Non-restricted
Cross River	21.4	21.5	Restricted
Croton Falls	21.8	22.1	Restricted
Kensico	8.3	8.2	Non-restricted
New Croton	24.2	24.8	Restricted

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

[2] Reservoirs and lakes with sample reductions in 2020 and 2021 had a minimum of three years of data included in the calculation.

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

3.6 Reservoir Total Phosphorus Patterns in 2022

In 2022, annual median total phosphorous (TP) levels were slightly elevated by 1-3 µg L^{-1} in seven of nine Catskill/Delaware System reservoirs, which includes West Branch and Kensico (Figure 3.5). Rain events in the spring, late summer, and autumn were often associated with elevated TP concentrations in Schoharie and in the West Basin of Ashokan. TP remained low in Ashokan's East Basin due in part to operational changes (i.e., Shandaken tunnel shutdown, dividing weir and release operations) as well as natural processes such as uptake by algae and sedimentation as water moves through the West Basin. In the Croton System, TP levels were elevated in nearly all reservoirs during the monitoring period (Figure 3.5, Table 3.4). In addition, elevated redox conditions are suggested as evidenced by historically high TP, TDP (where available) and low dissolved oxygen concentrations observed in the bottom waters of dam sites at Croton Falls, Cross River, Amawalk, Middle Branch, New Croton, Lake Gilead, and Titicus during multiple months of the August through November period. The duration of stratification was also unusually long for many of these reservoirs. For most, turnover occurs by October. However, the dam sites of many reservoirs remained stratified into November 2022, resulting in high TP concentrations for that month. Lack of rain during parts of the summer may also be a factor. In more developed regions, like portions of the Croton watershed, septic and wastewater treatment plant inputs can become a greater source of phosphorus during drought due to the lack of dilution from runoff.

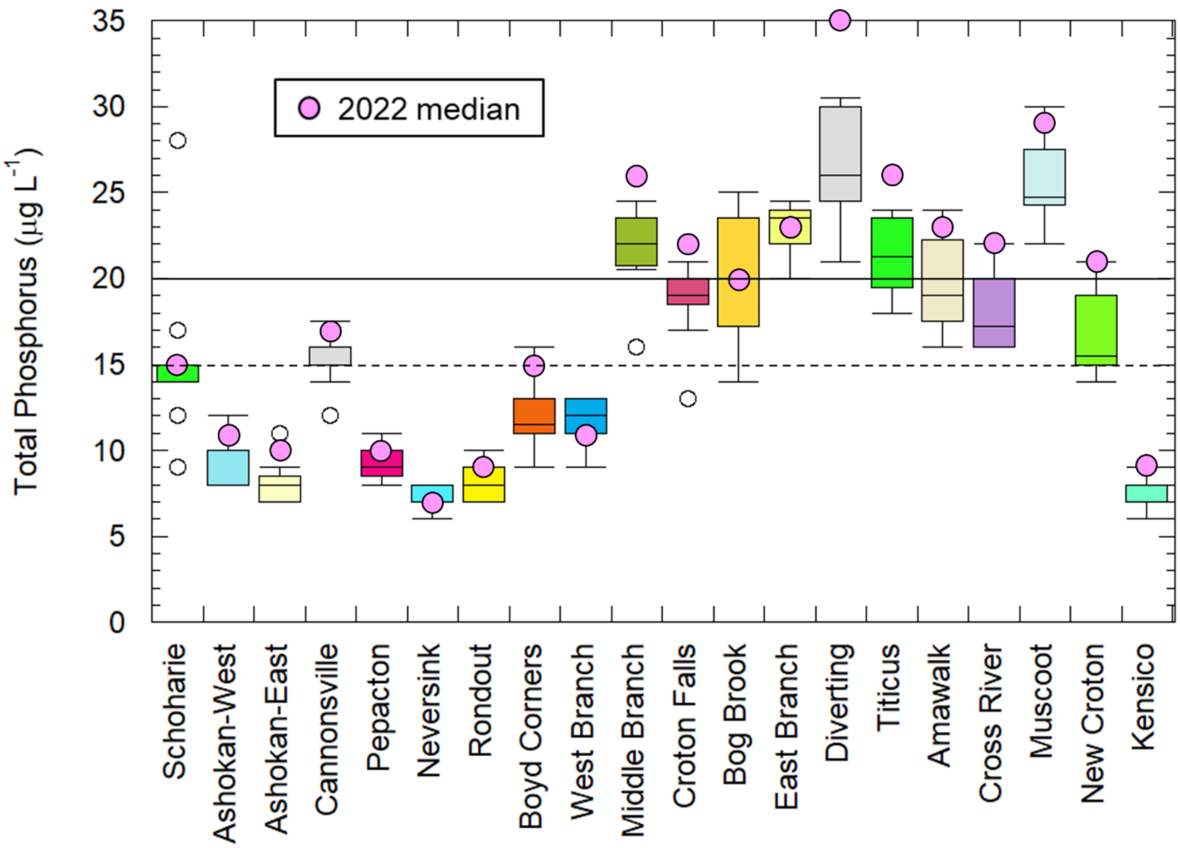


Figure 3.5 Annual median total phosphorus in NYC water supply reservoirs (2022 vs. 2012-2021), with the 2022 median values displayed as a solid dot and outliers as open circles. The horizontal dashed line at 15 µg L^{-1} refers to the NYC Total Maximum Daily Load (TMDL) guidance value for source waters. The horizontal solid line at 20 µg L^{-1} refers to the NYSDEC ambient water quality guidance value for reservoirs other than source waters.

Table 3.4 Total phosphorus summary statistics for NYC controlled lakes (µg L^{-1}).

Lake	Median Total Phosphorus (2012-2021)	Median Total Phosphorus (2022)
Gilead	19	32
Gleneida	16	14
Kirk	26	24

3.7 Reservoir Comparisons to Benchmarks in 2022

The New York City reservoirs and water supply system are subject to the federal SWTR standards, New York State ambient water quality standards, and DEP's own guidelines. Water quality data for 2022 for the terminal reservoirs is evaluated by comparing the results to the water quality benchmarks listed in Table 3.5. Note that the benchmark values in this table are not necessarily applicable to all individual samples and medians described herein (e.g., SWTR limits for turbidity and fecal coliforms apply only to the source water point of entry to the system) and different values apply to Croton System reservoirs than to CAT/DEL reservoirs. Comparing the annual data to these benchmark values assists in assessing water quality status of the system and helps in identifying issues.

Comparisons of 2022 reservoir sample results to benchmark values are provided in Appendix G. Highlights of the benchmark comparisons for terminal reservoirs from 2022 include the following.

pH

Reservoir samples were generally in the circumneutral pH range (6.5-8.5) in 2022. In the Croton System, samples below pH 6.5 were from West Branch Reservoir, reflecting the characteristics of water transferred from the Delaware System. Exceedances above pH 8.5, an indicator of algal blooms, were relatively few, with the most exceedances in New Croton Reservoir (14% of samples collected). The West of Hudson reservoirs had a few exceedances above a pH of 8.5, with the majority in Cannonsville (10 of 13 samples) and Pepacton (7 of 13 samples). Samples below a pH of 6.5 occurred throughout the Catskill/Delaware reservoirs, reflecting the acidic characteristics of watershed soils and slow recovery from acid deposition (Stoddard et al. 1999). All exceedances in Neversink Reservoir were below pH 6.5. In Kensico Reservoir, values outside the circumneutral range were all below a pH of 6.5, reflecting the influence of water transferred from West of Hudson reservoirs.

Table 3.5 Reservoir and controlled lake benchmarks as listed in the WR&R (DEP 2019a).

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

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

Phytoplankton

Phytoplankton sampling summary statistics for 2022 are provided in Appendix G. There were few exceedances of counts for the single sample maximum of 2,000 ASU mL^{-1} for total phytoplankton, with the most occurring in Muscoot Reservoir (4 out of 5 samples). In 2022, there were a total of 12 NYSDEC harmful algal blooms (HABs) notifications (2022 Archived HABs Notices (ny.gov)). NYSDEC automatically categorizes blooms as "confirmed blooms" whenever DEP submits a Suspicious Algal Bloom Report Form via the reporting website.

Cannonsville Reservoir had the highest number of reported blooms for NYC reservoirs, with four blooms reported between August 9 – October 12. There were two reported blooms for Ashokan (October 25, November 1), Croton Falls (August 15, November 2), and Kirk Lake (September 4, November 4). Only one bloom was reported for New Croton (October 25) and Diverting (October 26).

Chlorophyll and Dissolved Organic Carbon

Chlorophyll *a* concentration is a surrogate measure of algal biomass. Of the reservoirs sampled, only three had exceedances for the chlorophyll *a* single sample maximum (SSM). Croton Falls had the most exceedances (29% of samples), while 11% of samples from Cannonsville and New Croton, and a single sample from West Branch Reservoir exceeded the SSM. Croton Falls Reservoir also exceeded the annual mean standard of 10 µg L^{-1} with a mean of 19 µg L^{-1}.

In 2022, there were no exceedances of either the single sample maximum or annual mean for DOC in any of the 12 reservoirs sampled for DOC including all Catskill/Delaware and source water and potential source water reservoirs.

Chloride

In the Delaware System, the only exceedances for chloride benchmark values were in Cannonsville Reservoir, which exceeded the single sample mean chloride concentration for 62% of all samples collected and the annual mean standard of 8 mg L^{-1} with a mean of 13 mg L^{-1} and Pepacton slightly exceeded the annual mean with a mean of 8.2 mg L^{-1}. Of the Croton System reservoirs sampled in 2022, all samples collected in Boyd Corners, Croton Falls, and New Croton exceeded the single sample maximum of 40 mg L^{-1} and annual mean benchmark of 30 mg L^{-1}. West Branch Reservoir exceeded the annual mean benchmark of 8 mg L^{-1} (16.4 mg L^{-1}) and 60% of the 15 samples collected exceeded the single sample maximum. Kensico Reservoir slightly exceeded the annual mean value of 8 mg L^{-1} (10.6 mg L^{-1}). All chloride samples were well below the health secondary standard of 250 mg L^{-1}.

Turbidity

Turbidity was generally low in all Delaware System reservoirs, with the highest number of exceedances of the single sample maximum of the 5 NTU benchmark value in Cannonsville (27% of samples). There were no exceedances in Rondout Reservoir. As typical for the Catskill reservoirs, Schoharie had the highest number of exceedances (80%) and Ashokan West Basin had the second highest (44%), but these percentages were lower than the previous year. Turbidity was generally low in the Croton System. The Croton System had relatively few turbidity exceedances, except Croton Falls (23%). There were no exceedances of the turbidity benchmark value in West Branch and Kensico reservoirs in 2022.

Nutrients

In the Delaware System, Cannonsville had the greatest number of total phosphorus (TP) single sample maximum exceedances of 15 µg L^{-1} (60% of all samples, all depths, and 65% of samples collected in the epilimnion at a depth of 3 m), Pepacton had fewer exceedances (14% with 25% in the epilimnion), and Neversink had no exceedances of the TP benchmark value. In the Catskill System, Ashokan East Basin had few exceedances (5% for all samples, with no exceedances in the epilimnion), Ashokan West Basin had 10% exceedances (all samples, with 8% in the epilimnion). In the Croton System, TP exceedances were high throughout, with the lowest number of exceedances in Boyd Corners (45%) and Lake Gleneida (44%). West Branch, with influences from the local watershed and the Delaware System, had few exceedances (19%). The benchmark value for the bioavailable form of phosphorus (soluble reactive phosphorus or SRP) was exceeded in five reservoirs: Cross River (8%), New Croton (5%), Croton Falls (2%), Pepacton (1%), and Kensico (1%).

For nitrate/nitrite for reservoirs sampled, only Cannonsville, Croton Falls and New Croton had exceedances of the single sample maximum value (21%, 11%, and 2% of samples, respectively). None of the reservoirs sampled for nitrate/nitrite exceeded the annual mean benchmark for nitrate/nitrite of 0.30 mg L^{-1} except Cannonsville, which slightly exceeded the mean benchmark of 0.30 mg L^{-1} with an annual mean of 0.32 mg L^{-1}.

Fecal Coliform Bacteria

Fecal coliform bacteria were low in reservoirs throughout the system in 2022. There were no exceedances of the single sample maximum of 20 fecal coliforms $100mL^{-1}$ in Ashokan West, Ashokan East, West Branch, and Middle Branch, and a single sample exceedance in Kensico. The highest number of exceedances was in Schoharie Reservoir (19% of samples), although there were fewer exceedances than in the previous year (45%). In the Croton System, the highest number of exceedances were in Titicus (15%) and Diverting (12%). In the Delaware System, there were few exceedances of the single sample maximum (2% in Cannonsville and Pepacton, 4% in Rondout, and 6% in Neversink).

3.8 Reservoir Trophic Status in 2022

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. A low trophic state is desirable because such reservoirs produce better water quality and better tasting water at the tap. Trophic state indices are generally calculated from data collected in the photic zone of the reservoir during the growing season (May through October). In 2022, the full complement of chlorophyll *a* samples were collected from the Catskill/Delaware System as well as from the EOH FAD basins.

Historical (2012-2021) annual median TSI based on chlorophyll *a* concentration is presented in boxplots for all reservoirs in Figure 3.6. This analysis generally indicates that all West of Hudson reservoirs (including Kensico and West Branch) and East of Hudson reservoir Boyd Corners fall into the mesotrophic category. East of Hudson reservoirs Croton Falls and Cross River tend to fall into the meso-eutrophic to eutrophic range. Comparisons to historic data were made using only the months collected from each reservoir in 2022.

In 2022, TSI was close to historic median levels in Schoharie Reservoir, higher than historic levels at Ashokan West but lower at Ashokan East (Figure 3.6). Elevated TSI at Ashokan West was correlated to elevated TP and particularly to elevated total dissolved phosphorus (TDP) (data not shown) brought into the reservoir via rain events. Additional conditions were also suitable for algal growth. Surface water temperatures were one to two degrees warmer than historic levels during the growing season and turbidity levels were never high enough to limit sunlight. In contrast, TSI was at its lowest since 2012 at Ashokan East despite better growing conditions (i.e., similar TP, temperature, and much lower turbidity) than at Ashokan West. The low TSI is likely related to reservoir operations. From mid-May to mid-October the West Basin was drawn down and the dividing weir gates closed which prevented the higher TSI West Basin water from entering the East Basin.

TSI levels in the Delaware System source water reservoirs were within their historical interquartile ranges but higher than their historical medians. Like the Catskill System, the slightly elevated TSI is probably related to phosphorus inputs from rain events. In contrast, the downstream reservoirs of the Delaware System were close to their historic medians (i.e., Rondout) or were much lower (i.e., West Branch and Kensico). Low TSI at West Branch was probably related to its operational status. In 2022, West Branch was operated almost exclusively in “reservoir” mode allowing the relatively low TSI water from Rondout to dominate the blend of waters making up West Branch.

TSI trends varied in the Croton System. TSI was lower than historic levels at EOH FAD basins Boyd Corners, Croton Falls, and Cross River. Although total and dissolved phosphorus were elevated in all the EOH FAD basins, much of the phosphorus was in particulate form and therefore not immediately available to algae. We also hypothesize that non-motile algae could not utilize dissolved phosphorus released from bottom sediments during the summer/autumn period due to an extended period of stratification in 2022. In contrast, productivity was elevated at New Croton Reservoir in 2022, especially in the spring, and algal counts remained elevated throughout the year.

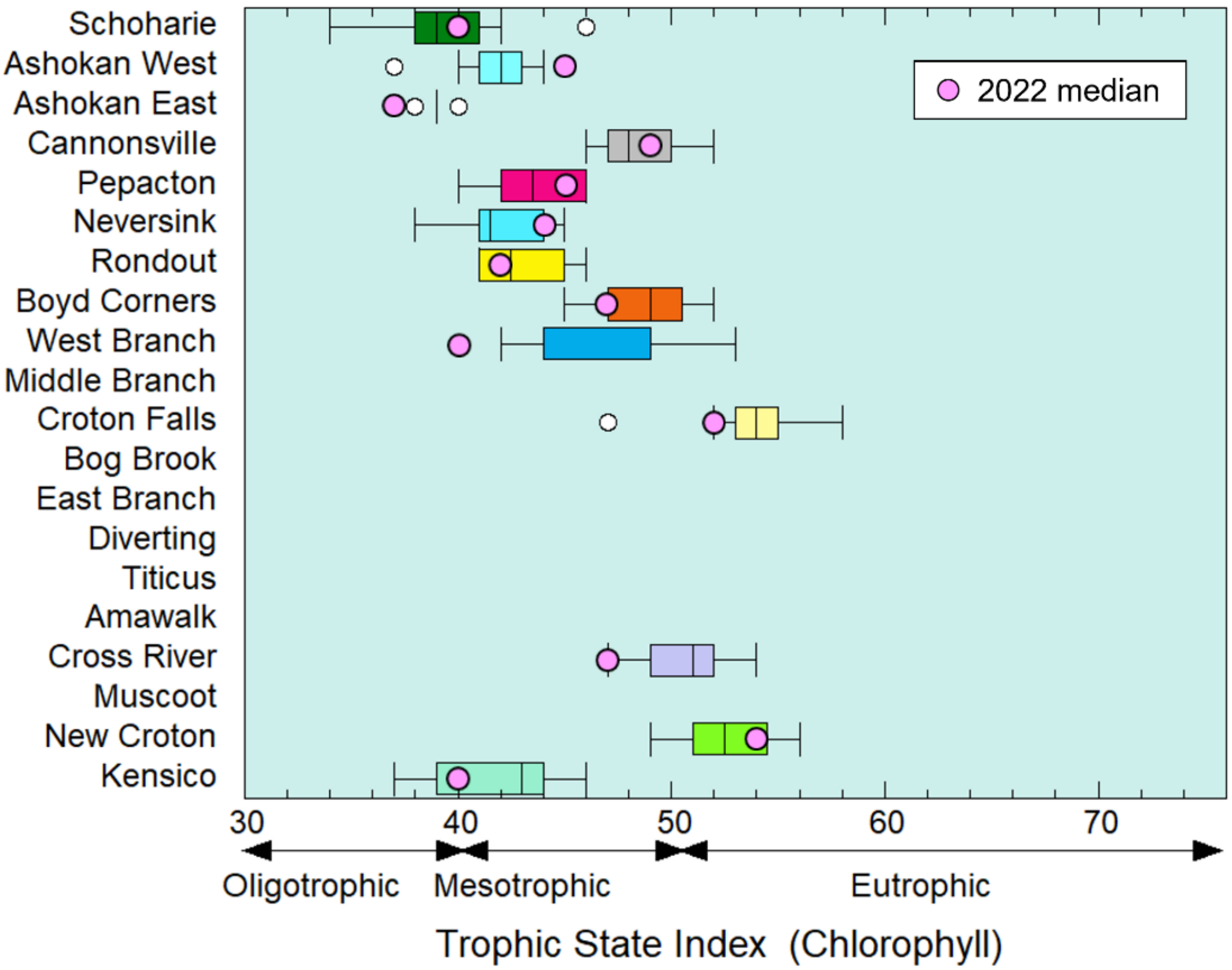


Figure 3.6 Annual median Trophic State Index (TSI) in NYC Water Supply reservoirs (2022 vs. 2012-2021), with the median displayed as a solid dot and outliers as open circles. In general, data were obtained from epilimnetic depths at multiple sites. Sample frequency is described in section 3.1. TSI is based on chlorophyll *a* concentration.

3.9 Water Quality in the Major Inflow Streams in 2022

The stream sites discussed in this section are listed in Table 3.6, with locations shown in Figure 3.7. These stream sites were chosen because they are immediately upstream from the six Catskill/Delaware System reservoirs and five of the Croton reservoirs. They represent the bulk of the water entering the reservoirs from their respective watersheds. The exception is New Croton Reservoir, whose major inflow is from the Muscoot Reservoir release. Kisco River and Hunter Brook are tributaries to New Croton Reservoir and represent water quality conditions in the New Croton watershed.

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

The 2022 results presented here are based on routine grab samples generally collected once a month, but also include additional samples from locations (Esopus Creek at Boiceville, West Branch Delaware River at Beerston, and Neversink River near Claryville) where ongoing studies include fixed frequency samples that would be comparable to the routine samples and increase the number of samples for the year. Note that monitoring of EOH streams did not start until June of 2022. The 2022 results are plotted by collection date and superimposed on the historic monthly boxplots which are centered on the 15th of the month. The figures in this section show the 2022 results with a boxplot of historical (2012-2021) monthly values for comparison.

Table 3.6 Site codes and site descriptions for the major inflow streams.

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

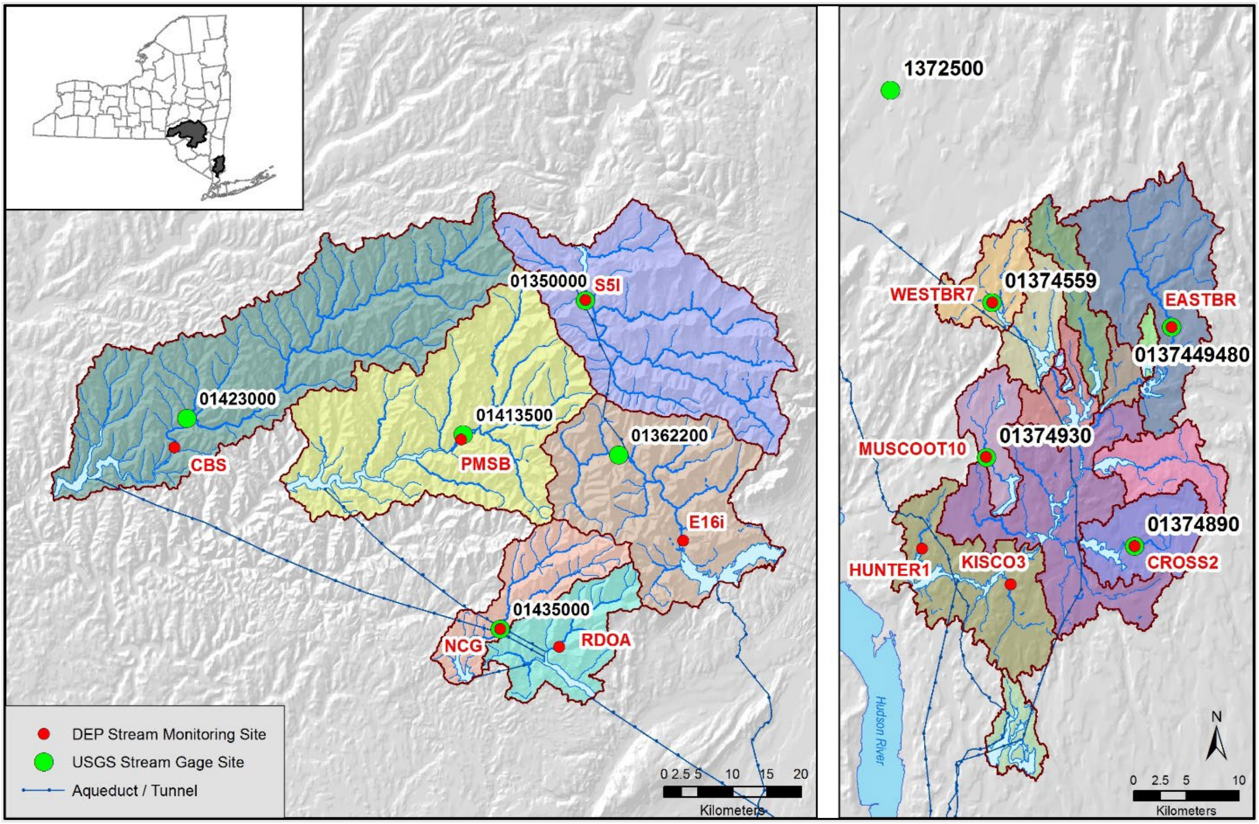


Figure 3.7 Locations of major inflow stream water quality sampling sites and USGS gage stations used to calculate areal-normalized streamflow values (see Section 2.3).

Turbidity

High-frequency monitoring at the main inflows for five of six WOH reservoirs (all except Pepacton) captures the dynamic picture of turbidity in near-real-time. An evaluation based on grab sample data from routine fixed-frequency monitoring showed that all WOH streams exceeded or were equivalent to their historical 75th percentiles for turbidity on at least one occasion during the February to April period (Figure 3.8). Snowmelt events in February and March and rain events from February to April were associated with the elevated turbidity. However, for streams located in predominately forested watersheds (PMSB, NCG, and RDOA) grab sample turbidity results were relatively low, with a maximum of 4.2 NTU during this period. Much higher grab sample turbidity peaks occurred at CBS (40 NTU), S5I (110 NTU), and E16I (240 NTU) in watersheds with higher amounts of agricultural land (CBS) or in watersheds with easily erodible clays (S5I and E16I). Except for the Neversink River (NCG) and Esopus Creek (E16I) in June, turbidity levels were mostly low for the remainder of the year due to generally low rainfall from May-August and for some watersheds in October. Although samples were limited in the EOH system, turbidities were largely within historical monthly interquartile ranges or lower. Occasional excursions above the historic 75th percentile occurred when samples were collected within three days post rain events, with turbidity ranging up to 4.6 NTU at the Kisco River (KISCO3), 12 NTU at the East Branch Croton River (EASTBR), 13 NTU at Hunter Brook (HUNTER1), and 17 NTU at the West Branch of the Croton River (WESTBR7).

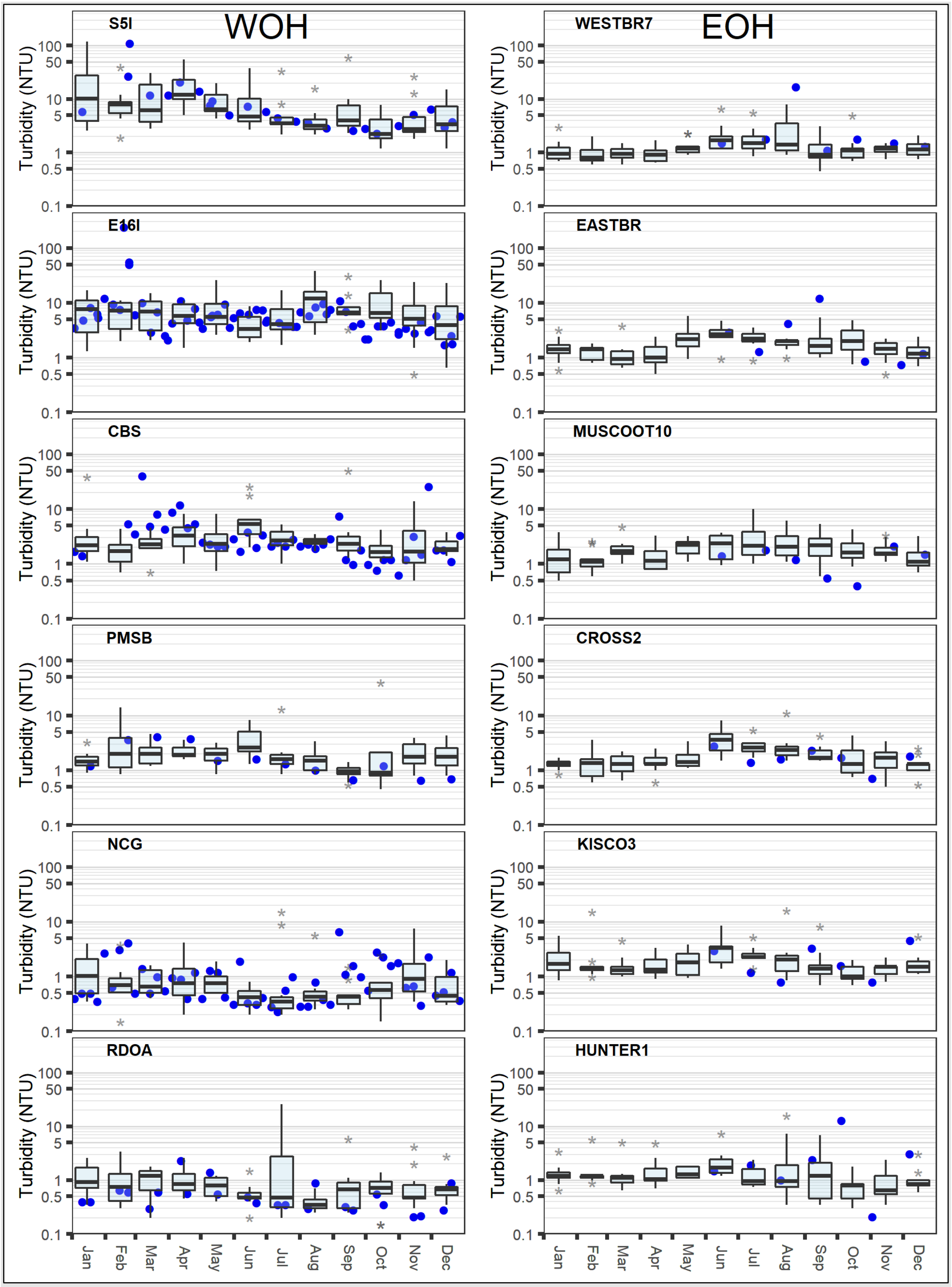


Figure 3.8 Turbidity values in 2022 from routine stream samples with a monthly boxplot of the historic (2012-2021) routine monthly samples. Note the y-axis is a log scale.

Total Phosphorus

The 2022 total phosphorus (TP) concentrations (Figure 3.9) generally followed the same patterns observed for turbidity. In cases where turbidity was high, particulate phosphorus (TP-TDP) was the dominant form and likely explained by the rain and snowmelt events discussed in the turbidity section. Several notable exceptions to the positive turbidity-phosphorus correlation were observed at CROSS2, HUNTER1, and KISCO3 where elevated TP was not associated with elevated turbidity. In these cases, much of the phosphorus was dissolved (i.e., soluble reactive phosphorus) which may have both anthropogenic (i.e., septic effluent) or natural sources (e.g., animal feces or microbial breakdown of plant material).

Fecal Coliform Bacteria

Fecal coliform bacteria in the WOH main inflow streams exceeded their historical monthly medians on several occasions during the January through May period (Figure 3.10). Like turbidity and TP results, high fecal coliform counts were frequently associated with elevated stream flow resulting from snowmelt and rain events. Stream flow steadily declined through August except for some minor rain events. As a result, fecal coliform counts mostly stayed near their respective interquartile ranges with some very low values recorded in July at S5I and NCG. Despite an increase in system-wide and more localized rain events starting in late August, WOH stream fecal coliform counts only occasionally exceeded their historic 75th percentile levels for the remainder of the year. From June to August, fecal coliform results were usually lower or within historical monthly ranges in the EOH streams coinciding with the low rainfall and flows observed during this time. Following this period of accumulation and a large rain event in early September, the highest fecal coliform counts of the year were observed in most of the EOH streams with fecal coliform from four streams ranging from 600 to 3,500 fecal coliforms 100mL^{-1}. Higher counts were also observed in October and December following rain events in early and mid-October and throughout December. A fecal coliform benchmark of 200 coliforms 100mL^{-1} relates to the NYSDEC water quality standard for fecal coliforms (which is a monthly geometric mean of five samples) (6NYCRR §703.4b). Of the major inflow stream samples collected in 2022, HUNTER1 and KISCO3 exceeded the benchmark five times, MUSCOOT10 and CROSS2 three times, and EASTBR one time. Most of the highest excursions can be attributed to rain events and the resulting runoff.

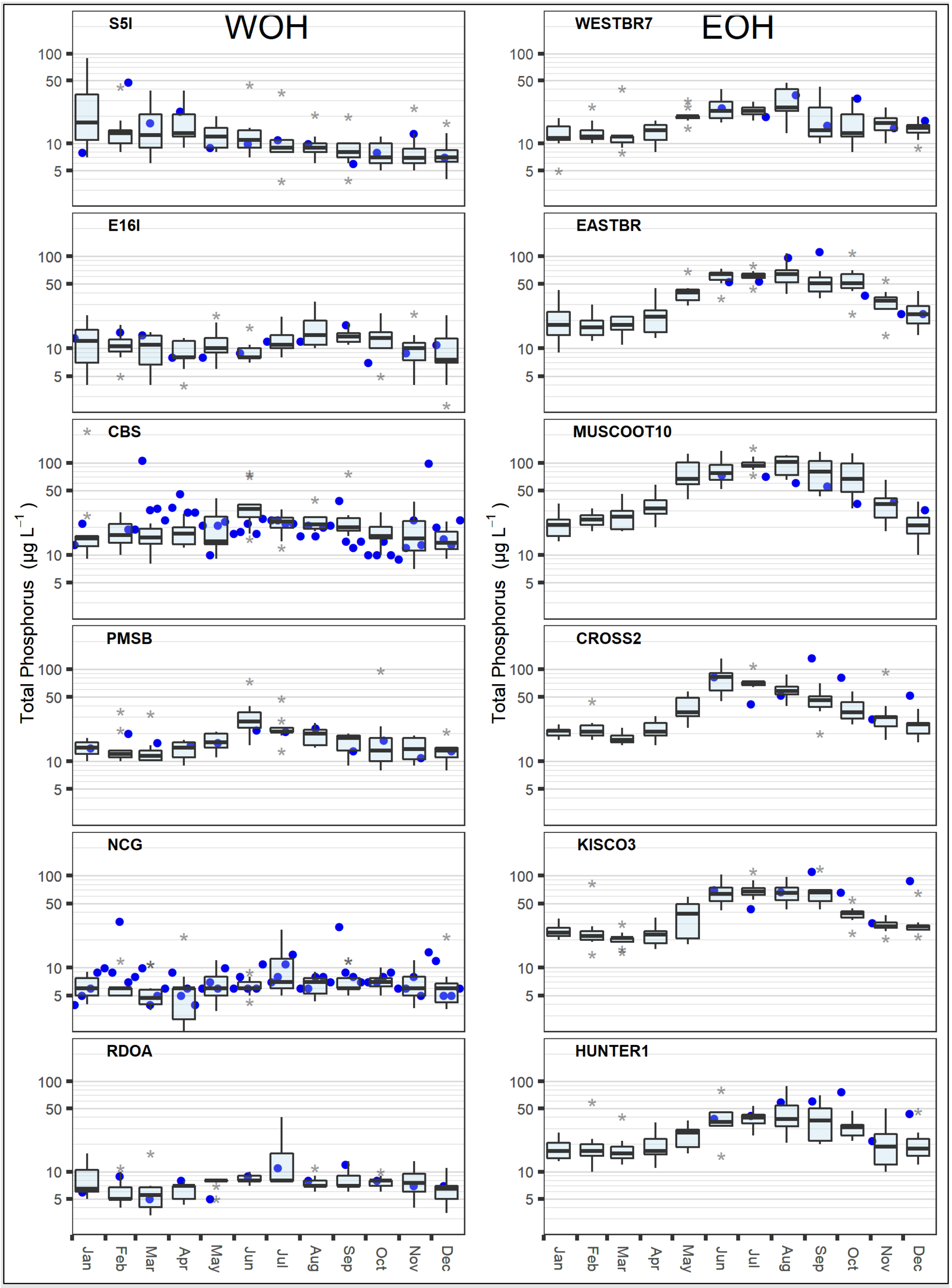


Figure 3.9 Total phosphorus values in 2022 from routine stream samples with a monthly boxplot of the historic (2012-2021) routine monthly samples. Note the y-axis is a log scale.

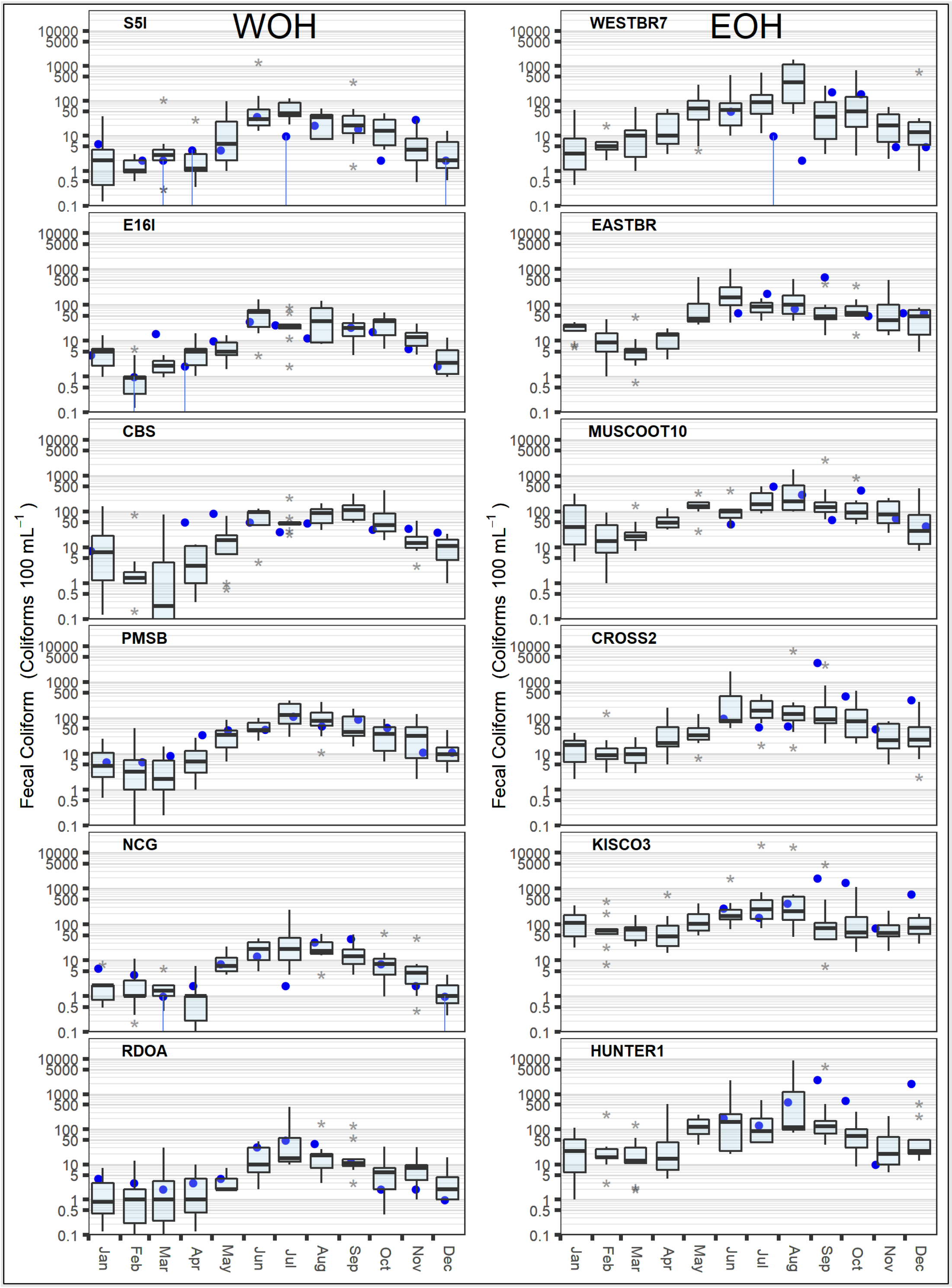


Figure 3.10 Fecal coliform values in 2022 from routine stream samples with a monthly boxplot of the historic (2012-2021) routine monthly samples. Note the y-axis is a log scale.

3.10 Stream Comparisons to Benchmarks in 2022

Select water quality benchmarks have been established for reservoirs and reservoir stems (any watercourse segment which is a tributary to a reservoir and lies within 500 feet of the full reservoir) in the WR&R (DEP 2019a). In this section, the application of these benchmarks has been extended to 40 streams and reservoir releases to evaluate stream status in 2022. The benchmarks are provided in Table 3.7.

Table 3.7 Stream water quality benchmarks as listed in the WR&R (DEP 2019a). The benchmarks are based on 1990 water quality results.

Analyte	**Croton System**		**Catskill/Delaware Systems**	
	Annual Mean	**Single Sample Maximum**	**Annual Mean**	**Single Sample Maximum**
Alkalinity (mg $CaCO_3$ L^{-1})	N/A	$\geq$40.00	N/A	$\geq$10.00
Ammonia-N (mg L^{-1})	0.1	0.2	0.05	0.25
Dissolved chloride (mg L^{-1})	35	100	10	50
Nitrite+Nitrate (mg L^{-1})	0.35	1.5	0.4	1.5
Organic Nitrogen [1]	0.5	1.5	0.5	1.5
Dissolved sodium (mg L^{-1})	15	20	5	10
Sulfate (mg L^{-1})	15	25	10	15
Total dissolved solids (mg L^{-1})[2]	150	175	40	50
Total organic carbon (mg L^{-1})[3]	9	25	9	25
Total suspended solids	5	8	5	8

[1] Organic nitrogen is not analyzed currently as a total fraction but dissolved organic nitrogen can be calculated.

[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 H along with site descriptions, which appear next to the site codes. Note that the Catskill/Delaware System criteria are applied to the release from West Branch Reservoir (WESTBRR) since that release usually is affected by Delaware System water. Below is a discussion of selected sites and analytes. Please note that non-FAD basin EOH streams were generally only sampled from June through December, so 2022 results will not necessarily be comparable to past years. Samples at WOH streams and at several FAD basin EOH stream sites (BOYDR, CROFALLSVC, CROSSRVVC) were collected all 12 months.

Alkalinity

Alkalinity is a measure of water's ability to neutralize acids and is largely controlled by the abundance of carbonate rocks/surficial materials in a watershed and by the amount of precipitation the watershed receives. Elevated precipitation lowers alkalinity by diluting the cations that contribute to alkalinity while periods of drought can have a concentrating effect. 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. Streams from these watersheds were below the alkalinity single sample benchmark of 10 mg L^{-1} in 85 of 120 samples collected in 2022. In contrast, higher buffering capacity is generally observed in the Cannonsville, Pepacton, and Schoharie watersheds. Here, only 16 of 167 stream samples were below the 10 mg L^{-1} benchmark. A benchmark of 40 mg L^{-1} is used for the Croton System streams; the higher benchmark reflects the much higher natural buffering capacity of this region. However, less buffering capacity does occur in the Boyd Corners and West Branch watersheds with samples from stream sites WESTBR7, BOYDR, GYPSYTRL1 generally below the single sample benchmark.

Chloride

The Catskill/Delaware System annual mean benchmark of 10 mg L^{-1} was exceeded in 11 of the 24 streams monitored in the Catskill/Delaware System with the highest mean, 32.9 mg L^{-1}, occurring at site NK6 on Kramer Brook in the Neversink watershed. In contrast to Kramer Brook, chloride concentrations in two additional monitored streams in the Neversink watershed, Aden Brook (NK4) and the Neversink River (NCG), were quite low, averaging 4.4 and 3.5 mg L^{-1}, respectively. The Kramer Brook watershed is very small (<1 square mile), is bordered by a state highway and contains pockets of development, all of which contribute to the relatively high chloride levels. The single sample Catskill/Delaware chloride benchmark of 50 mg L^{-1} was not exceeded in 2022.

Other Catskill/Delaware System streams which exceeded the annual mean chloride benchmark included Bear Kill at S6I (24.6 mg L^{-1}), Manor Kill at S7I (10.2 mg L^{-1}) and Schoharie Creek at S5I (11.8 mg L^{-1}), all located within the Schoharie watershed; Trout Creek at C-7 (17.8 mg L^{-1}), Loomis Brook at C-8 (15.0 mg L^{-1}), and the West Branch of the Delaware River at CBS (13.8 mg L^{-1}), all tributaries to Cannonsville Reservoir; and Chestnut Creek at RGB (16.6 mg L^{-1}), a tributary to Rondout Reservoir. Two Pepacton streams, Tremper Kill at P-13 (11.2 mg L^{-1}) and, the East Branch of the Delaware River at PMSB (13.3 mg L^{-1}), exceeded the average annual benchmark in 2022. In general, higher chloride concentrations correlate with the percentage of impervious surfaces (e.g., roads, parking lots) in the watersheds (Mayfield and Van Dreason 2019).

The Croton System annual mean chloride benchmark of 35 mg L^{-1} was exceeded in all 16 monitored Croton streams. Annual means exceeding the benchmark ranged from 38.0 mg L^{-1} in Cross River at CROSS2 to 183.9 mg L^{-1} in Michael Brook at MIKE2. The mean 2022 chloride concentration for all 16 Croton streams was 75.2 mg L^{-1}, substantially higher than the streams of the Catskill/Delaware System, which together averaged 10.2 mg L^{-1}. The single sample chloride benchmark is 100 mg L^{-1} for streams of the Croton System. In 2022, this benchmark was commonly exceeded at Michael Brook at MIKE2, the Muscoot River at MUSCOOT10, the Kisco River at KISCO3, the Amawalk Reservoir Release at AMAWLKR and at the Long Pond outflow at LONGPD1. Road salt is considered the primary source of chloride in these systems, while secondary sources include septic system leachate, water softening brine waste, and wastewater treatment plant effluent. The much greater chloride concentrations in the Croton System are due to higher road and population densities in these watersheds (Van Dreason 2022) 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 H).

Total Dissolved Solids

The analysis of 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 2022, 14 of 24 Catskill/Delaware streams had at least one value greater than the TDS single sample maximum of 50 mg L^{-1}. These same streams plus WESTBRR also exceeded the TDS annual mean benchmark of 40 mg L^{-1}. TDS in Catskill/Delaware streams was strongly correlated with chloride with chloride accounting for 92 percent of the variation in TDS (Figure 3.11). All excursions of the single sample maximum were associated with chloride concentrations that exceeded approximately 11.7 mg L^{-1}.

Like the Catskill/Delaware streams, Croton stream TDS was strongly correlated to chloride concentrations (Figure 3.12). The much higher Croton TDS is mostly due to greater road density and deicer usage in the Croton watersheds. The TDS single sample maximum of 175 mg L^{-1} was exceeded in 14 of 16 streams while the annual mean benchmark of 150 mg L^{-1} was exceeded in 15 of 16 Croton streams in 2022. Three stream sites, LONGPD1, CROFALLSVC and MIKE2, exceeded the standard throughout the year.

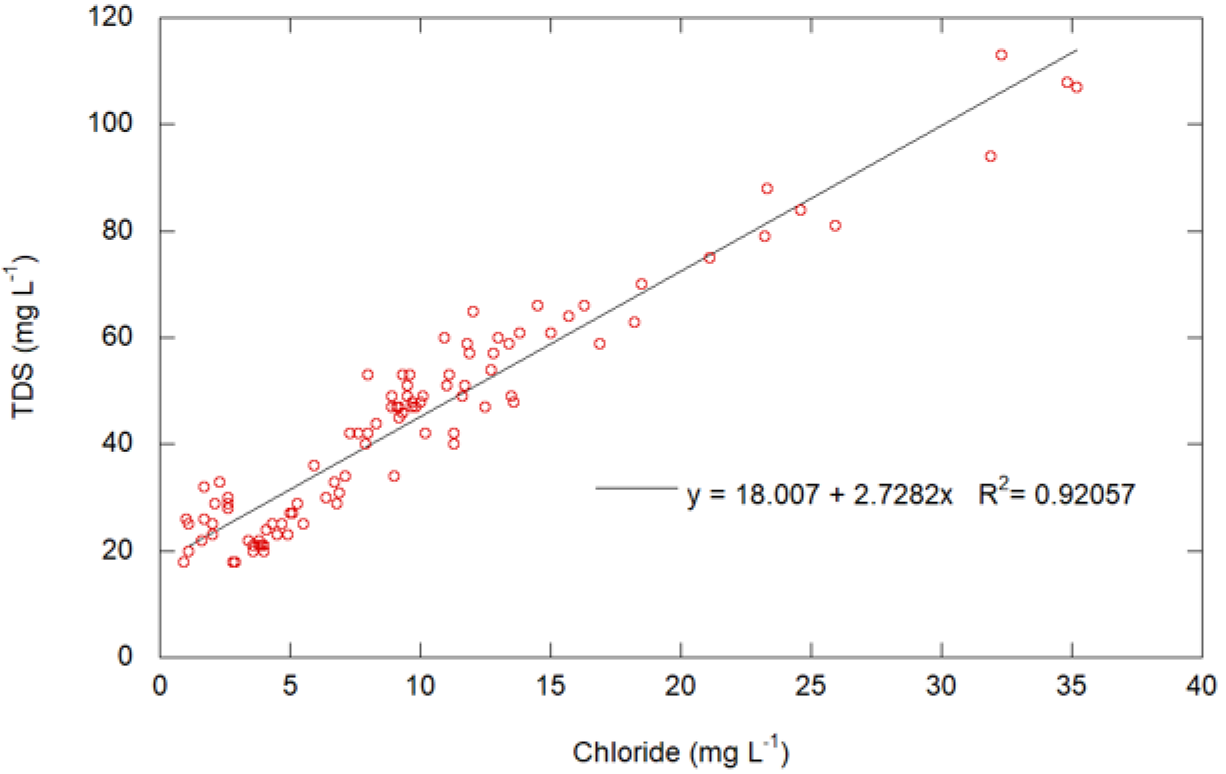


Figure 3.11 Total Dissolved Solids (TDS) versus chloride for Catskill/Delaware System streams in 2022.

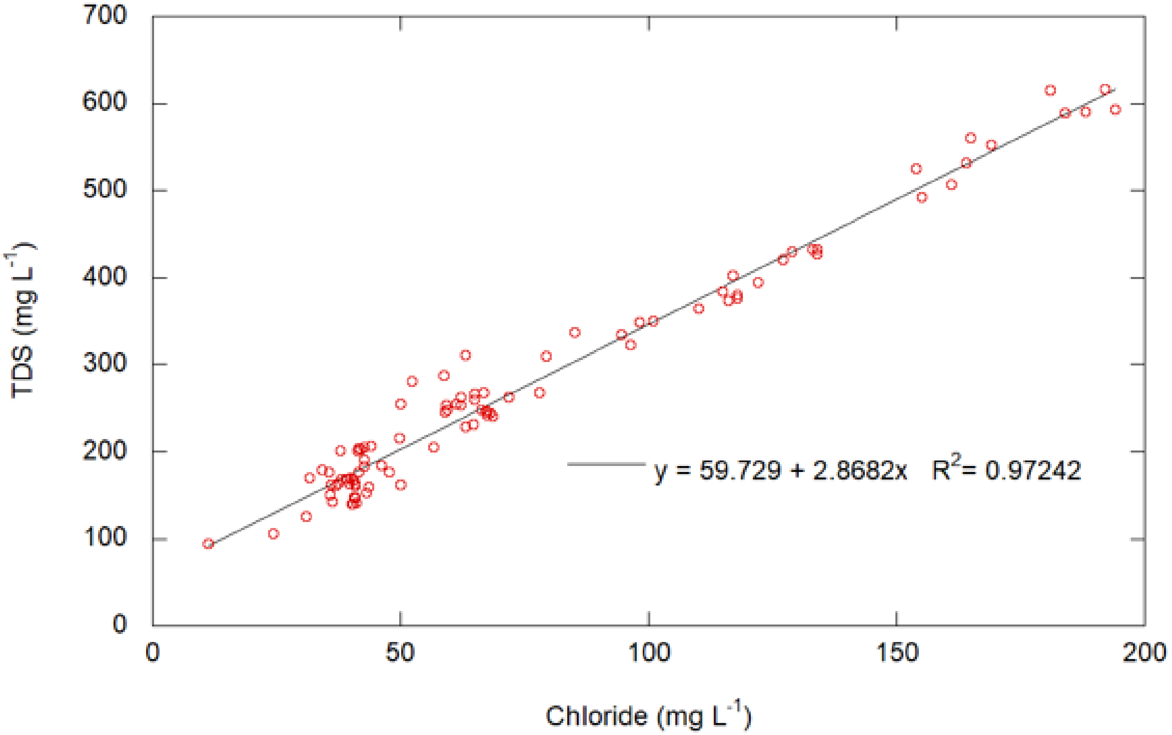


Figure 3.12 Total Dissolved Solids (TDS) versus chloride for Croton System streams in 2022.

Nitrogen

Nitrogen results were generally below benchmarks in the Catskill/Delaware System in 2022. No stream exceeded the single sample nitrate benchmark of 1.5 mg L^{-1}. The mean annual benchmark of 0.40 mg L^{-1} was only exceeded at the West Branch of the Delaware River at CBS (0.52 mg L^{-1}) and at Fall Clove at P-8 (0.42 mg L^{-1}). Likely sources for nitrate at CBS are fertilizers associated with the relatively high agricultural activity in this basin and multiple wastewater treatment plants that discharge to the river. Reasons for the high nitrate at P-8 are not clear as parcel density and agricultural density are relatively low and wastewater treatment plants are not present in this basin.

Michael Brook at MIKE2 (6.71 mg L^{-1}), Muscoot River at MUSCOOT10 (0.36 mg L^{-1} and), and the Kisco River at KISCO3 (0.46 mg L^{-1}), were the only Croton streams to exceed the nitrate annual mean benchmark of 0.35 mg L^{-1} in 2022. The single sample nitrate benchmark of 1.5 mg L^{-1} was also exceeded at Michael Brook in all seven monthly samples with the highest concentrations, 9.05-9.66 mg L^{-1}, occurring in summer months when streamflow was low. Possible nitrogen sources are plentiful given the relatively high development in the Michael

Brook, Muscoot River and Kisco River watersheds, including inputs from local wastewater treatment plants.

All ammonia results complied with the single sample ammonia benchmark of 0.25 mg L^{-1} and the mean ammonia annual benchmark of 0.05 mg L^{-1} in the Catskill/Delaware System in 2022. Ammonia was only detected in 19 of 283 samples (all streams combined) with detected concentrations relatively low, ranging from 0.02 to 0.07 mg L^{-1}. Three Croton streams exceeded the ammonia single sample maximum of 0.20 mg L^{-1} in 2022. The release from Cross River Reservoir (CROSSRVVC) exceeded the benchmark in November (0.31 mg L^{-1}) and in December (0.21 mg L^{-1}). The release from Croton Falls Reservoir (CROFALLSVC) exceeded the benchmark in October (0.22 mg L^{-1}) while a result of 0.31 mg L^{-1} was observed at the Boyd Corners release (BOYDR) in September. These elevated results are likely due to the release of ammonia from upstream anoxic reservoir sediments in late summer/autumn.

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 2022. Individual sample results ranged from 2.0 to 14.24 mg L^{-1} with a collective average of 3.6 mg L^{-1}. Two Croton stream results were above the Croton System single sample maximum of 25 mg L^{-1} in November of 2022: Michael Brook at MIKE2 (31.8 mg L^{-1}) and the East Branch of the Croton River at EASTBR (25.4 mg L^{-1}). Sulfate is a common ingredient in personal care products (e.g., soaps, shampoos, and toothpaste) and mineral supplements that can be introduced to waterbodies in the household waste stream. Note that USEPA does not consider sulfate to be a health risk and has only established a secondary maximum contaminant level of 250 mg L^{-1} as a benchmark for aesthetic consideration (i.e., salty taste).

Dissolved Organic Carbon

Dissolved organic carbon (DOC) was used in this analysis instead of total organic carbon since the latter is not routinely analyzed as part of the DEP monitoring program. Previous work has shown that DOC constitutes most of the organic carbon in stream and reservoir samples. The DOC single sample benchmark of 25 mg L^{-1} and annual mean benchmark of 9.0 mg L^{-1} were not surpassed by any stream in the Catskill/Delaware or Croton systems in 2022. In the Catskill/Delaware System, single samples ranged from 0.6 to 4.7 mg L^{-1} and stream annual means ranged from 0.9 to 2.8 mg L^{-1}. DOC is generally higher in the Croton System compared to the Catskill/Delaware System (although still well below benchmarks) due to a higher occurrence of wetlands in the Croton watersheds. Mean DOC in the Croton System ranged from 3.2 to 6.0 mg L^{-1} in 2022, and the highest single sample DOC, 9.6 mg L^{-1}, occurred at Cross River (CROSS2).

3.11 Water Quality Evaluation for 1997 NYSDEC MOU Addendum E

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

3.11.1 Data Analysis

The means of the analytes required for Addendum E were calculated for each site and compared to the stream water quality guidance values listed in Table 3.8. Values below the detection limit were converted to one-half the detection limit for the purpose of calculating mean values. The median is used for total coliform and the geometric mean is used for the fecal coliform evaluations. Coliform values listed as "CONF" in the dataset were not used in the summary statistics for each sampling site because they could not be converted into a numerical value. To calculate the compliance of streams with the Addendum E pH standards ($6.5 \leq \text{pH} \leq 8.5$), this protocol converts pH values to hydrogen ion concentrations, calculates the mean, and compares the mean to the pH standards also expressed as hydrogen ion concentrations (*i.e.*, $3.1623 \times 10^{-7} \geq [H^+] \geq 3.1623 \times 10^{-9}$).

Table 3.8 Water quality guidance values used to compare routine stream monitoring data for Addendum E.

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

3.11.2 Water Quality Results

In 2022, 522 samples were collected at 75 sites, analyzed, and later compared to water quality guidance values. Table 3.9 lists sites where either the mean value contravened water quality standards, or if data from a site included more than two "spikes" in one or more of the seven parameters tested. A "spike" is defined by Addendum E as an ambient water quality concentration found to be above the guidance value by three standard deviations of the mean at a given site. There were 14 sites at which the mean value contravened the Table 3.8 guidance values, but few exceeded the spike threshold (see fifth column of Table 3.9). For information regarding biomonitoring impairment ratings during 2022, see Section 3.13.

Table 3.9 Routine stream sampling sites with contraventions of water quality guidelines in 2022.

Reservoir Basin	Site	Mean contravened water quality guidelines	Analytes exceeding spike threshold[1]	Number exceeding spike threshold	Spike threshold contravention
Kensico Basin					
Kensico	N5-1	TP	Fecal coliform	1	N
		TP	Total coliform	1	N
New Croton System					
Amawalk	MUSCOOT10	TP	none	0	
Cross River	CROSS2		none	0	
East Branch	EASTBR		none	0	
New Croton	HUNTER1	Fecal coliform			
	KISCO3				
		TP	none	0	
	STONE5	Fecal coliform			
		TP	none	0	
Catskill System					
Ashokan	AEHG	pH (acid)	none	0	
Schoharie	SSHG		none	0	
Delaware System					
Neversink	NCG	pH (acid)	TP	2	N
	NK4		Fecal coliform	1	N
	NK6	pH (acid)	none	0	
Rondout	RDOA	pH (acid)	none	0	
	RRH		none	0	

[1] There is no spike threshold for dissolved oxygen.

3.12 Zebra Mussel Monitoring

DEP monitored Amawalk, Muscoot, and New Croton reservoirs in 2021 and 2022 for the presence of zebra mussel (*Dreissena polymorpha*) using multiplate settlement substrates.

A high intensity precipitation event in August through early September 2021 transported both veligers and rafting adult zebra mussels from Lake Mahopac into Amawalk Reservoir. The first attached adult zebra mussels recorded in the NYC water supply were found in Amawalk Reservoir on the multi-plate sampling apparatus in September 2021. Surveys of Amawalk Reservoir in 2022 showed a significant advancement of the infestation with most nearshore substrate colonized by several year classes of zebra mussels. This advancement was also evident during a late summer 2022 drawdown of Amawalk Reservoir exposing nearshore substrate that was colonized by zebra mussels.

A survey conducted in New Croton Reservoir in June 2022 revealed the presence of settled adults on naturally occurring substrate near the weir separating Muscoot from New Croton Reservoir indicating successful downstream transport. A July 2022 snorkeling survey of New Croton Reservoir revealed the presence of low densities of attached adults distributed throughout the entire length of the reservoir. Additionally, low concentrations of veligers were detected in plankton samples throughout the New Croton Reservoir. DEP is continuing to monitor this emerging infestation. A multi-directorate working group within BWS has been convening on a regular basis to develop management and impact mitigation plans. These discussions have led to additional sampling in New Croton Reservoir, planned remotely operated vehicle (ROV) surveys of vulnerable infrastructure, updating DEP's boat and equipment decontamination protocols, and enhanced consideration of activities that could spread them to unimpacted reservoirs. DEP is also convening an expert panel consisting of experts from academia, other impacted utilities, and control specialists to help identify potential risks to water quality and infrastructure, and to propose treatment and mitigation options to address those risks. The outcome of the panel's work will aid in development of response plans. The panel will meet in 2023.

3.13 Stream Biomonitoring

Biomonitoring assessments are made following protocols developed by the New York State Stream Biomonitoring Unit (NYSDEC 2021). Five metrics, each a different measure of biological integrity, are calculated and averaged to produce a multi-metric Biological Assessment Profile (BAP) score ranging from 0-10. These scores correspond to four levels of impairment (non-impaired, 7.5-10; slightly impaired, 5-7.5; moderately impaired, 2.5-5; severely impaired, 0-2.5). The five metrics used in the analysis are total number of taxa (species richness); EPT richness (Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies)); Hilsenhoff Biotic Index for taxa tolerance to organic pollution (HBI), Percent Model Affinity (PMA), and since 2012, Nutrient Biotic Index-Phosphorus (NBI-P).

In 2022, DEP collected samples from 36 sites in 23 streams throughout New York City's watershed: 11 sites in the Croton System, 12 sites in the Catskill System, and 13 sites in the Delaware System (for site locations, see). This total is comprised of 20 routine sites that are monitored annually and 16 Rotating Integrated Basin Studies (RIBS) that get sampled on a five-year schedule, although some of the rotating sites were sampled at longer intervals.

East of Hudson – Croton System

Of the 11 sites sampled in 2022, all six routine sites ranked as slightly impaired while all five RIBS sites were moderately impaired. Nine of the 11 sites had BAP scores lower than their respective period of record means (sites 146, 140, 142, 102, 109, 134, 112, 151, 122) and two sites (sites 105 and 130) scored higher (Figure 3.13). The lower-than-mean BAP score at the routine sites are indicative of a general decline in BAP scores over the period of record (Figure 3.14).

Two (Angle Fly Brook - site 102 and the Stonehill River – site 142) of the six routine Croton System sites assessed in 2022 showed a decreased BAP compared to the previous year. The remaining sites showed slight improvements (Figure 3.13 and Figure 3.14). Angle Fly Brook showed a slight decrease in BAP scores in 2022 after five consecutive years of improving BAP scores that elevated Angle Fly Brook from moderately to slightly impaired. It remained slightly impaired in 2022. The absence of stoneflies and the decreased abundance and diversity of mayflies in 2022 influenced the PMA and was responsible for the observed decrease. The mayflies still present in 2022 were intolerant, suggesting that water quality was not the limiting factor. Site 102 was dry on August 15, 2022 and could not be sampled. There was sufficient flow on September 27, 2022 to complete this site and this flow regime may have influenced the macroinvertebrate community and BAP score. Slight differences in percent EPT influenced the decline at site 142 between 2021 and 2022.

The increased BAP score seen at the Muscoot River (site 112) between 2021 and 2022 (Figure 3.14) is largely the result of greater species richness including stoneflies, which were absent in 2021, and a decreased dominance by beetles. DEP will continue to monitor these sites in 2023.

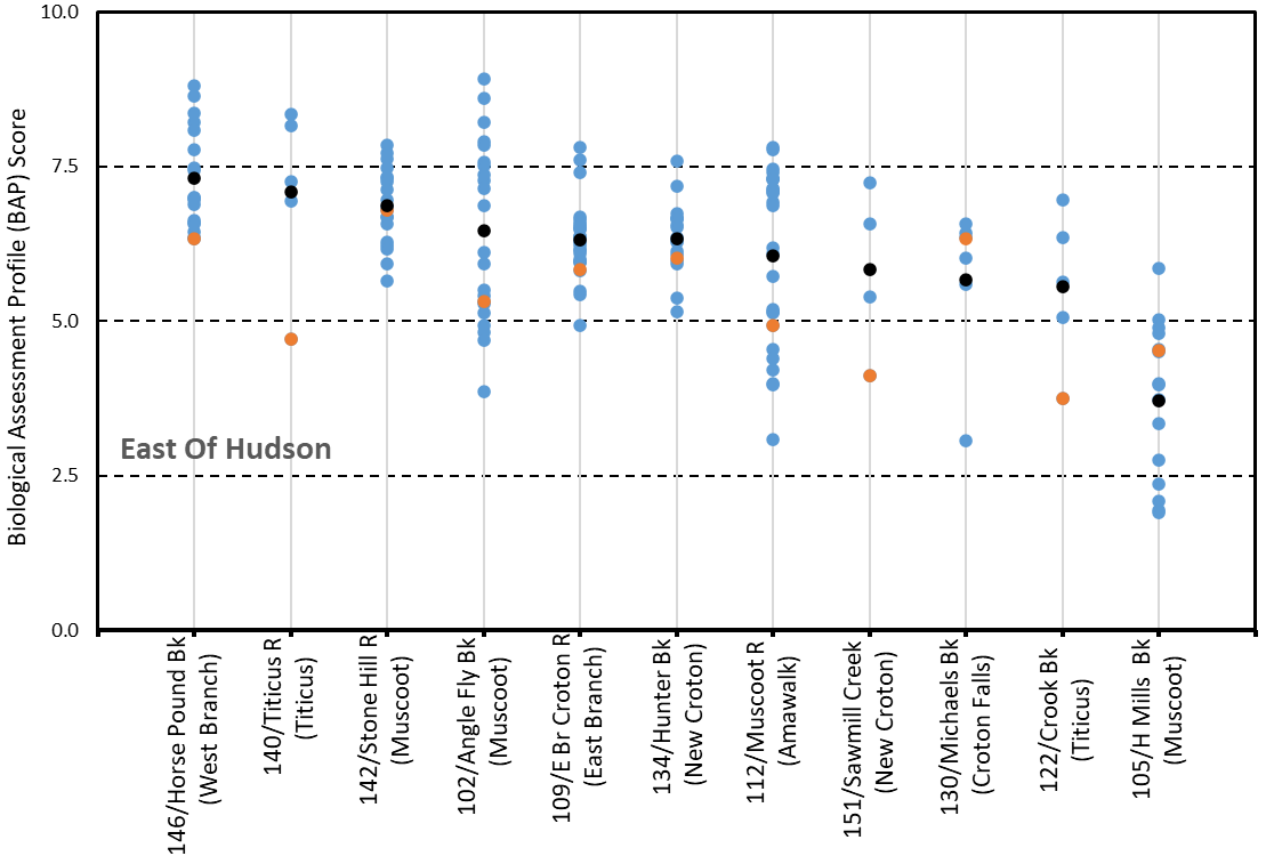


Figure 3.13 BAP scores for East of Hudson biomonitoring sites sampled in 2022, arranged by mean score from highest to lowest. Black dots represent the mean score, orange dots the 2022 score, and the blue dots the pre-2022 scores. The watershed is indicated in parentheses.

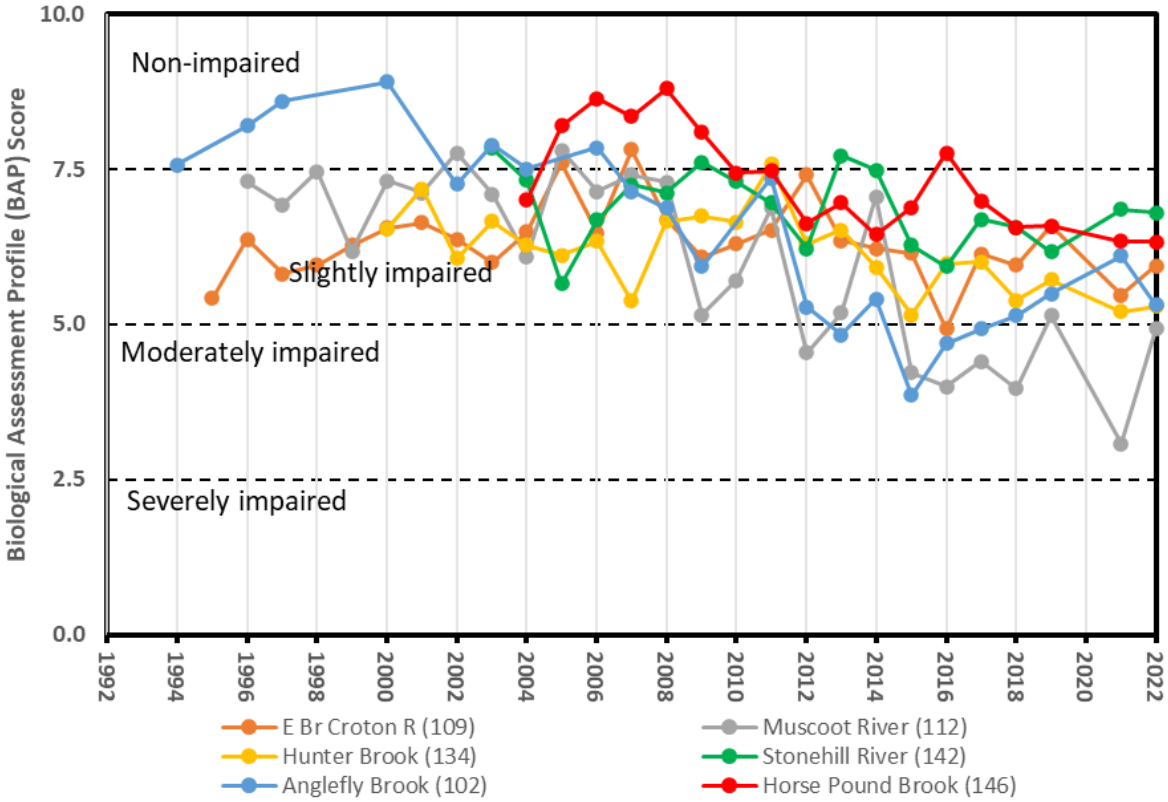


Figure 3.14 BAP scores for Croton System routine biomonitoring sites from 1994-2022.

Scores for two of the five rotating sites sampled in the Croton System in 2022 increased as compared to their last sampling rotation (sites 105 and 130), while the remaining three decreased (sites 122, 140, and 151) (Figure 3.15). Crook Brook (site 122) and the Titicus River (site 140), both tributaries of the Titicus Reservoir, declined from slightly to moderately impaired, as did Sawmill Brook (site 151), a New Croton Reservoir tributary (Figure 3.15). The differences observed in Crook Brook (site 122) in 2022 versus the last rotation (2017) arise from lower numbers of mayflies and caddisflies, and greater numbers of generalist beetles (67%), which drive species richness, PMA, NBI, and thus the lower BAP score. Despite the decline seen in 2022, the most abundant mayflies at site 122 were highly intolerant and their presence suggests good water quality.

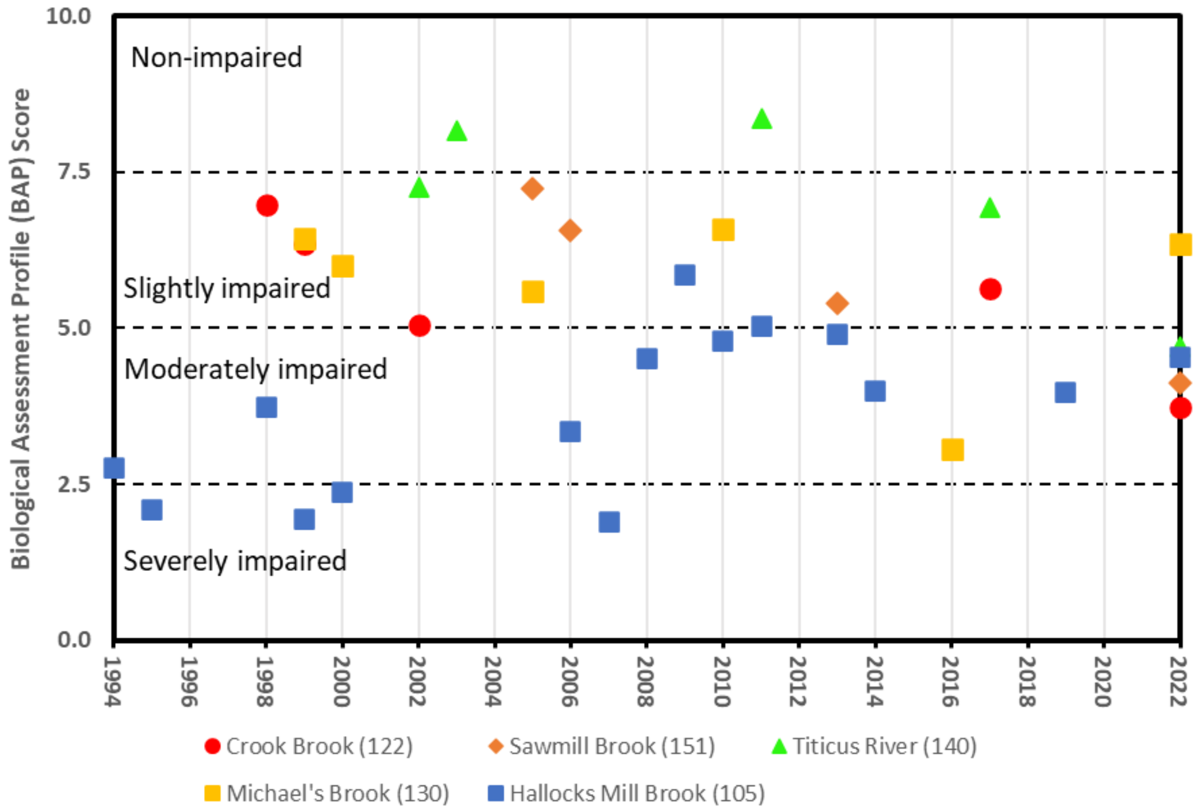


Figure 3.15 BAP scores for 2022 Croton System RIBS sites within the East of Hudson District.

The Titicus River (site 140) showed a decrease in BAP scores for the third consecutive sampling (2011, 2017, 2022) and has moved from non-impaired to moderately impaired (Figure 3.15). The presence of many generalist taxa, the dominance of beetles (47% of the total), and the loss of stoneflies influenced the score. The presence of several intolerant taxa (e.g., *Maccaffertium modestum* and *Isonychia bicolor*) in 2022 suggests that water quality remains good and may not be a factor.

The Sawmill Brook (site 151) has exhibited a declining BAP score over the past three sampling events spanning 16 years (Figure 3.15). Contributing to this decline is the dominance of generalist taxa, in this case Hydropsychidae caddisflies (53 % of the sample), a general loss of species richness, and a deviation from the model community (PMA). Despite this decline, highly intolerant stoneflies were found in the sample suggesting that water quality may not be the main factor driving this decline.

West of Hudson - Catskill/Delaware System

Of the 12 Catskill System sites assessed in 2022, six of the seven routine sites (sites 202, 204, 206, 215, 216, 227) and two of the five RIBS sites (sites 203 and 221) had BAP scores lower than their respective period of record means (Figure 3.16). Four of the routine sites (sites 204, 206, 216, and 227) ranked as slightly impaired, two as non-impaired (sites 202 and 229), and one fell on the line between the two categories (site 215)(Figure 3.17).

The Schoharie Creek (site 204) declined between 2021 and 2022, yielding the lowest BAP score on record for this site and nearly downgrading the site to moderately impaired (Figure 3.17). Reduced species richness and the dominance of generalist taxa (68%) drove down the score in 2022. Several species of intolerant stoneflies and mayflies were in the 2022 sample suggesting the decline may be due to a physical factor rather than water quality. Similar declines were also seen in the Esopus Creek (site 227) between 2021 and 2022 (Figure 3.17). As with site 204, several highly intolerant taxa were still present indicating the decline was likely due to changing substrate conditions rather than water quality. Site 216 exhibited the second consecutive year of decline to its lowest score on record (Figure 3.17). The difference is largely attributed to declines in the percent EPT and species richness. However, the dominant organism in the 2022 sample (43%) was a mayfly which is ranked as intolerant, indicating that water quality remains high.

The Batavia Kill (site 206) showed the third consecutive year of increasing scores (Figure 3.17) influenced by small increases in all metrics, with improved species richness impacting the score the most. The Catskill RIBS sites exhibited no substantial changes except for the Batavia Kill at site 233 which improved from moderately impaired to non-impaired (Figure 3.18).

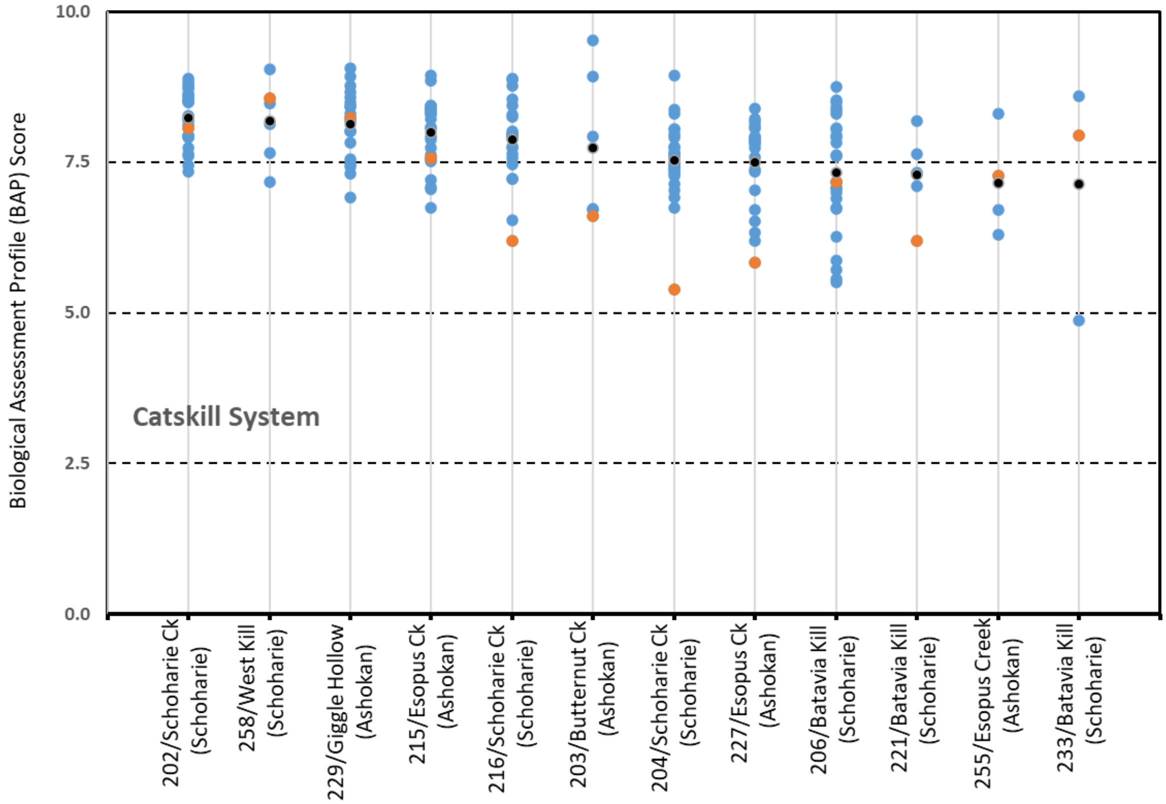


Figure 3.16 BAP scores for the Catskill System biomonitoring site sampled in 2022 arranged by mean score from highest to lowest. Black dots represent the mean score, orange dots the 2022 score, and blue dots the pre-2022 scores. The watershed is indicated in parentheses.

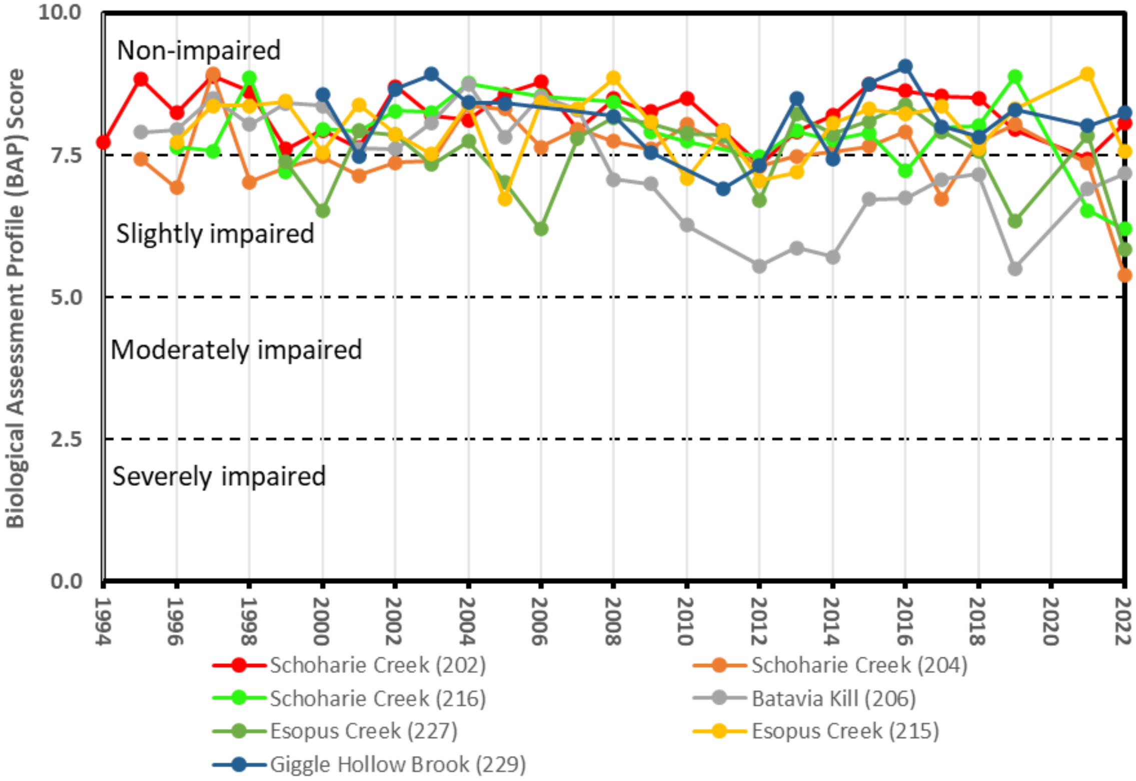


Figure 3.17 1994-2022 BAP scores for all routine sample sites within the Catskill System.

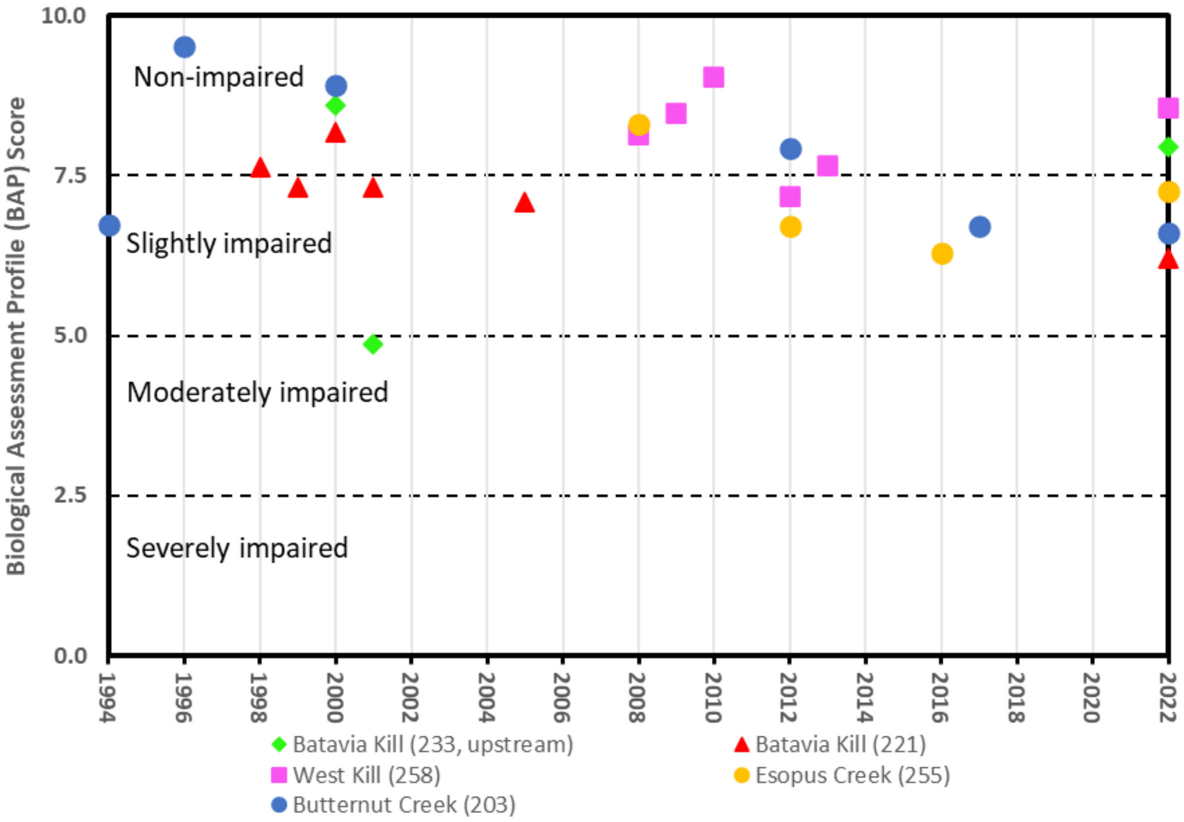


Figure 3.18 1994-2022 BAP scores for Catskill System RIBS sites within the West of Hudson System.

Of the seven routine Delaware System sites assessed in 2022, three were considered slightly impaired (sites 301, 304, and 321). The remaining sites all ranked as non-impaired and showed improvements versus 2021 (Figure 3.19 and Figure 3.20). Sites 304 and 321 both exhibited marginal declines between 2021 and 2022, while the remaining sites improved. Site 307 (Aden Brook) moved to unimpaired status after five consecutive years of decline. Five of the 13 sites (sites 301, 304, 326, 321, 314) ranked lower than their respective period of record means (Figure 3.19). Three of the five RIBS sampled in the Delaware System in 2022 showed increasing BAP scores (sites 313, 325, and 339), which elevated their assessments from slightly to unimpaired (Figure 3.21). The two other sites showed little or no changes.

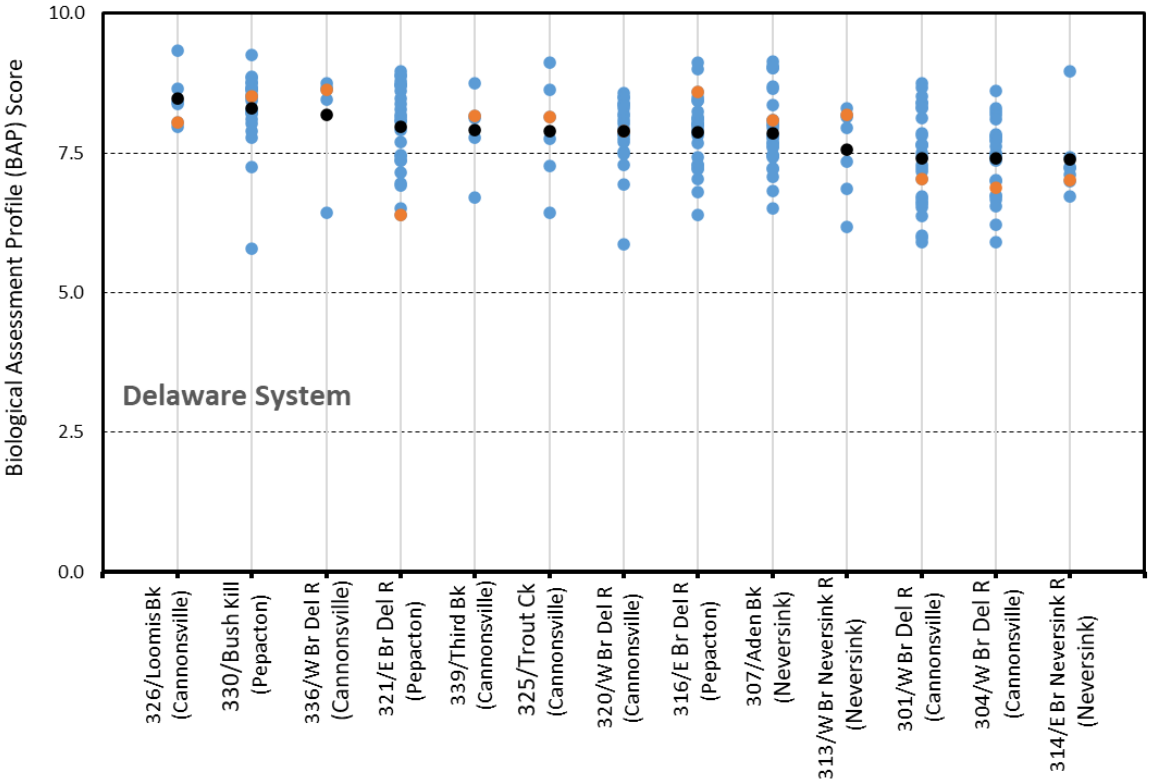


Figure 3.19 BAP scores for the Delaware System biomonitoring sites sampled in 2022, arranged by mean score from highest to lowest. Black dots represent the mean score, orange dots the 2022 score, and blue dots the pre-2022 score. The watershed is indicated in parentheses.

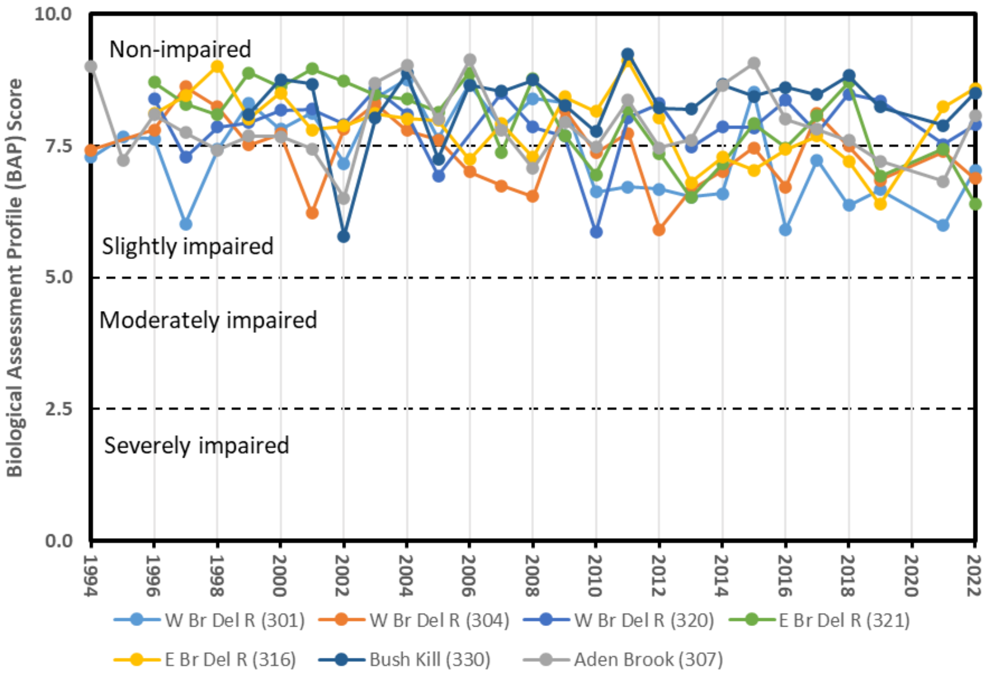


Figure 3.20 1994-2022 BAP scores for routine 2022 sample sites in the Delaware System.

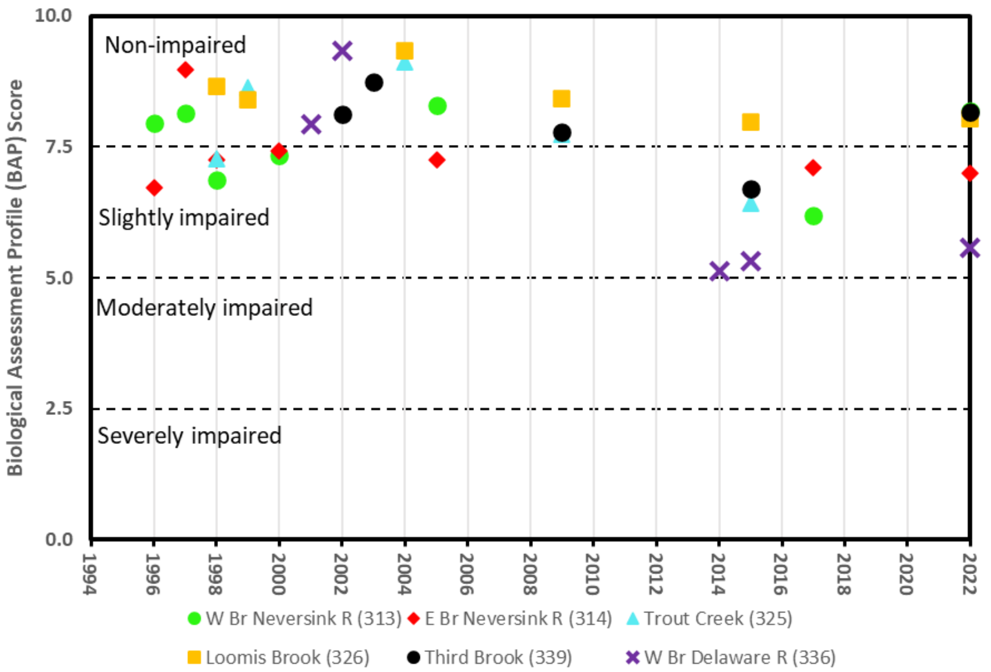


Figure 3.21 1994-2022 BAP scores for 2022 RIBS sites in the Delaware System.The 2022 data points for Sites 313 and 325 are hidden behind sites 326 and 339.

3.14 Supplemental Contaminant Monitoring

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

To supplement required distribution system monitoring, DEP collects one sample at key sites throughout the upstate watersheds during the last quarter of the year to test for many volatile and semi-volatile organic compounds as well as the herbicide glyphosate. The list of compounds is provided in Appendix J and the sites sampled are provided below in Table 3.10. The compounds analyzed in 2022 were generally the same as those analyzed in 2021, with Aldrin added in 2022. All samples were shipped to a contract lab for analysis. In 2022, only one compound at one site was detected above its detection limit. Chloroneb, a fungicide used for treating seeds and turf, was detected in a sample collected on October 25, 2022, at the Ashokan Reservoir keypoint EARCM at a concentration of 4.6 µg L^{-1}. Resampling was initiated May 5, 2023, and the result was below the detection limit. While a specific state or federal water quality standard has not been developed for this compound, the initial result was below the NYCRR MCL of 50 µg L^{-1} for unspecified organic contaminants.

Table 3.10 Sampling sites for VOC, SVOC, and glyphosate monitoring.

Site Code	Site Description	Reason for Site Selection
	East of Hudson	
CROGH(CRO1B)	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 Reservoir Effluent	Represents Ashokan water
NRR2CM (NR2)	Neversink Tunnel Outlet	Represents Neversink water
PRR2CM (PR3)	East Delaware Tunnel Outlet	Represents Pepacton water
SRR2CM	Shandaken Tunnel Outlet Intake	Schoharie water entering Esopus
RDRRCM	Rondout Reservoir Effluent	Represents Rondout water
WDTOCM (CR2)	West Delaware Tunnel Outlet	Represents Cannonsville water

If a diversion is off-line at the collection time, the sample is drawn from the reservoir elevation tap that corresponds to the tunnel intake depth as if that reservoir were on-line. In 2022, sampled elevation taps are indicated in parentheses.

3.14.2 Metals Monitoring

Supplemental, noncompliance sampling of the Catskill, Delaware, and Croton systems is conducted to determine background concentrations for a variety of metals as outlined in Table 3.11 and Table 3.12. These metals are monitored quarterly at the keypoint sites listed in Table 3.11 or at the appropriate elevation tap if an aqueduct is offline. Note that the August quarterly sample at EARCM was not included in the data review in 2022 because it was determined to have been treated with chlorine dioxide.

In 2022, elevation tap CR2 was sampled in place of WDTOCM in February and May; elevation tap CRO1B was sampled in place of CROGH in May, August, and November. The elevation tap NR2 was sampled in place of NRR2CM in all four quarterly samples.

Table 3.11 Keypoint sampling sites for trace and other metal occurrence monitoring.

Reservoir Basin	Site(s)
West of Hudson	
Catskill System	
Ashokan	EARCM[1]
Schoharie	SRR2CM[1]
Delaware System	
Cannonsville	WDTOCM[1]
Pepacton	PRR2CM[1]
Neversink	NRR2CM[1] (NR2)
Rondout	RDRR2CM[1]
East of Hudson	
Kensico	CATALUM, DEL17, DEL18DT, DEL19LAB
New Croton	CROGH[1] (CRO1B)
West Branch	DEL9, DEL10, CWB1.5

[1] Elevation tap samples will be collected when the reservoir is offline.

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 3.12) and the New York State Department of Environmental Conservation, Water Quality Regulations, Title 6, Chapter X, Part 703.5 (Table 3.13).

Table 3.12 USEPA National Primary and Secondary Drinking Water Quality Standards.

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

Table 3.13 Water quality standards for metals from NYSDEC Title 6 regulations.

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

In 2022, most metal sample results were well below federal and state benchmarks (Table 3.12, Table 3.13). Antimony, arsenic, beryllium, cadmium, chromium, lead, mercury, selenium silver, and thallium were not detected at any monitored site in 2022.

Nickel was detected just above the detection limit (1.0 µg L^{-1}) in all four samples from New Croton Reservoir ranging from 1.2-1.4 µg L^{-1}; at the detection limit at NR2; and in one sample from PRR2CM (8.7 µg L^{-1}), all well below the NYSDEC regulation (Title 6, Chapter X, Part 703.5) of 100 µg L^{-1}. Barium was detected in all 55 samples, ranging from 5.1 µg L^{-1} at SRR2CM to 52.8 µg L^{-1} at CRO1B. Copper was detected in 49 of 55 samples with concentrations ranging from 1.0 µg L^{-1} to 20.9 µg L^{-1} due to plumbing fixtures at the various keypoint monitoring locations. Zinc was detected in 3 of 55 samples with detected values ranging from 10.3 at PRR2CM to 19.1 µg L^{-1} at DEL18DT. Iron was detected in 48 of 55 samples with concentrations ranging from 30 µg L^{-1} at DEL9 and DEL19LAB to 276 µg L^{-1} at SRR2CM. All detected barium, copper, zinc, and iron results were below their respective standards.

Standards for manganese and aluminum were occasionally surpassed in 2022. The manganese secondary standard of 50 µg L^{-1} was exceeded twice at SRR2CM (70 µg L^{-1} and 178 µg L^{-1}) and once at EARCM (71 µg L^{-1}), CROGH (63 µg L^{-1}) and CRO1B (1300 µg L^{-1}), while the aluminum secondary standard of 50 µg L^{-1} was exceeded twice at NR2 (52.0 and 64.6 µg L^{-1}), and three times at both CATALUM (56.0, 63.9, and 86.7 µg L^{-1}) and SRR2CM (149, 215, and 229 µg L^{-1}). While iron, aluminum, and manganese exceedances may pose aesthetic concerns (e.g., taste, staining), they are not considered a health risk.

3.15 Special Studies

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

3.15.1 Delaware Shaft 10 Chlorination Study

In response to a 2021 violation of the Stage 2 Disinfection Byproducts (DBP) rule violation and based on a recommendation from a Water Research Foundation (WRF) DBP expert panel, DEP piloted a "step-chlorination" concept at Delaware Shaft 10 to study its effects on DBP formation potential from January 5, 2022, through March 6, 2022. The intent was to determine if the chlorine-reactive component of the organic carbon pool could be reduced via physio-chemical or biological degradation by chlorinating upstream of Kensico Reservoir. The 60-day pilot study was approved by NYSDOH on December 23, 2021, and notification was made to NYSDEC on December 8, 2021. During the bench testing phase, Total Trihalomethane (TTHM) concentrations decreased, but Haloacetic Acid (HAA5) concentrations remained consistent. In addition, during the full scale pilot, TTHM and HAA5 were effectively formed as result as evidenced by detections in Kensico Reservoir. While TTHM was detected at Delaware Shaft 18 near the end of the full-scale pilot, HAA5 was not detected. The operational changes and chlorination reductions that occurred during this period proved to have the greatest impact on reducing DBP concentrations entering Hillview Reservoir downstream of Kensico Reservoir. An after-action report that captured the details of this study was circulated on April 18, 2022.

3.15.2 Taste and Odor Sampling

Taste and odor (T&O) compounds such as geosmin (GSM) and 2-methyisoborneol (MIB) can be detected by consumers of drinking water at concentrations as low as 10 ng L^{-1}. DEP monitors consumer complaints in the distribution system via the NYC 311 system, and water quality calls are categorized based on the type of water quality complaint. When GSM or MIB concentrations are greater than the 10 ng L^{-1} threshold, musty water quality consumer complaint calls can increase. DEP uses water quality consumer complaint data in conjunction with GSM and MIB data to monitor and manage T&O events. DEP has been monitoring for GSM and MIB in the Croton System since autumn 2019.

In 2022, a total of 589 samples were collected at a total of 35 sites with most monitoring occurring at New Croton Reservoir keypoints and elevation taps. After Tropical Storm Ida inundated the watershed heavy rainfall on September 1-2, 2021, concentrations of MIB decreased into autumn and remained undetectable until early May of 2022. At that time, concentrations began to increase at the middle (CRO163) and top (CRO183) elevations at the Croton Lake Gatehouse with concentrations peaking at 26 ng L^{-1} at CRO183. MIB was detectable above 10 µg/L threshold at one or more elevation tap sites until the end of October, when concentrations were then undetectable through the remainder of 2022.

In 2022, DEP also expanded monitoring for GSM and MIB throughout the Croton System to better understand the extent of the distribution of taste and odor compounds. Samples were collected at several release locations including Croton Falls, Cross River, Boyd Corners, Diverting, Amawalk, Middle Branch, and Titicus reservoirs. MIB and geosmin were detected at all these locations at various times throughout the year indicating a system-wide presence of these taste and odor compounds.

3.15.3 Copper Sulfate Treatment Monitoring

Based on a recommendation from a Water Research Foundation Taste and Odor Expert Panel Workshop held in May of 2022, DEP conducted copper sulfate pilot treatment at New Croton and Muscoot reservoirs. The intent was to control algal populations that may be releasing taste and odor compounds into the water column. Based on routine monitoring results, DEP confirmed the presence of blue-green algae capable of producing GSM and MIB throughout the Croton System reservoirs. In late spring 2022, and when monitoring indicated an abundance of taste and odor producing algae (e.g., *Aphanizomenon* and *Oscillitoria*) within New Croton and Muscoot reservoirs, DEP contracted with Solitude Lake Management to treat portions of these reservoirs.

Water quality monitoring was conducted before and after treatment and included dissolved copper, photosynthetic production, phytoplankton presence and abundance, and MIB and GSM. In total, throughout the 2022 growing season, DEP treated on three separate occasions: June 22, 2022, near New Croton Reservoir water quality sampling locations 1CNC and 4CNC; June 27, 2022, near Muscoot Reservoir sampling location 1CM; and September 22, 2022, within New Croton Reservoir from the Muscoot dam/weir near 8CNC downstream through sampling location 5CNC.

Copper sulfate was applied via boat using an on-board tank and calibrated pump system to disperse the copper sulfate at 0.3 mg L^{-1}. All treatment applications were successful in depressing algal growth within the portion of the water column that was treated. The length of depression of algal growth varied by location, and therefore further study is warranted. Further details of the treatment applications can be found in the after-action report that was circulated March 7, 2023.

3.15.4 Emerging Contaminant Monitoring

DEP continued to monitor for per- and polyfluoroalkyl substances (PFAS) in 2022 with quarterly monitoring at the Catskill/Delaware and Croton source water monitoring locations and annual monitoring at Kensico tributaries E9, E10, E11, and Kensico Reservoir limnology Site 6 (6BRK0).

Consistent with 2019, 2020, and 2021, the outflow of Kensico Reservoir (DEL18DT) had no detections of the PFAS compounds tested. Monitoring of the outflow of New Croton Reservoir (CROGH) or the alternate tap location when offline (CRO1B) resulted in the detection of four of the 18 compounds tested (Table 3.14). Detections were at or slightly above the MRL (0.0020 µg L^{-1}) for these four compounds. Although not drinking water, results were below the New York State Drinking Water Standards for PFOS and PFOA (0.010 µg L^{-1} each). Results were also below the New York State Ambient Water Quality Guidance Values for PFOS (0.0027 µg L^{-1}) and PFOA (0.0067 µg L^{-1}) during all four quarters.

Table 3.14 PFAS results from New Croton Reservoir outflow (CROGH) or tap (CRO1B), 2022 (µg L^{-1}).

PFAS compound	Jan 27 CROGH	April 13 CRO1B	August 9 CRO1B	November 2 CRO1B
Perfluorobutanesulfonic acid (PFBS)	0.0023	0.0022	0.0021	0.0022
Perfluorohexanoic acid (PRHxA)	0.0022	<0.0020	<0.0020	0.0024
Perfluorooctanoic acid (PFOA)	0.0032	0.0030	0.0032	0.0033
Perfluoroctanesulfonic acid (PFOS)	0.0020	<0.0020	0.0021	0.0023
Remaining 14 compounds	**<0.0020**	**<0.0020**	**<0.0020**	**<0.0020**

Kensico limnology site 6BRK0 was collected in August 2022 and had no detections of PFAS compounds. The results for **s**amples collected at the three tributary sites (E9, E10, and E11), also collected in August 2022, are provided in Table 3.15. Tributaries E9, E10, and E11 had detections of two, nine, and seven PFAS compounds, respectively. The compounds detected in the streams were consistent with previous monitoring in 2021. Concentrations of the compounds during this August 2022 sampling were also in the range of quarterly data from 2019, with E10 concentrations one to three orders of magnitude higher than E9 and E11.

Table 3.15 PFAS results for stream sites E9, E10 and E11 August 9, 2022 (µg L^{-1}).

PFAS compound	E9	E10	E11
11-chloroeicosafluoro-3-oxaundecane-sulfonic acid (11Cl-PF3OUdS)	<0.0020	<0.0020	<0.0020
4,8-dioxa-3H-perfluorononanoic acid (ADONA)	<0.0020	<0.0020	<0.0020
9-chlorohexadecafluoro-3oxanone-sulfonic acid (9Cl-PF3ONS)	<0.0020	<0.0020	<0.0020
Hexafluoropropylene oxide dimer acid (HFPO-DA)	<0.0020	<0.0020	<0.0020
N-ethyl perfluorooctanesulfonamidoacetic acid (NEtFOSAA)	<0.0020	<0.0020	<0.0020
N-methyl perfluorooctanesulfonamidoacetic acid (NMeFOSAA)	<0.0020	<0.0020	<0.0020

PFAS compound	E9	E10	E11
Perfluorobutanesulfonic acid (PFBS)	<0.0020	0.025	0.0027
Perfluorodecanoic acid (PFDA)	<0.0020	0.0036	<0.0020
Perfluorododecanoic acid (PFDoA)	<0.0020	<0.0020	<0.0020
Perfluoroheptanoic acid (PFHpA)	<0.0020	0.075	0.026
Perfluorohexanesulfonic acid (PFHxS)	<0.0020	0.42	0.013
Perfluorohexanoic acid (PFHxA)	<0.0020	0.16	0.039
Perfluorononanoic acid (PFNA)	<0.0020	0.057	0.0072
Perfluorooctanesulfonic acid (PFOS)	0.0031	0.58	0.013
Perfluorooctanoic acid (PFOA)	0.0047	0.24	0.024
Perfluorotetradecanoic acid (PFTA)	<0.0020	<0.0020	<0.0020
Perfluorotridecanoic acid (PFTrDA)	<0.0020	<0.0020	<0.0020
Perfluoroundecanoic acid (PFUnA)	<0.0020	0.006	<0.0020

4. Kensico Reservoir

4.1 Kensico Reservoir Overview

Kensico Reservoir in Westchester County is the terminal reservoir for the City's raw source water from the Catskill/Delaware water supply. Protection of this reservoir is critically important to prevent water quality degradation and to maintain DEP's 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). Sampling site locations are shown in Figure 4.1. The WWQMP prescribes monitoring to maintain compliance with all federal, state, and local regulations; enhance the capability to make current and future predictions of watershed conditions and reservoir water quality; and ensure delivery of the best water quality to consumers through ongoing high frequency surveillance.

The approximate number of water quality samples collected within the Kensico watershed during 2022 are summarized in Table 4.1. These tallies include monitoring from four programs within the Kensico watershed which have returned to pre-pandemic sampling levels. Completion of the Kensico Shoreline Stabilization Project reduced the number of turbidity samples collected in the reservoir. Completion of the Catskill Aqueduct rehabilitation during 2021 allowed for water transfer from Ashokan Reservoir throughout autumn 2022, which had previously been shut down for the past two years during that season.

Table 4.1 Summary of Kensico watershed water quality samples collected in 2022.

Kensico sampling programs	**Turbidity**	**Fecal Coliform**	***Giardia/ Crypto-sporidium***	**Phyto-plankton**	**Other Analyses**
Keypoint effluent	2,191/365*	365	52	162	2,613
Keypoint influent	495	489	105	104	3,489
Reservoir	599	378		84	3,072
Streams	139	138	84		1,529

*2,191 samples collected for SWTR turbidity compliance, and 365 samples collected for process control

Since compliance with the Safe Drinking Water Act Surface Water Treatment Rule (SWTR) (USEPA 1989) is required to maintain the Filtration Avoidance Determination, fecal coliform and turbidity are critical components of Kensico water quality monitoring and the focus of analysis within this chapter. Fecal coliform and turbidity results during 2022 consistently met compliance requirements for water leaving Kensico Reservoir. The predominantly low fecal coliform results are in large part due to a combination of the ongoing success of the Waterfowl Management Program discussed in Section 4.4.1 and effective operational decisions.

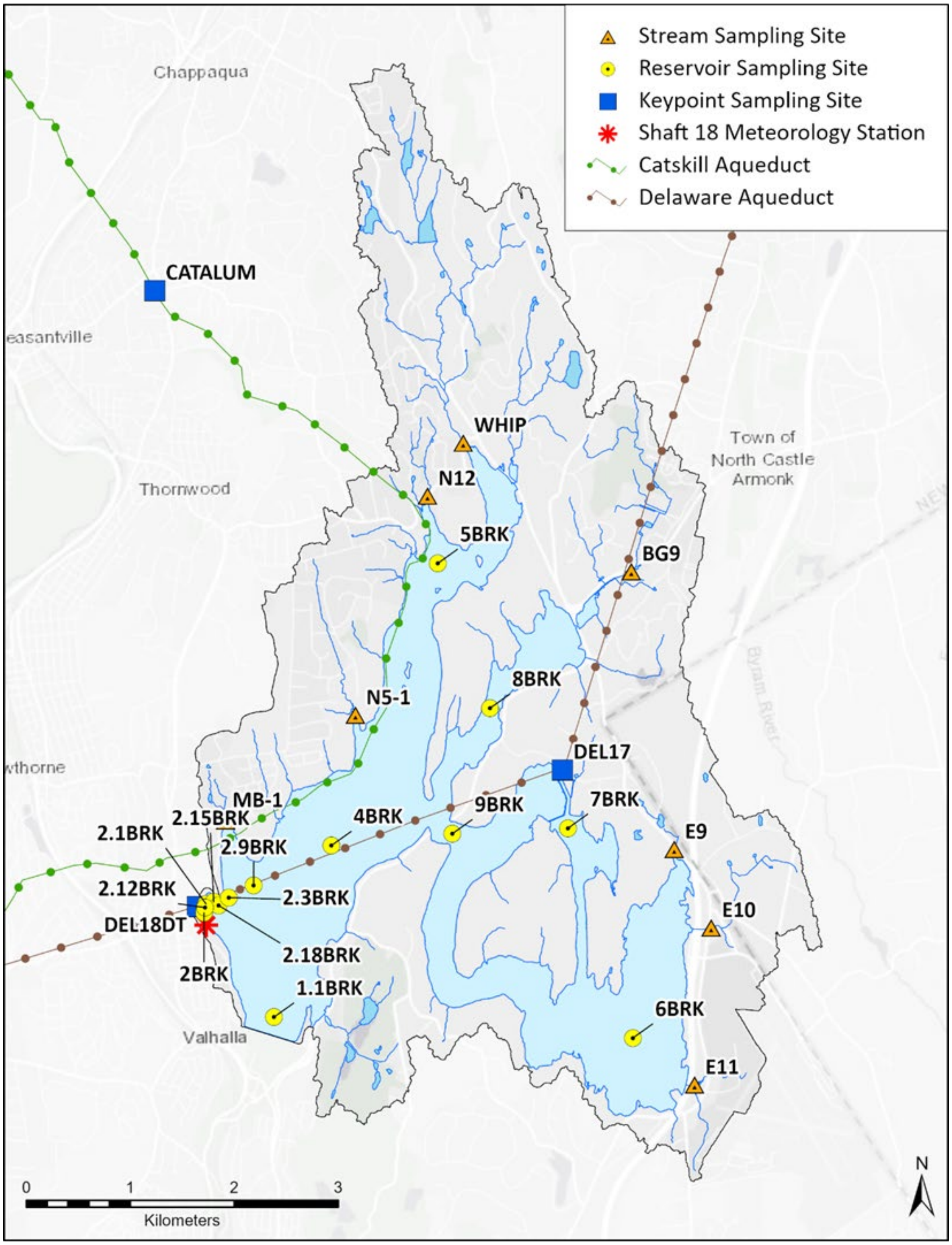


Figure 4.1 Kensico Reservoir showing limnological, hydrological, and keypoint sampling sites; meteorology stations; and aqueducts

4.2 Reservoir Raw Water Quality Compliance

DEP routinely conducts water quality compliance monitoring at the Kensico Reservoir aqueduct keypoints. The CATALUM and DEL17 influent keypoints represent water entering Kensico Reservoir from the upstate reservoirs of the Catskill/Delaware System via the Catskill and Delaware aqueducts, respectively. The monitoring for CATALUM and DEL17 includes requirements defined by the Catskill Influent Chamber and Delaware Aqueduct (DEL17) SPDES permits, NY-026-4652 and NY-026-8224, respectively. The DEL18DT effluent keypoint represents water leaving the Delaware Aqueduct Shaft 18 facility via reservoir, float, or bypass operational mode at a point just prior to disinfection, after which the water travels down to Hillview Reservoir then into the distribution system.

Analytical results from all three keypoint locations are used as an indicator of water quality entering and discharging from Kensico Reservoir. These data are utilized to optimize operational strategies to ensure the delivery of the best quality water leaving the reservoir. Operational strategies are also informed by the continuous monitoring instrumentation for temperature, pH, conductivity, and turbidity at all three locations in near-real time. Table 4.2 outlines the routine grab sample monitoring that occurred at these three aqueduct keypoint locations in 2022.

Table 4.2 Water quality monitoring for Kensico Reservoir aqueduct keypoints via routine grab samples for 2022.

Site	Fecal and Total Coliforms, Turbidity, Specific Conductivity, Scent, Apparent Color	Field, pH, and Temperature	Turbidity	Phytoplankton	UV254	TP	DOC	Alkalinity, Ammonia, NOx, Orthophosphate, TDP, Total Suspended Solids, TN, TDN,	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
* SWTR Compliance
M – Sampled Monthly
Q – Sampled Quarterly

+For fecal coliform, a minimum of 5 samples per week are required and samples must be taken every day that the turbidity exceeds 1.49 NTU. DEP voluntarily samples 7 days per week.

Annual median and single sample maximum for turbidity and fecal coliform are included as a partial assessment of the overall water quality for 2022 and can be compared to the previous year (Table 4.3). Assessment of individual 2022 routine grab samples for each of the Kensico aqueduct locations was conducted graphically (Figure 4.2, Figure 4.3, and Figure 4.4) by comparing results to SWTR limits. Influent sites (DEL17 and CATALUM) are not subject to the SWTR limits, so the SWTR limit line is provided for reference purposes.

Table 4.3 Kensico keypoint fecal coliform and turbidity metric results.

Analyte	Kensico Sampling Location	Median		Single Sample Maximum	
		2021	2022	2021	2022
Fecal coliform (coliforms $100mL^{-1}$)	CATALUM	<1	<1	E4	>60
	DEL17	1	1	E120	34
	DEL18DT	1	1	E82	E16
Turbidity (NTU)	CATALUM	1.8	2.3	9.6	7.0
	DEL17	0.8	0.9	3.1	2.4
	DEL18DT	0.8	0.8	2.1	1.9

The 2022 turbidity and fecal coliform metrics were similar or decreased as compared to the previous year's values except for the fecal coliform single sample maximum (SSM) and turbidity median at CATALUM. While the CATALUM SSM for fecal coliform coincided with a flow increase and a switch from the West to East Basin at Ashokan, fecal coliform levels in Ashokan keypoints were low at this time. For the CATALUM mean turbidity, water was being drawn from the Ashokan West Basin for a greater portion of the year as compared to the previous year and the Ashokan West Basin had a higher mean turbidity than the Ashokan East Basin. Overall, CATALUM results were below the fecal coliform and turbidity reference limits except when following a precipitation event in the Ashokan watershed or an operational change. For DEL17, all turbidity results were less than 5 NTU (Figure 4.2) while four results exceeded the 20 fecal coliform $100mL^{-1}$ reference limit. Overall DEL17 results were below the fecal coliform and turbidity reference limits except when following a precipitation event.

The SWTR establishes a 5 NTU limit for turbidity and the requirement that no more than 10 % of fecal coliform samples over the previous six months exceed 20 fecal coliforms $100mL^{-1}$. For DEL18DT, all turbidity results were less than 5 NTU (Figure 4.4) and the SWTR criteria for fecal coliform was met throughout the year. The percentage for fecal coliform began at 3.28% due to the remnants of Hurricane Ida and a late October 2021 storm event. However, during 2022 there were no results greater than 20 fecal coliform $100mL^{-1}$ which resulted in the percentage being reduced to 0.00 % by the end of the year (Figure 4.4).

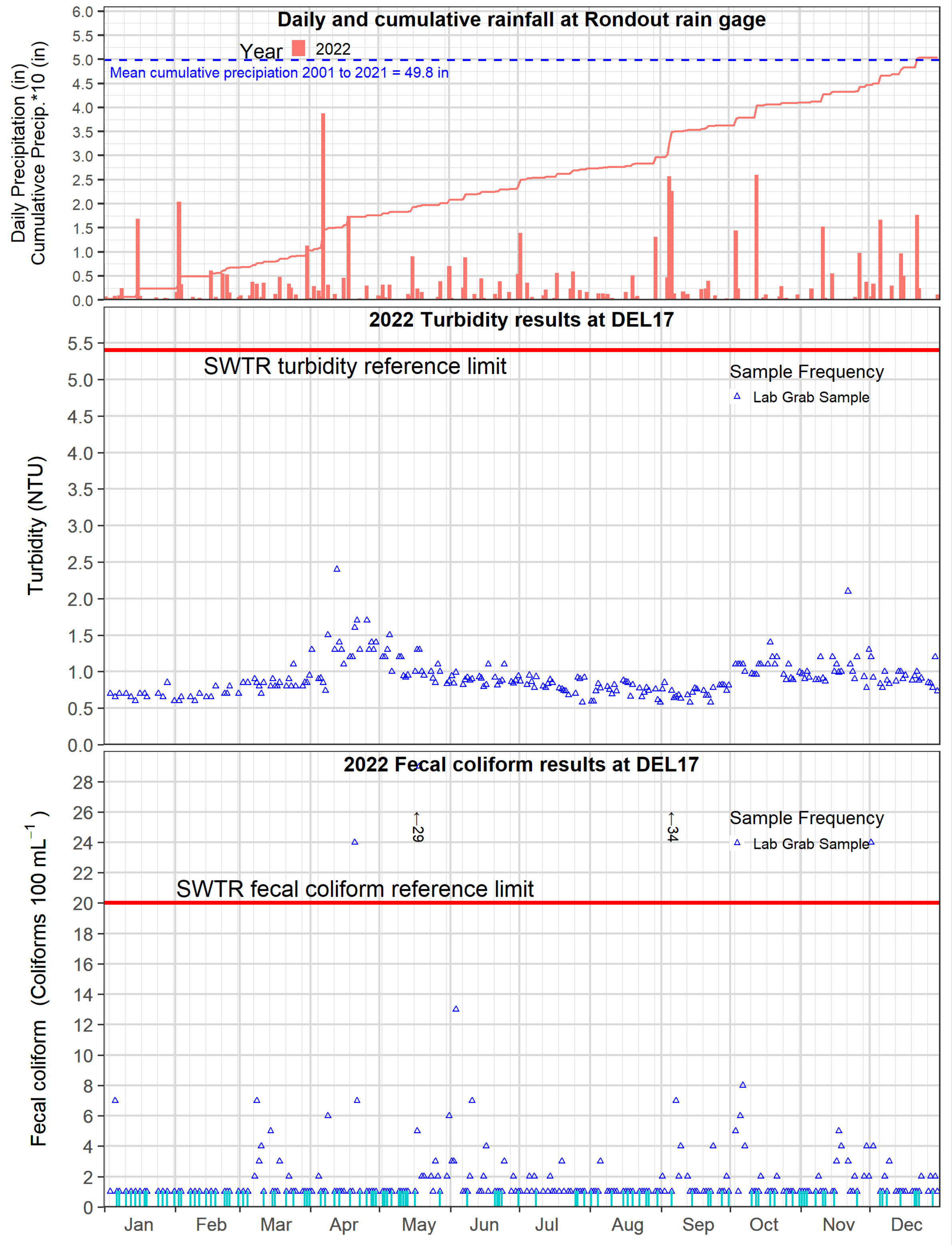


Figure 4.2 Five-day-per-week turbidity and fecal coliform grab samples at DEL17. Drop lines indicate censored values.

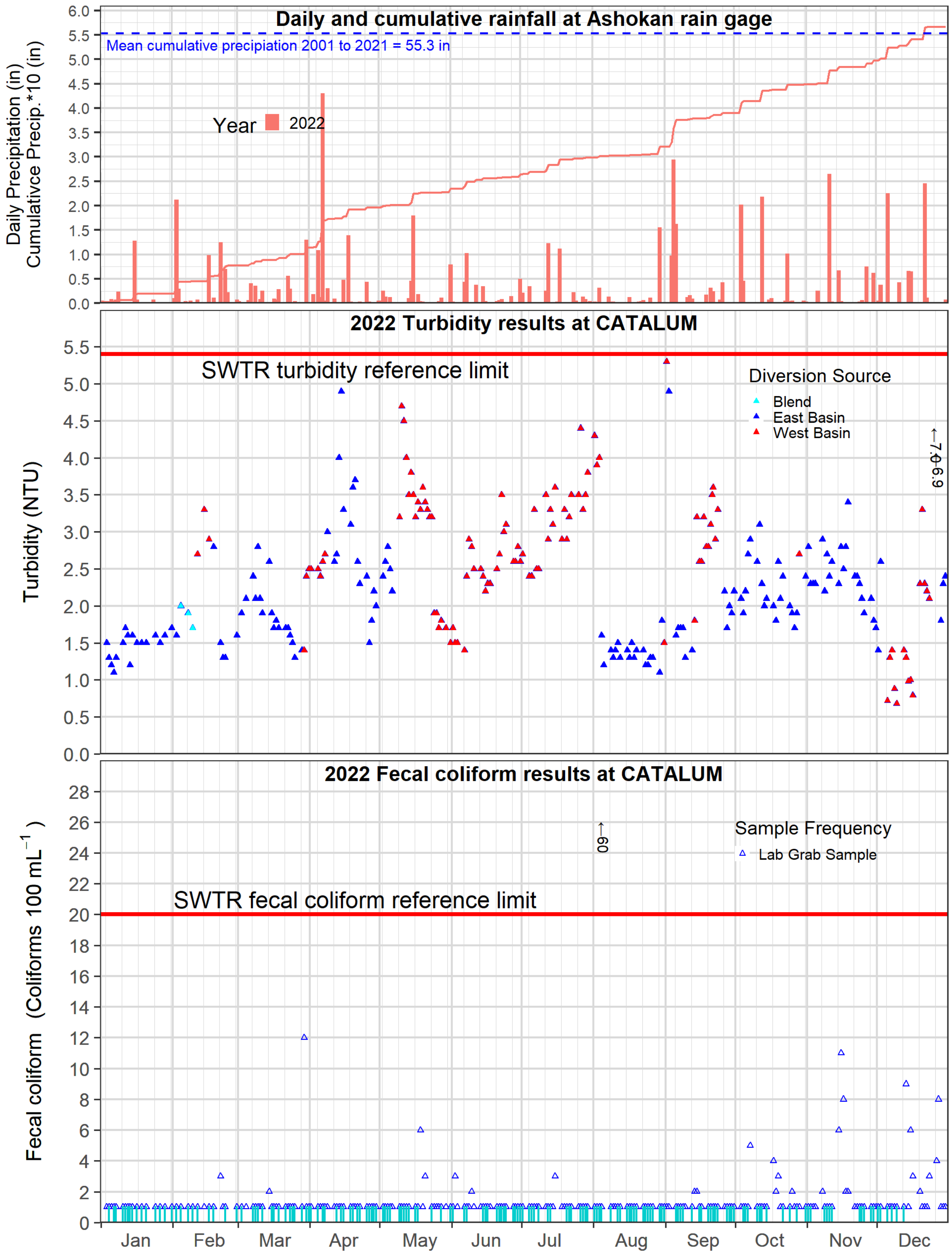


Figure 4.3 Five-day-per-week turbidity and fecal coliform grab samples at CATALUM. Drop lines indicate censored values.

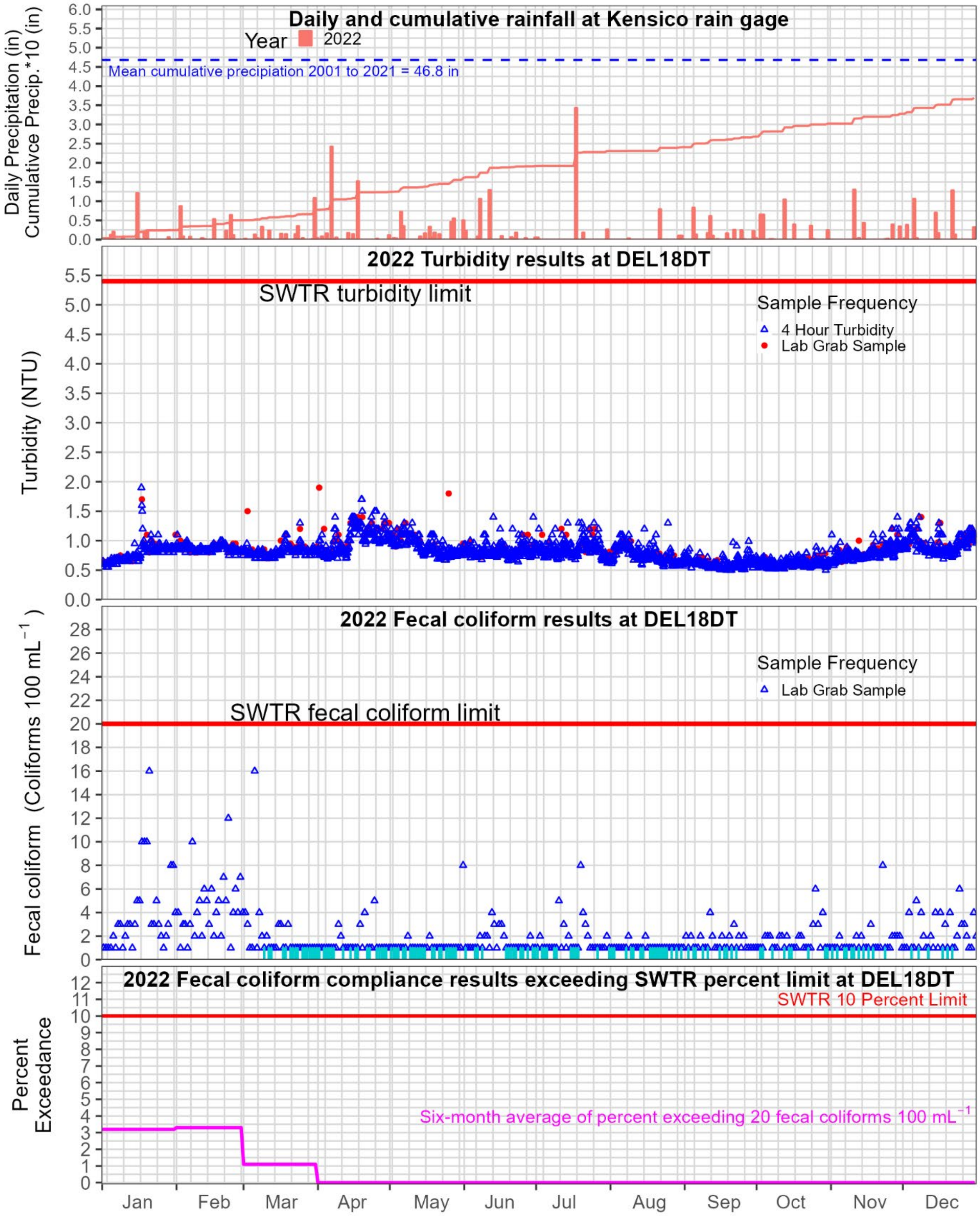


Figure 4.4 Seven-day-per-week turbidity and fecal coliform grab samples at DEL18DT. Drop lines indicate censored values.

4.3 Kensico Watershed Monitoring and Turbidity Curtain Inspections

4.3.1 Kensico Watershed Monitoring

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

Kensico perennial streams have continuous flow measurement equipment except for E10 which is offline. WHIP (Whippoorwill Creek) and BG9 (Bear Gutter) flows are determined via a rating curve. E11 (Stream E11), E10 (Stream E10), MB-1 (Malcolm Brook), and N5-1 (Stream N5-1) flows are determined via a V-notch weir. N12 (Stream N12) and E9 (Stream E9) flows are determined via an H-flume that accommodates a wider range of flows. With each watershed having a different drainage area and BMP type, the hydrograph can be shaped differently, and same-day monitoring can occur at a different position on the hydrograph. The nearby USGS flow gage Cross River near Cross River provides an estimate of flow conditions within the Kensico watershed (Figure 2.3). Turbidity and fecal coliform 2022 routine monitoring results for these streams were typically near or below the previous 10-year monthly median concentrations except when monitoring was influenced by storm event flow (Figure 4.5). The most prominent elevated turbidity and fecal coliform results occurred during the September 2022 monthly sampling which coincided with samples collected at the peak daily mean flow related to a precipitation event.

For all Kensico Reservoir 2022 routine monitoring turbidity grab samples, the annual median turbidity concentration was 0.8 NTU (Figure 3.1) with individual results ranging from <0.1 to 3.0 NTU (Figure 4.6). Figure 4.6 shows interpolated concentrations, where shading and contour lines are an estimate of turbidity concentrations and may not fully represent actual concentrations in those portions of the reservoir. Profile location 5BRK had the highest mean turbidity concentration (1.65 NTU) since it is heavily influenced by incoming Catskill System water. Fecal coliform results were also generally low; the 75th percentile in 2022 was 2 fecal coliform 100mL^{-1} (Figure 3.2) with approximately 52% of the monthly reservoir grab samples resulting in no detectable fecal coliforms and two results greater than 20 fecal coliform 100mL^{-1}; associated with a September 2022 precipitation event within the Kensico watershed. Fecal coliform results cannot be plotted as a contour plot because of the number of censored values.

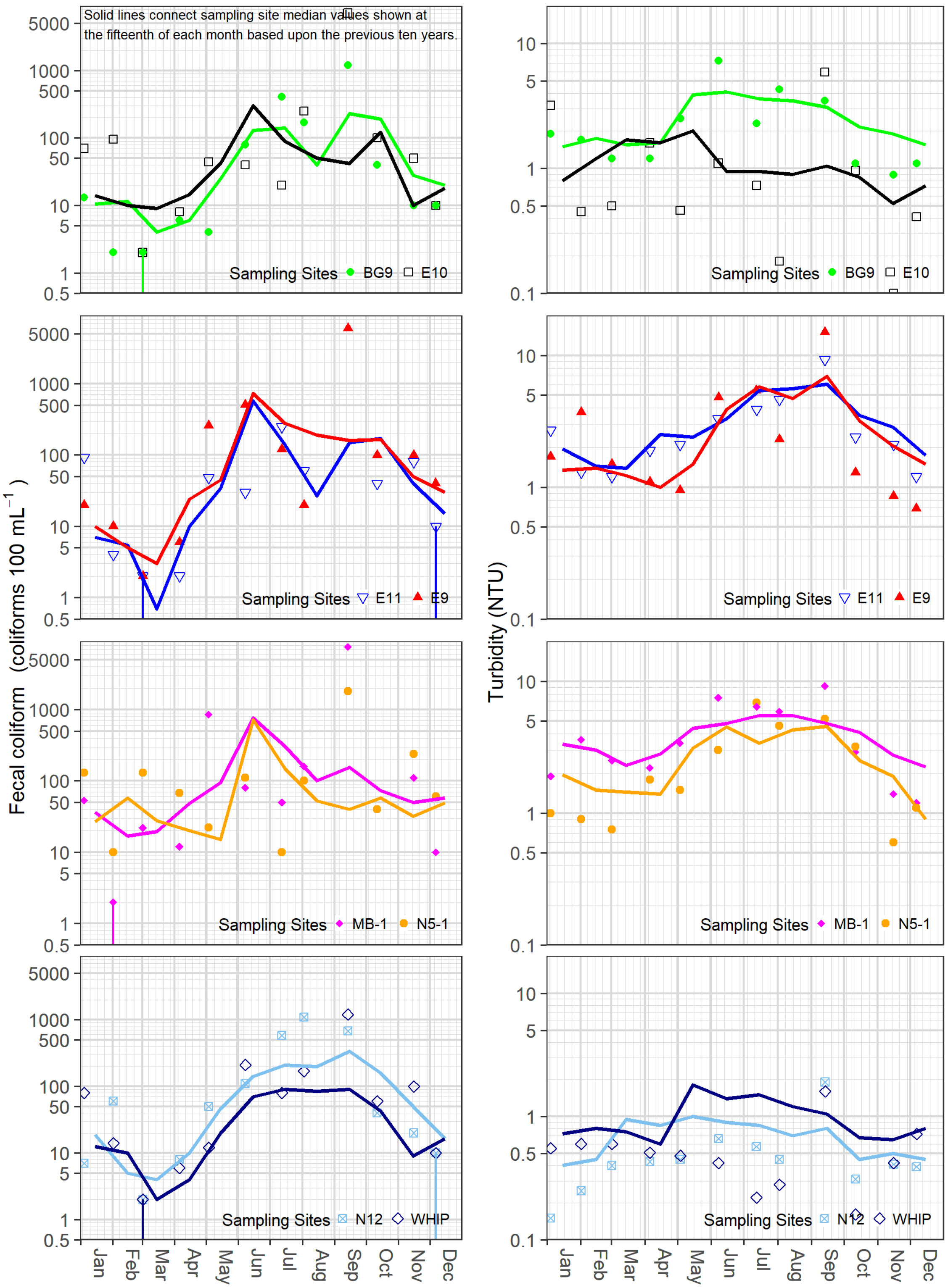


Figure 4.5 Routine Kensico stream monitoring fecal coliform and turbidity results compared to previous ten-year median.

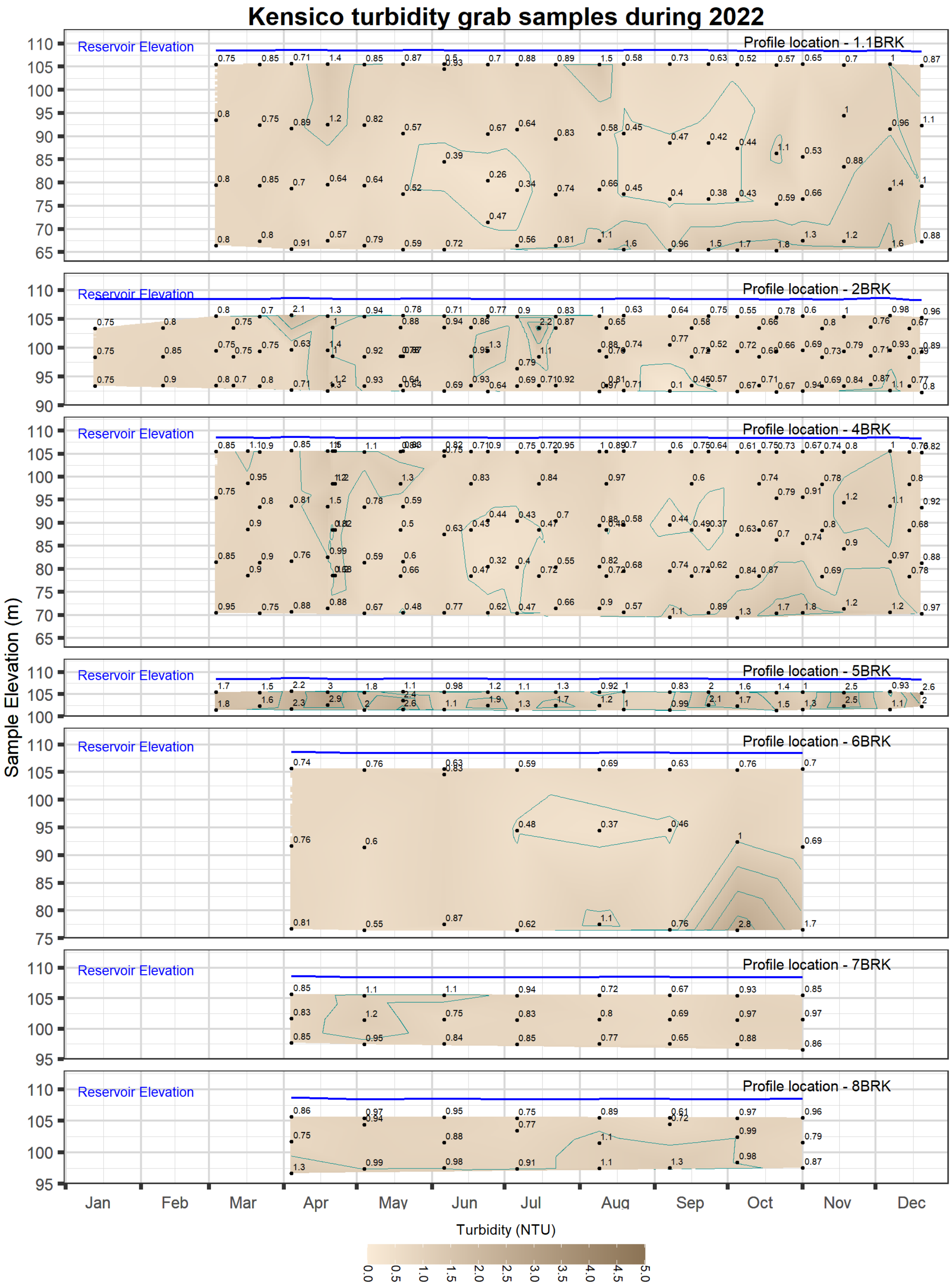


Figure 4.6 Kensico Reservoir turbidity grab sample results for 2022 with analytical measurements marked as points overlaying an interpolated concentration map.

4.3.2 Turbidity Curtain Inspection

While the Catskill Upper Effluent Chamber (CATUEC) has been off-line since 2012, the three turbidity curtains in that cove are designed to redirect water from the CATUEC cove into the main waterbody of Kensico Reservoir to minimize impacts of storm events from Malcolm Brook (MB-1). Since September 2012, when the Catskill/Delaware Ultraviolet Light Disinfection Facility came on-line, CATUEC has been off-line. DEP BWS Water Treatment Operations staff visually inspect the turbidity curtains at least monthly from fixed shore locations around the cove as part of the ongoing maintenance program. Water Quality staff receive the inspection reports and provide input on the condition, positioning, and maintenance of the curtains where appropriate. Operations staff perform the appropriate repairs or adjustments.

4.4 Wildlife Management

4.4.1 Waterfowl Management

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

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

Historic water quality monitoring data collected at the two main water influent and effluent facilities at Kensico demonstrated that higher levels of fecal coliform bacteria were leaving the reservoir than what was contributed through aqueducts from the upstate reservoirs (DEP 1992). It was apparent then that a local source of fecal coliform bacteria was impacting Kensico. One of DEP's Watershed Protection Programs objectives was to identify and mitigate all potential sources of fecal coliform bacteria at Kensico Reservoir. Implementation of waterbird dispersal actions starting in autumn 1993 demonstrated an immediate and marked decline in bacteria. Based on these data, DEP determined that waterbirds were the most important contributor to seasonal fecal coliform bacteria loads to Kensico.

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

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

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

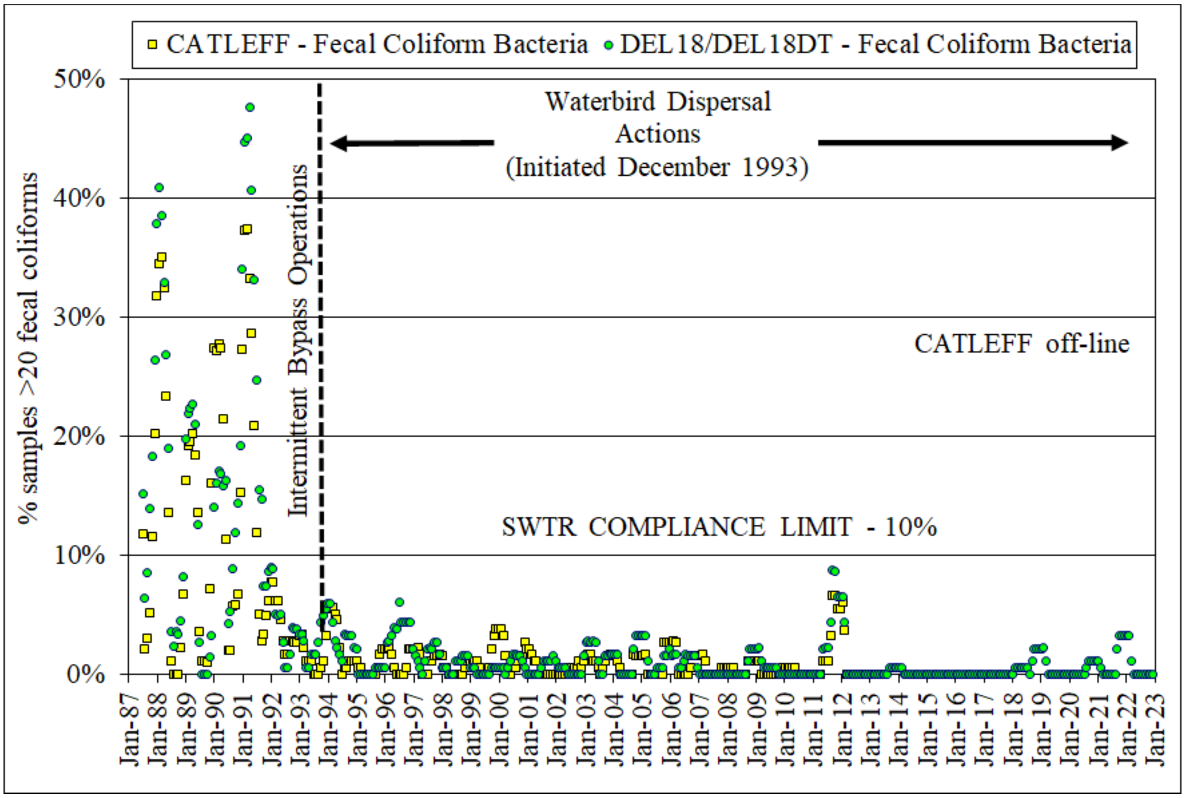


Figure 4.7 Percent of keypoint fecal coliform samples at Kensico Reservoir greater than 20 fecal coliforms $100mL^{-1}$ for the previous six-month period, 1987-2022. The first vertical dashed line indicates the year in which the WMP was implemented.

4.4.2 Terrestrial Wildlife Management

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

During 2022, DEP and its contractor conducted 30 wildlife sanitary surveys at Shaft 18 in advance of significant precipitation events at Kensico Reservoir (Table 4.4). Of the 2,139 fecal samples collected, 67.3% were attributed to white-tailed deer (*Odocoileus virginianus*), 3.5% to rabbits (*Sylvilagus spp.*), 0.4% to bobcat (*Lynx rufus*), 0.3% to raccoons (*Procyon lotor*) and coyote (*Canis latrans*), and approximately 1.2% to other mammals. Avian species excrement included 20.3% from Canada geese (*Branta canadensis*) and 6.7% from passerine bird species. One additional sanitary survey was conducted at Kensico Reservoir N-12 stream corridor located 5.7 miles north of the Delaware Aqueduct Shaft 18 facility on May 13, 2022. Survey results included fecal samples from four white-tailed deer and one raccoon.

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

Date of Survey	White-tail Deer	Raccoon	Rabbit	Canada Goose	Coyote	Bobcat	Passerine (birds)	Other/ Unknown Mammal	Total (all species)
1/16/2022	101	0	0	0	0	0	0	0	**101**
1/28/2022	148	0	0	0	1	0	0	2	**151**
2/2/2022	6	0	1	0	0	0	0	0	**7**
2/16/2022	68	0	2	0	0	0	0	1	**71**
2/21/2022	29	0	0	0	0	0	0	0	**29**
2/24/2022	48	0	1	0	0	0	0	1	**50**
3/6/2022	78	0	1	3	1	0	0	0	**83**
3/11/2022	29	0	0	0	0	0	0	1	**30**
3/23/2022	18	0	1	0	0	0	0	1	**20**
4/5/2022	7	0	4	9	0	0	19	0	**39**
4/13/2022	0	0	0	132	0	0	0	0	**132**
4/18/2022	0	0	0	200	0	0	0	0	**200**
6/7/2022	0	0	0	91	0	0	7	0	**98**
7/17/2022	43	0	0	0	0	0	31	1	**75**
7/20/2022	19	0	0	0	0	0	0	0	**19**
8/5/2022	38	1	1	0	1	0	13	0	**54**
8/21/2022	81	0	2	0	0	0	0	0	**83**
8/30/2022	8	0	0	0	0	3	0	0	**11**
9/5/2022	26	0	3	0	0	1	0	0	**30**
9/11/2022	10	1	10	0	0	0	0	1	**22**
9/21/2022	11	0	0	0	0	0	20	0	**31**
9/30/2022	68	2	10	0	0	0	3	0	**83**
10/12/2022	57	0	3	0	0	0	38	0	**98**
10/16/2022	0	1	0	0	0	0	0	0	**1**
10/23/2022	263	0	0	0	0	1	0	8	**272**
11/10/2022	35	0	2	0	0	0	0	5	**42**
11/27/2022	87	1	0	0	0	1	0	3	**92**
11/29/2022	62	0	23	0	2	0	10	2	**99**
12/15/2022	57	0	6	0	1	0	0	0	**64**
12/22/2022	42	0	5	0	1	2	2	0	**52**
Total by species	**1,439**	**6**	**75**	**435**	**7**	**8**	**143**	**26**	**2,139**

4.5 Special Investigations

4.5.1 Special Investigations in the Watershed

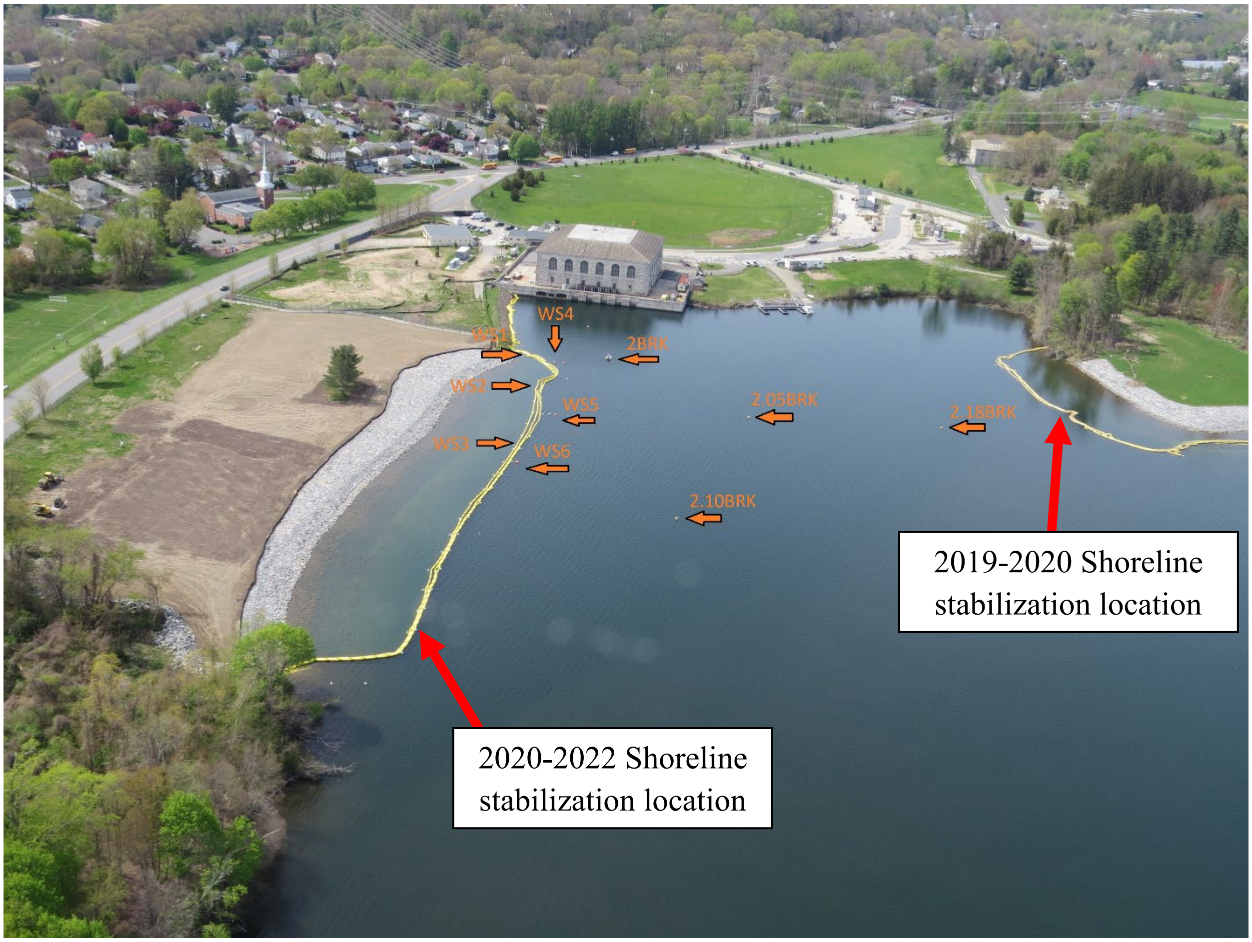
Two special investigations occurred within the Kensico Reservoir watershed during 2022. Each of these special investigations evaluated the potential impacts to drinking water quality to inform operational decisions.

4.5.1.1 Kensico Shoreline Stabilization Project: 2022

Kensico Reservoir shorelines around the Delaware Shaft 18 facility were identified as areas that contributed to elevated turbidity during periods of sustained northeast winds. In 2012, the effect of Hurricane Sandy underscored the need to stabilize and strengthen portions of the shoreline at Kensico Reservoir against extreme storms in the future. Stabilization of the shoreline area farthest away from the intake was completed in December 2020, and stabilization of the shoreline adjacent to Delaware Shaft 18 was completed in November 2022. An intensive monitoring plan was developed since construction had the potential to cause and contribute to reservoir turbidity issues.

The construction contractor was responsible for monitoring turbidity within the work zone sheet piles, as well as the turbidity curtains that enclosed the construction area. DEP WQI staff implemented a monitoring plan outside the construction zone to monitor for turbidity contraventions. DEP's monitoring consisted of the deployment of three fixed depth automated monitoring buoys outfitted with turbidity sensors. DEP also benefitted from data from the fixed-depth buoys on Kensico Reservoir at sites 2.9BRK and 2BRK that are part of the routine monitoring program.

In 2022, two of the automated monitoring buoys were located at the new construction area, while one buoy remained near the original shoreline project area to monitor any post-construction issues. Figure 4.8 shows a recent overview photo of both construction areas. The automated monitoring buoys collected turbidity data at 15-minute intervals and these data were displayed in near real time via the Water Quality Water Hub dashboard. BWS Water Quality and Operations staff constantly monitored the dashboard to ensure that turbidity levels remained at baseline levels. In 2022, no contraventions of the SWTR turbidity limit were experienced at Shaft 18. This project is now considered completed and the monitoring buoys have been removed.



2019-2020 Shoreline stabilization location

2020-2022 Shoreline stabilization location

Figure 4.8 Kensico Reservoir shoreline stabilization locations.

4.5.1.2 Storm Event: September 2022

A rainfall event occurred on September 5 and 6, 2022. Recorded at Westchester County Airport near White Plains, NY, rainfall was 0.34 inches for September 5 and 0.85 inches for September 6 for a storm total of 1.19 inches. Fecal coliform counts peaked at 26,000 CFU 100 mL^{-1} at MB-1 and 20,000 CFU 100 mL^{-1} at N5-1 but returned to baseline by September 7, 2023. UV254 levels went from 0.096 to 0.231 abs cm^{-1} at MB-1 and 0.117 to 0.227 abs cm^{-1} at N5-1 before slowly declining. Despite the impacts to the streams, water quality at DEL18DT remained stable with a maximum fecal coliform count of 2 CFU 100 mL^{-1} and UV254 of 0.036 abs cm^{-1}.

5. Pathogen Monitoring

5.1 Introduction

Samples collected for protozoan analysis in 2022 were analyzed by Method 1623.1 with EasyStain and heat dissociation. In addition, samples were collected and analyzed by a cell culture immunofluorescent assay (CC-IFA) to monitor for infectious *Cryptosporidium* in water leaving Hillview Reservoir. Kensico outflow results are posted weekly on DEP's website (https://data.cityofnewyork.us/Environment/DEP-Cryptosporidium-And-Giardia-Data-Set/x2s6-6d2j) and reported annually in this report.

5.2 Source Water Results

DEP completed its monitoring requirements for the Long Term 2 Enhanced Surface Water Treatment Rule (LT2, USEPA 2006) in 2018; however, the calculation procedure described in the LT2 is performed annually by DEP to measure results against the thresholds. For the period of 2021 and 2022, there were a total of 103 samples collected at the Delaware outflow of Kensico Reservoir at Site DEL18DT. The *Cryptosporidium* mean of monthly means for this 24-month period was 0.0015 oocysts L^{-1}.

In 2022, 13 of 104 Kensico inflow samples (CATALUM and DEL17) were positive for *Cryptosporidium,* for a combined average inflow detection rate of 12.5%. This is within the five-year historical range from 7.1% to 15.1%, with inflow concentrations ranging from 0 to 2 oocysts $50L^{-1}$. Concentrations for the Kensico and Croton outflows (DEL18DT and CROGH) or equivalent tap (CRO1B) ranged from 0 to 1 oocysts $50L^{-1}$. For *Giardia*, 50 of 104 Kensico inflow samples (CATALUM and DEL17) were positive for *Giardia*, for a combined average inflow detection rate of 48.1%. This is within the five-year historical range from 47.6% to 70.7%. Concentrations ranged from 0 to 54 cysts $50L^{-1}$. Concentrations for the outflow (DEL18DT and CROGH) ranged from 0 to 6 cysts $50L^{-1}$. Results are presented in Table 5.1 and Figure 5.1 and Figure 5.2. As in previous years, there were seasonal variations in *Giardia* concentrations at the Kensico inflows and outflow, with seasonally elevated *Giardia* concentrations during the colder months.

Table 5.1 *Cryptosporidium* and *Giardia* - Kensico and New Croton keypoints.

Analyte	Site	Number of Positive Samples	Detection Rate (%)	Mean Count[2]	Maximum Count
Cryptosporidium (Oocysts $50L^{-1}$)	CATALUM (n=52)	6	11.5	0.15	2
	DEL17 (n=52)	7	13.5	0.17	2
	DEL18DT (n=52)	4	7.7	0.08	1
	CROGH[1] (n=4)	0	0	0.00	0
Giardia (cysts $50L^{-1}$)	CATALUM (n=52)	21	40.4	3.36	54
	DEL17 (n=52)	29	55.8	1.52	9
	DEL18DT (n=52)	21	40.4	0.79	6
	CROGH[1] (n=4)	1	25.0	0.25	1

[1] May include alternate sites sampled to best represent outflow during “off-line” status. In 2022, CRO1B was substituted for CROGH during the 2nd, 3rd, and 4th quarters.

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

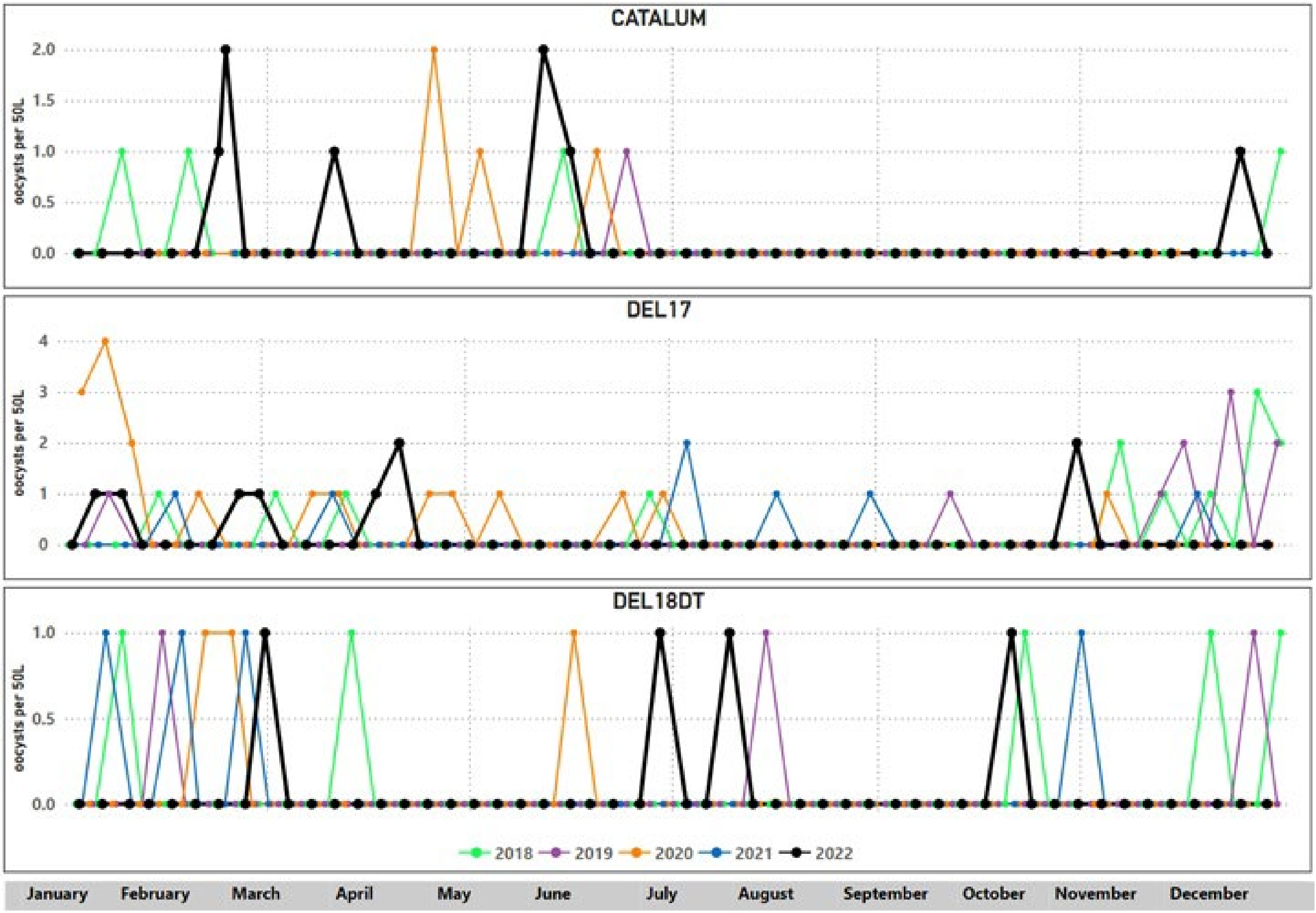


Figure 5.1 Kensico keypoint *Cryptosporidium.*

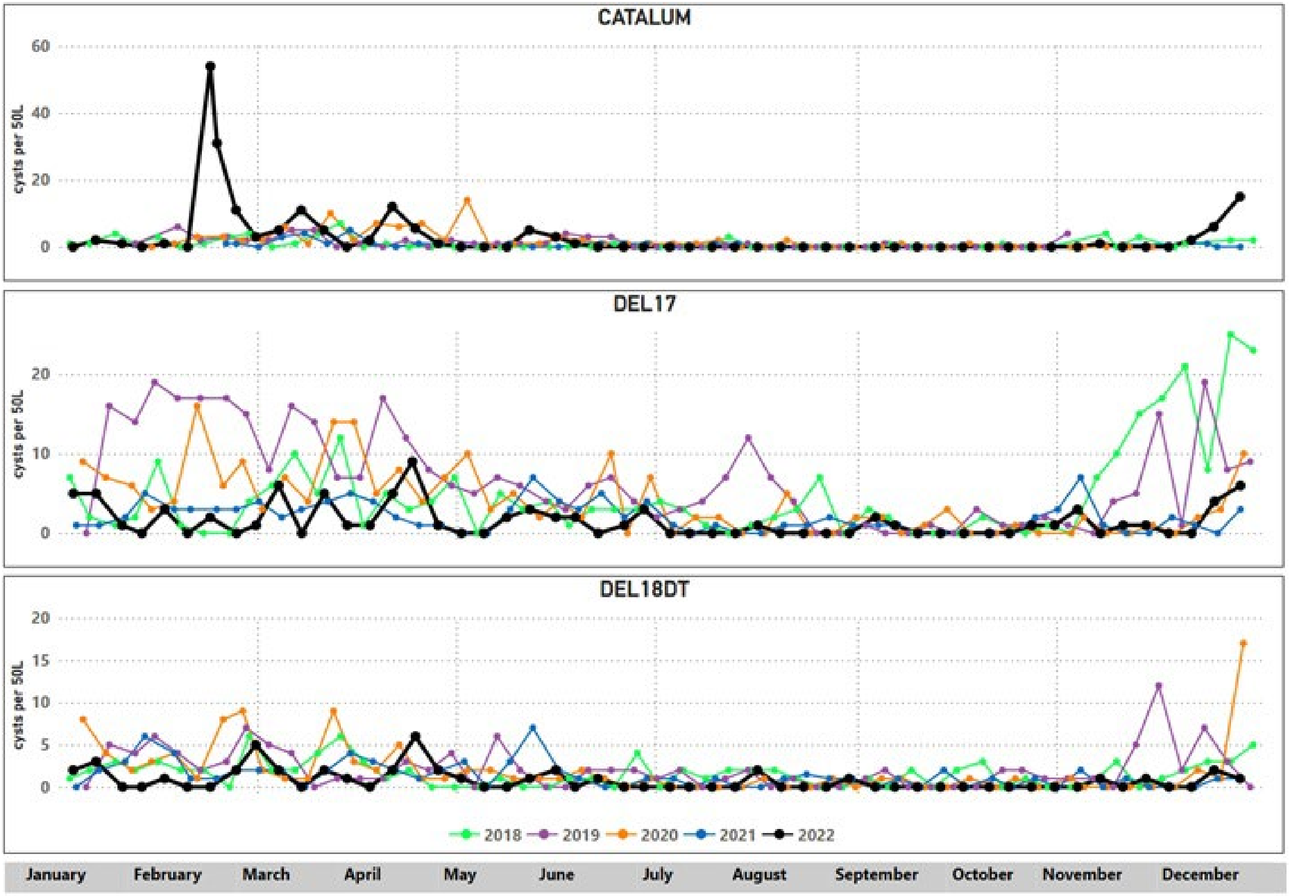


Figure 5.2 Kensico keypoint *Giardia.*

In response to an elevated *Giardia* count of 54 cysts $50L^{-1}$ at CATALUM on February 14, 2022, additional samples were collected on February 16, 2022, and February 22, 2022, with results of 31 and 11 cysts $50L^{-1}$, respectively. A sample was also collected at the Ashokan Reservoir raw water site EARCM on February 17, 2022, with a result of 17 cysts $50L^{-1}$. Since DEP was diverting water from the West Basin at Ashokan, samples were collected from the middle elevation of the West Basin (site WM) on February 22, 2022, and February 28, 2022, with results of 35 and 24 cysts $50L^{-1}$, respectively. Sampling upstream of the reservoir occurred on February 28, 2022, with samples collected from the Schoharie Reservoir Keypoint (SRR1CM) and the Esopus Creek at Cold Brook (E16I). Those results were also elevated at 19 and 38 cysts $50L^{-1}$, respectively. In addition to pathogen sampling, site surveys were conducted by Watershed Water Quality Operations and Wildlife Studies staff to attempt to identify potential sources. There was no evidence of septic failures in the area, and no unusual wildlife activity noted. Samples were sent to the Centers for Disease Control and Prevention (CDC) for genotyping, but the laboratory was not successful in amplifying *Giardia* DNA for sequencing. DEP switched to an East Basin diversion on February 18, 2022, and *Giardia* counts returned to typical levels by February 28, 2022, with a result of 3 cysts $50L^{-1}$. While no definitive source was identified, Source Water Operations staff did report finding approximately 15 dead moles on the West Basin Gate Chamber screens on March 1, 2022.

5.2.1 2022 Source Water Quality Control Results

Quality control (QC) testing included ongoing precision and recovery (OPR) samples and matrix spike (MS) samples. Weekly OPR testing involves spiking reagent-grade water with known amounts of oocysts and cysts. Acceptable OPR results of 42% to 100% for *Cryptosporidium* and 35% to 100% for *Giardia* were required before processing weekly samples. Ranges of recovery for protozoan OPR samples in 2022 were 47% to 89% for *Cryptosporidium* and 7% to 81% for *Giardia*, with re-testing conducted as necessary. To determine MS recoveries, sample matrices are spiked with known amounts of oocysts and cysts and analyzed according to the same method used for routine samples. In 2022, matrix spike recoveries ranged from 5% to 78% for *Cryptosporidium* and 12% to 66% for *Giardia*, with complete results provided in Table 5.2.

Table 5.2 Keypoint matrix spike results - 2022.

Date	Site	***Cryptosporidium*** **% Recovery**	***Giardia*** **% Recovery**
1/24/2022	CATALUM	70	66
7/5/2022	CATALUM	5	12
11/14/2022	CATALUM	36	20
4/18/2022	DEL17	69	50
8/29/2022	DEL17	45	50
1/10/2022	DEL18DT	59	39
5/23/2022	DEL18DT	74/78	37/45
10/3/2022	DEL18DT	38	53

5.3 Pathogen Monitoring of West of Hudson Source Waters

Pathogen monitoring at West of Hudson keypoint sites was suspended at the start of the COVID-19 pandemic. In July 2022, DEP permanently discontinued routine monitoring at West of Hudson Keypoint sites to better utilize resources for other monitoring projects, infrastructure support, and treatment operations. Therefore, no data were collected during 2022. DEP may temporarily resume certain pathogen monitoring during periods of high turbidity, runoff events, storms, or any other upset conditions.

5.4 Watershed Streams

West of Hudson Streams

Pathogen monitoring at West of Hudson (WOH) stream sites was suspended at the start of the COVID-19 pandemic. In May 2022, DEP permanently discontinued monitoring WOH watershed streams for pathogens since data from this monitoring has not resulted in significant changes to DEP's watershed protection or operational strategies. Therefore, no data were collected during 2022. DEP will conduct "as needed" watershed surveillance monitoring based on pathogen data from existing keypoint monitoring locations.

Kensico Streams

The Kensico perennial streams were monitored for protozoans monthly from March to December 2022. Percent detects and maximum counts for each site are summarized in Table 5.3, and individual results are displayed in Figure 5.3 - Figure 5.6. Overall, *Cryptosporidium* oocysts were detected in 29 out of 84 (35.0%) stream samples in 2022 and *Giardia* cysts were detected in 63 out of 84 samples (75%).

Table 5.3 *Cryptosporidium* and *Giardia* - Kensico streams.

		Cryptosporidium			***Giardia***		
Site	**N**	**% Detects**	**Max($50L^{-1}$)**	**95%[1]**	**% Detects**	**Max($50L^{-1}$)**	**95%[1]**
BG9	10	10%	1	2.00	60%	6	23.35
E10	10	30%	1	2.30	40%	2	11.20
E11	10	0%	0	5.75	80%	8	51.20
E9	10	40%	4	4.45	100%	46	99.05
MB-1	11	55%	48	5.60	91%	185	27.60
N12	13	69%	129	14.60	92%	18	16.00
N5-1	10	10%	1	8.30	90%	16	20.30
WHIP	10	50%	3	2.00	40%	3	14.30

[1] 95% are based on the previous 10 years.

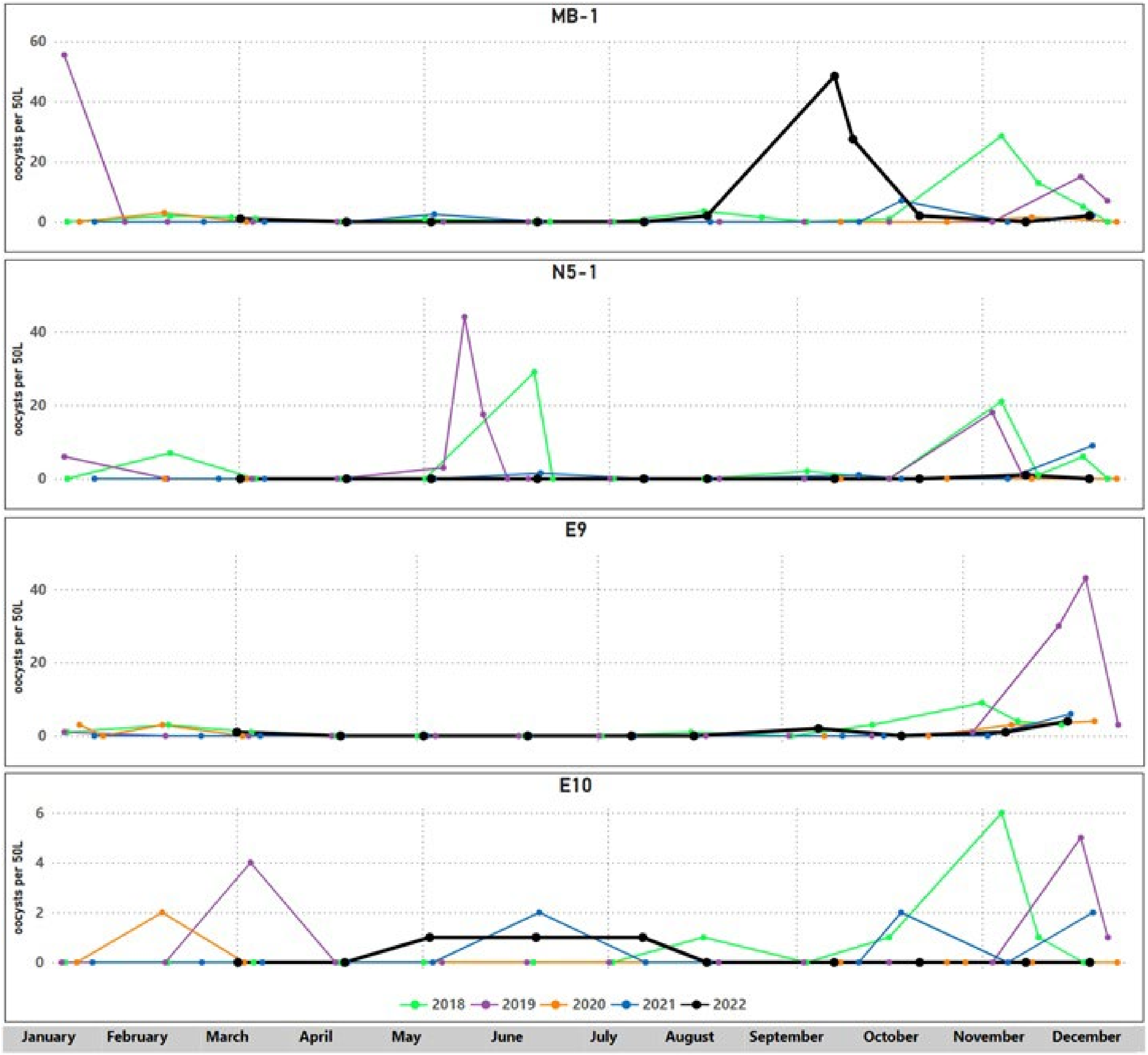


Figure 5.3 Kensico streams *Cryptosporidium* 2018-2022 (MB-1, N5-1, E9, E10).

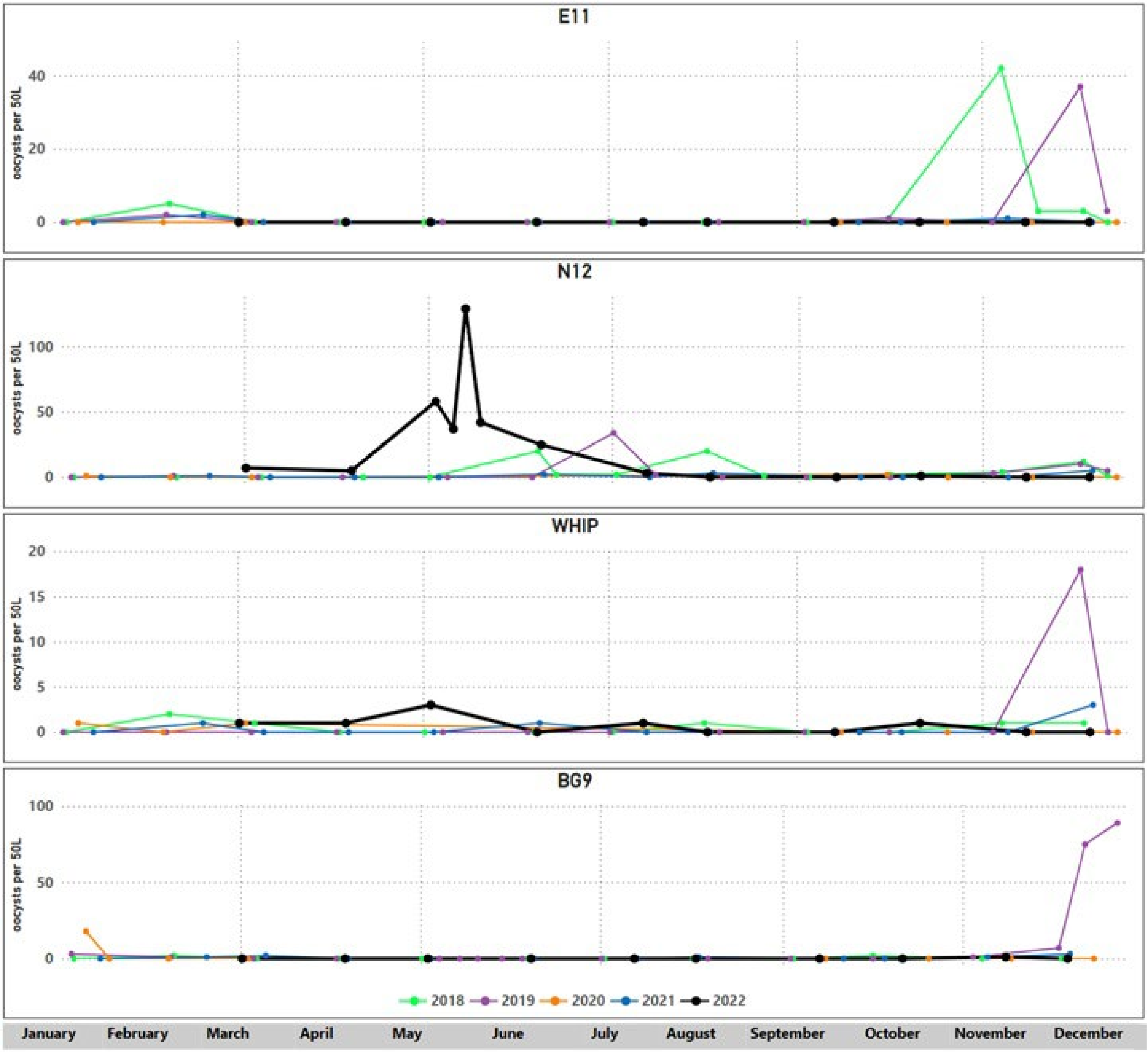


Figure 5.4 Kensico streams *Cryptosporidium* 2018-2022 (E11, N12, WHIP, BG9).

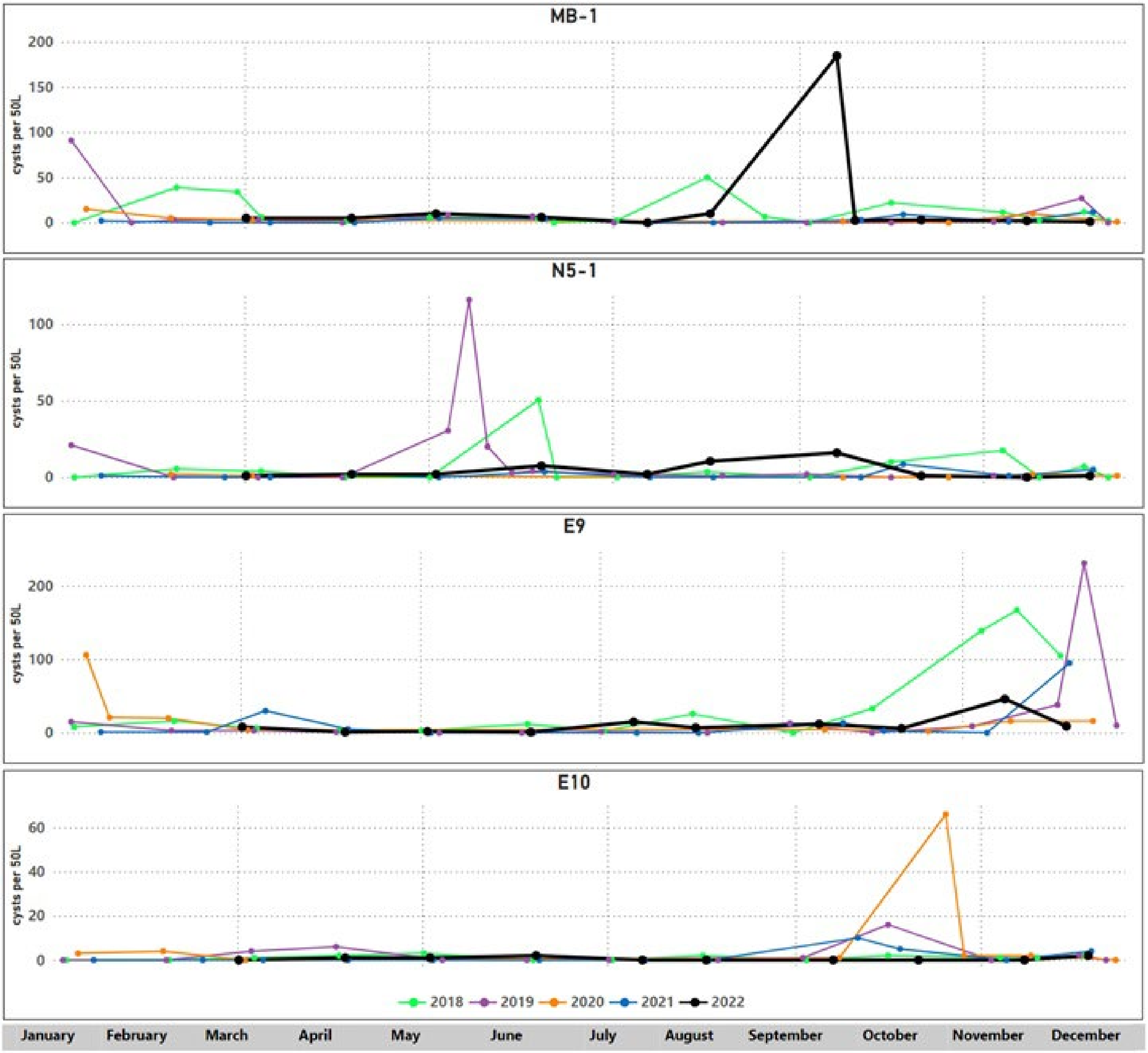


Figure 5.5 Kensico streams *Giardia* 2018-2022 (MB-1, N5-1, E9, E10).

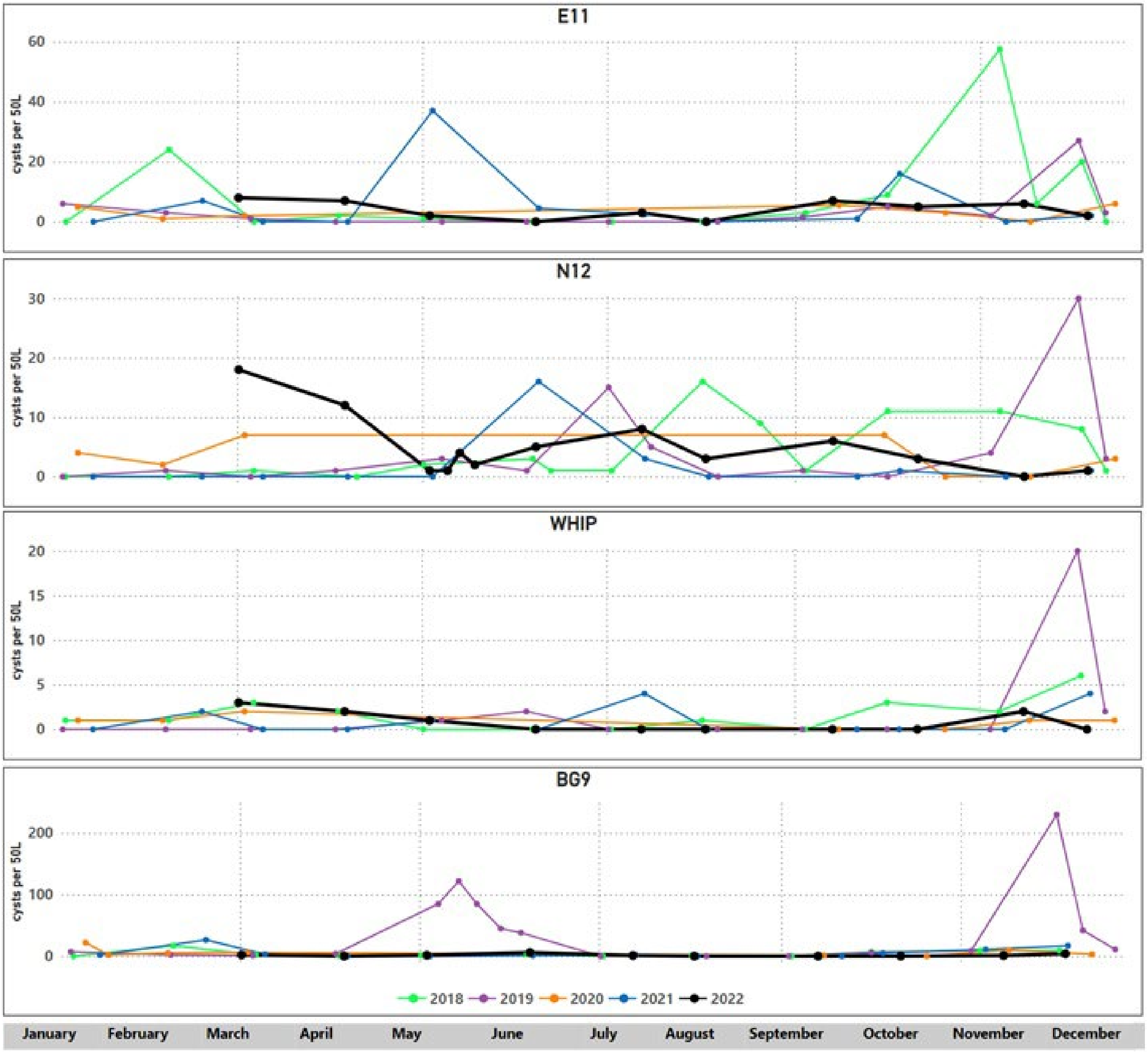


Figure 5.6 Kensico streams *Giardia* 2018-2022 (E11, N12, WHIP, BG9).

In addition to routine monthly monitoring, DEP may conduct resampling when counts exceed the 10-year 95th percentile for either *Cryptosporidium or Giardia.* Site N12 exceeded the criteria for *Cryptosporidium* on May 3, 2022, with a count of 58 oocysts 50L^{-1}. Resamples collected on May 9, 2022, May 13, 2022, and May 18, 2022, yielded results of 37, 129, and 42 oocysts 50L^{-1}, respectively. On May 13, 2022, and May 18, 2022, additional samples were collected upstream of N12 at sites N12above2 and N12above3 (see Figure 5.7) with counts ranging from 49 to 119 oocysts 50L^{-1}. Slide scraping from select samples were sent to the New York State Department of Health Wadsworth Center for *Cryptosporidium* genotyping, but no

DNA was recovered. The routine N12 sample collected on June 7, 2022, had a count of 25, with samples returning to normal ranges on July 12, 2022 (3 oocysts 50L^{-1}). Samples were also collected for Microbial Source Tracking (MST) on May 9, 2022, (N12), May 13, 2022, (N12 and N12above3) and May 18, 2022 (N12, N12above2 and N12above3) with no presence of human marker detected in the samples. Non-quantifiable amounts of ruminant marker were detected in samples collected at N12 and N12above2 on May 18, 2022, and canine marker was detected at quantifiable levels in the N12 sample collected on May 9, 2022, as well as the N12 and N12above2 samples collected on May 18, 2022. Despite the elevated stream counts, *Cryptosporidium* levels at the Kensico outflow at DEL18DT ranged from 0 to 1 oocysts 50L^{-1} during this period.

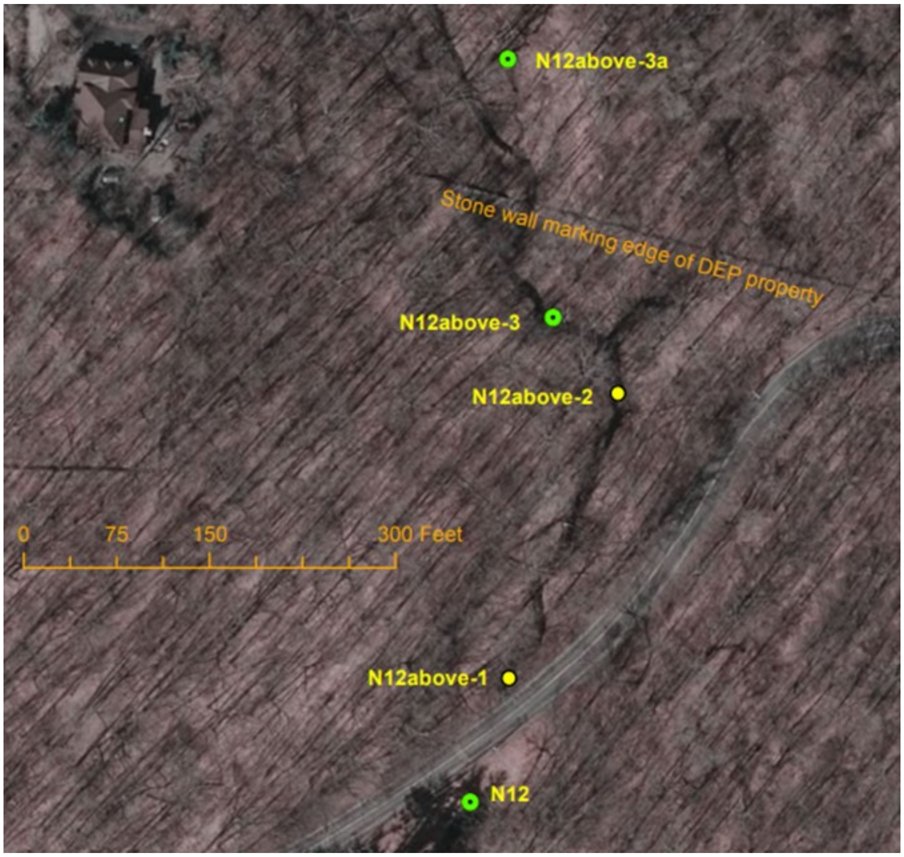


Figure 5.7 Kensico Tributary N12 Special Investigation map.

On September 13, 2022, MB-1 met the 95th percentile criteria for both *Cryptosporidium* and *Giardia* with counts of 48 oocysts 50L^{-1} and 185 cysts 50L^{-1}, respectively. A resample collected on September 19, 2022, had 27 oocysts 50L^{-1} and 3 cysts 50L^{-1}. *Cryptosporidium* and *Giardia* levels were back within typical ranges on October 11, 2022, at 2 oocysts 50L^{-1} and 3 cysts 50L^{-1}, respectively.

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

Catskill-Delaware Ultraviolet Light Disinfection Facility

Weekly monitoring at the outflow of the Catskill-Delaware Ultraviolet Disinfection Facility (CDUV) began in January 2018, at site CCCLAB, and continued through 2022. Results are presented in Table 5.4. This monitoring was initiated to demonstrate that *Cryptosporidium* oocysts and *Giardia* cysts can be recovered and counted with this method, even though they have been inactivated by UV light and are no risk to public health. After five years of data collection, this monitoring will be discontinued in 2023.

Table 5.4 CDUV protozoan monitoring results summary for 2022.

	Cryptosporidium **(oocysts 50L^{-1})**	***Giardia*** **(cysts 50L^{-1})**
n	52	52
Number of Detects	3	16
% Detects	5.8%	30.8%
Mean (50L^{-1})	0.08	0.46
Maximum (50L^{-1})	2	4

Hillview Reservoir Outflow (Site 3)

Giardia and *Cryptosporidium* are monitored weekly at Hillview Reservoir Site 3 as required by the Hillview Administrative Order on Consent. Results are summarized in Table 5.5. *Cryptosporidium* was detected in 3 of 52 samples in late summer and autumn 2022, with an annual mean concentration of 0.06 oocysts 50L-1 and detection rate of 5.8%. *Giardia* was detected in 12 of 52 samples, with an annual mean concentration of 0.40 cysts 50L^{-1} and detection rate of 23.1%. These are well within the historical ranges for both *Cryptosporidium* (0 - 11.1% and 0-2 oocysts 50L^{-1}) and *Giardia* detection rate (9.3 - 42.3% and 0-6 cysts 50L^{-1}). All infectivity results were negative. Data for 2022 are presented in Figure 5.8 and Figure 5.9. Matrix spike recoveries are shown in Table 5.6

Table 5.5 Hillview Site 3 protozoan detections from 2018 to 2022.

	Cryptosporidium		*Giardia*	
Year	**Detects**	**% Detect**	**Detects**	**% Detect**
2018	5	9.4%	9	17.0%
2019	2	3.8%	22	42.3%
2020	2	3.8%	17	32.7%
2021	4	7.7%	15	28.8%
2022	3	5.8%	12	23.1%

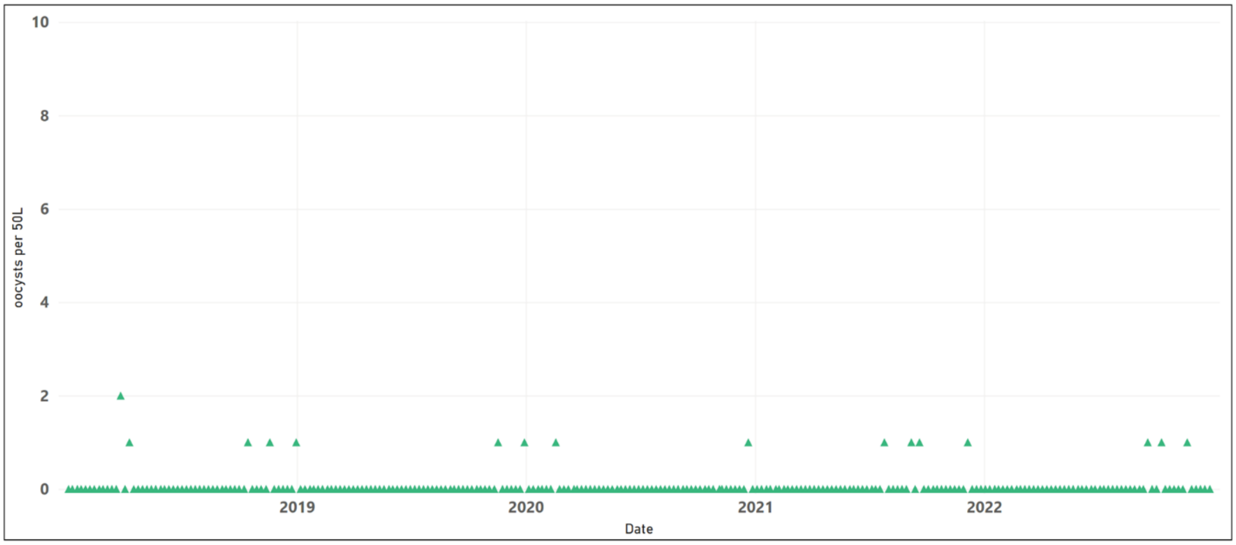


Figure 5.8 Hillview Site 3 *Cryptosporidium* (2018-2022).

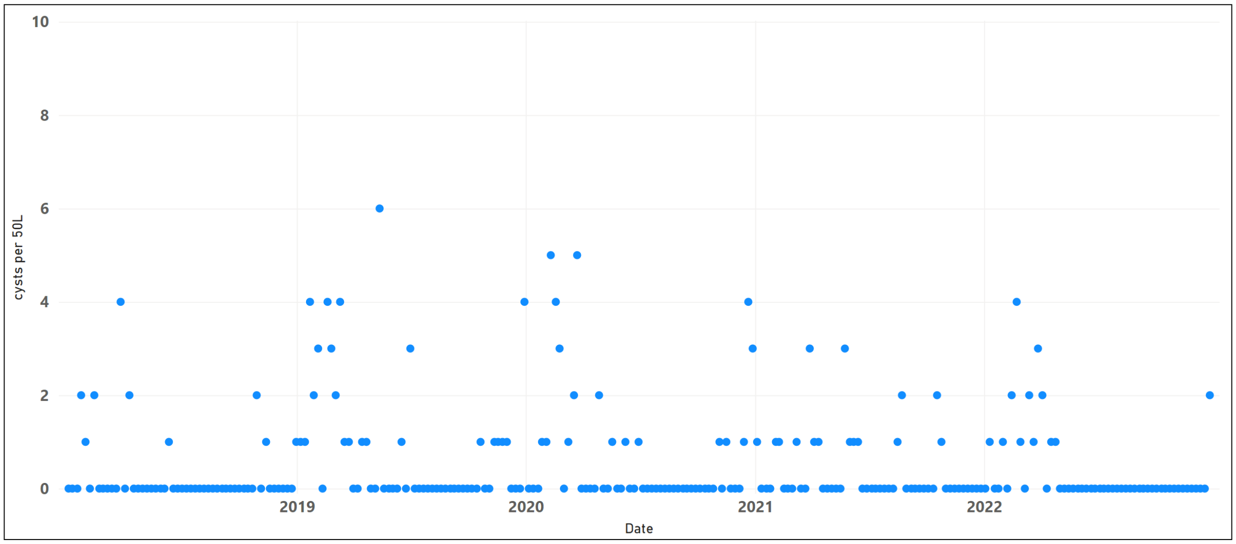


Figure 5.9 Hillview Site 3 *Giardia* (2018-2022).

Table 5.6 Hillview Site 3: Matrix Spike Results, 2022.

Date	*Cryptosporidium* % Recovery ($50L^{-1}$)	*Giardia* % Recovery ($50L^{-1}$)
1/10/2022	66	52
2/14/2022	67	50
3/14/2022	62	56
4/11/2022	70	62
5/16/2022	67	26
6/13/2022	57	64
6/13/2022*	55	31
7/18/2022	63	57
8/15/2022	38	57
8/15/2022*	35	43
9/19/2022	58	62
10/17/2022	56	50
11/7/2022	52	64
12/12/2022	41	52

*Additional matrix spike sample analyzed comparing 50L verses 40+10 filtration method technique.

5.6 Additional Sampling

As required under the Revised 2017 FAD, DEP conducted weekly monitoring at the Cross River and Croton Falls pump stations for one week on March 28, 2022. Both samples were non-detect for *Cryptosporidium*, with *Giardia* counts of 1 cyst $50L^{-1}$ for Cross River (CROSSRVVC) and 2 cysts $50L^{-1}$ for Croton Falls (CROFALLSVC).

In addition, one special investigation sample was collected before dechlorination at Hunter Highlands Wastewater Treatment Plant Site Hunter BD on January 19, 2022. The sample was negative for *Cryptosporidium* with a *Giardia* count of 14 cysts $50L^{-1}$.

6. Modeling and Analysis

6.1 Overview

DEP's Water Quality Modeling Program uses models to quantify the impact of climate change, changes in land use, individual and grouped components of the watershed protection program, operation of the water supply system, and water demand on the quantity and quality of water delivered to the City.

In 2022, DEP developed an aggregated index to describe the degree of extreme conditions for a given year relative to the reference period of 1970-2000. The index combined several extreme climate indicators. We also developed a bias correction method for multi-year precipitation extremes. Such a correction was necessary because of the underestimation of the magnitudes of multi-year precipitation extremes by global climate models (GCMs), resulting in an inaccurate estimation of the magnitudes of extremes in future scenarios. In 2022, DEP initiated a Soil and Water Assessment Tool (SWAT) model application to develop dissolved organic carbon (DOC) simulation capability in streams of West of Hudson (WOH) watersheds. Initial testing of the SWAT-Carbon (C) model was done for the Neversink watershed. DEP also started SWAT model setups for five East of Hudson (EOH) watersheds – Amawalk, Boyd Corners, Cross River, Titicus, and East Branch, which have natural inflow.

We also completed the development and testing of a turbidity model for West Branch Reservoir. During 2022, DEP proposed and validated a two-component, simple statistical approach to predict the formation potentials of the sum of five haloacetic acids (HAA5FP) and total trihalomethanes (TTHMFP) in inflows to Cannonsville and Neversink reservoirs using environmental variables (streamflow, total phosphorus, and soil temperature) and UV254 as a surrogate for DBP precursors. We also began testing of two-dimensional hydrothermal and water quality model CE-QUAL-W2 (W2) for predicting UV254 in Cannonsville and Neversink reservoirs.

We performed 615 OST simulations, supporting daily reservoir operations as well as long-term planning activities in 2022. We continued enhancing OST so that it better reflected current system rules and infrastructure status and provided guidance for various infrastructure outage applications, e.g., the planned 2023 RWBT outage. The modeling group also published one paper and presented seven papers at conferences during 2022.

6.2 Climate Change Indicators for the Watershed

The importance of understanding how climate change is impacting the water supply watershed has led DEP to develop climate change indicator metrics. Using existing datasets, the goal of this analysis is to describe long-term trends of climate conditions of meteorology, hydrology, and other aspects of the water supply system. With predictions of increased intensity of weather events and higher variability both in drought and flooding conditions, as well as generally warmer temperatures, DEP needs to understand how the climate is currently changing to better prepare for future changes.

The development of climate change indicators and trends began in 2019 and has been documented in previous Watershed Water Quality Annual Reports. In 2022, the analysis has been extended to create an index of climate indicators. The climate change index is intended to provide a snapshot of how extreme the climate conditions were in a given year relative to a standard reference period. Although it is not reliant on indicator trends, this index is an easily digestible overview metric to inform a deeper review of the individual indicators.

6.2.1 Data

To make the index more reliable, the data used have been pared down to the most reliable sources available. For the meteorology index, NOAA airport data are sourced from either the Global Summary of the Day or the Global Historical Climatology Network datasets. The number of airports used have been increased to a total of seven northeastern sites with a data period beginning prior to 1970 (Figure 6.1). Hydrology data from USGS gages are limited to the primary unregulated inflow gages for the WOH reservoirs (Figure 6.2).

6.2.2 Methods

The climate extreme index is computed based on the same queries used to calculate individual indicator trends. For each pre-processed indicator timeseries, the data are subset into three time periods: pre-1970, 1970-1999, and 2000-present. The 30-year period of 1970-1999 is used as the baseline period for comparison with the analytical period of 2000-present. Data prior to 1970 are not consistently available for all sites, so are excluded from the analysis.

The baseline period is used to calculate upper and lower threshold values for each indicator. Indicator values for a given year are considered extreme if they are above the 90th percentile or below 10th percentile thresholds (Figure 6.3). Extreme values are attributed with a value of 1 (> 90th percentile) or -1 (< 10th percentile) and summed across all indicators for each year. Extreme values can also be tagged as 1 for both 90th and 10th percentiles to create an absolute value of the extreme index. By treating both extremes equally, this version of the index may be more sensitive to variations of conditions among the individual indicators. Extreme sums are normalized by the number of indicators analyzed to produce a final timeseries of climate extremes during each period, which can then be analyzed for trends, either for individual sites or aggregated across all sites, and plotted for review.

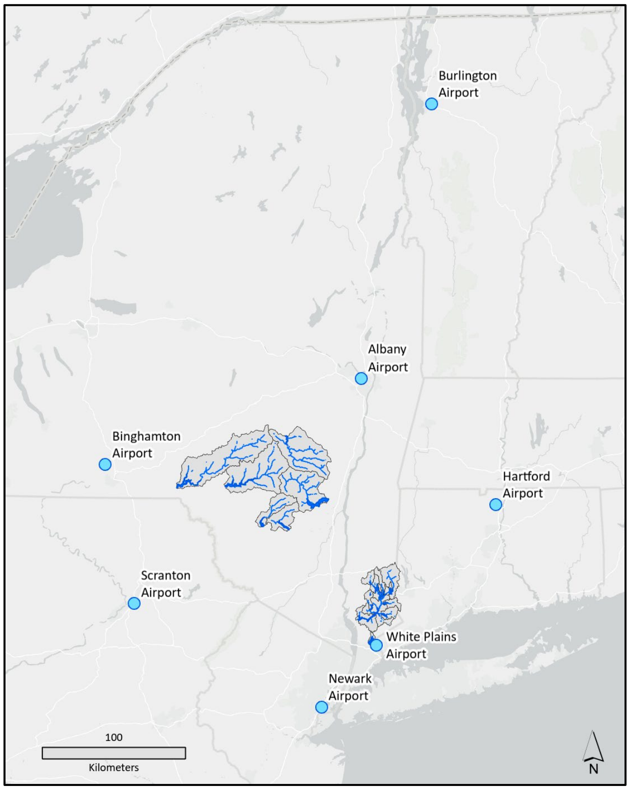


Figure 6.1 Meteorology indicator sites at NOAA airport locations.

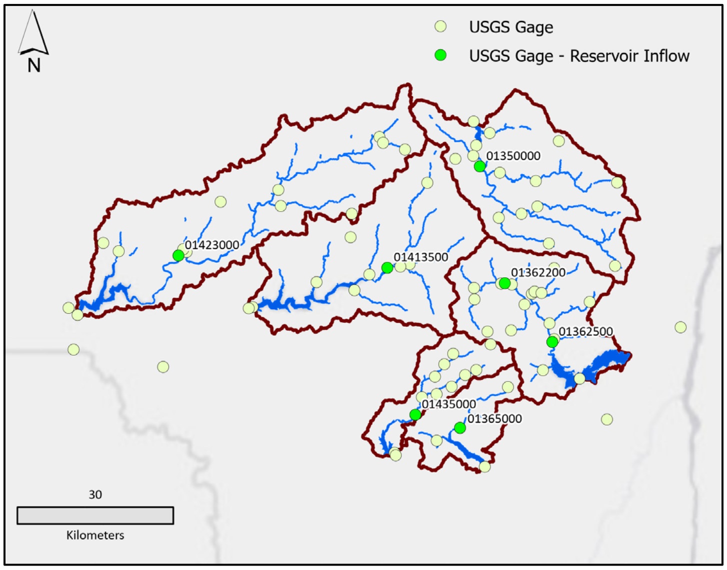


Figure 6.2 WOH Hydrology indicator sites at USGS gages.

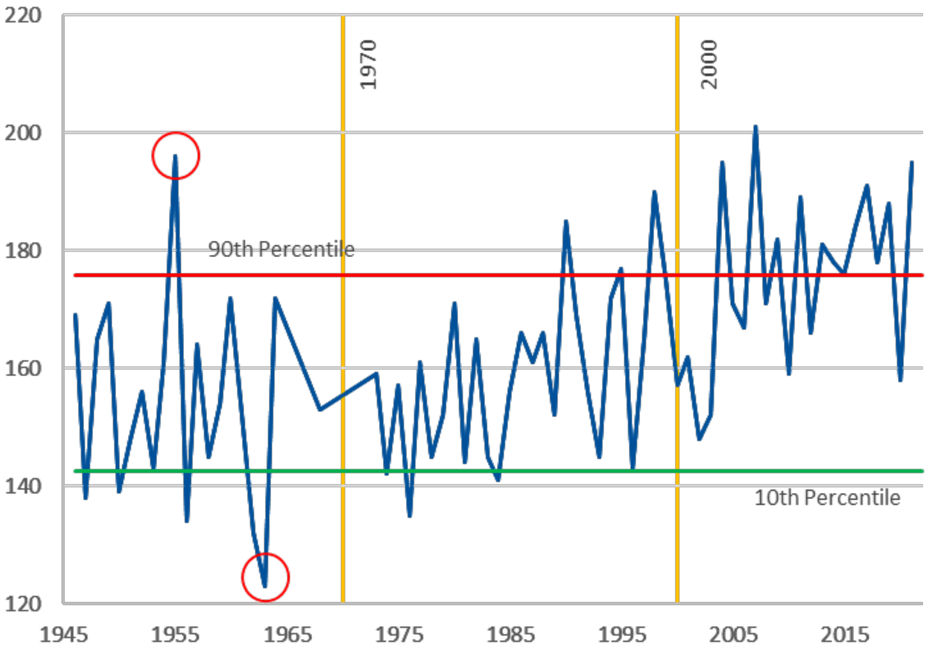


Figure 6.3 Example timeseries used to identify extreme conditions for climate change extreme index.

6.2.3 Results and Discussion

The climate extreme index is intended to provide an overview of the results of all climate change indicators. Some modifications had to be made to adjust the index to better fit the data available for analysis. Although the Danbury, CT Airport site is included in indicator trends analyses, it was excluded from the meteorological index calculation because of lack of precipitation data during the reference period. All meteorological climate indicators have been included in the index calculation. Likewise, the hydrology data have been limited to inflow sites to ensure that the index is not confounded by data gaps among the gages. The hydrology index has been calculated without certain indicators, such as the timing of peak flows, because trends in the results indicate that refinement of the indicators themselves is necessary.

Meteorology Index: The meteorology extreme index plot (Figure 6.4) shows that while the index for the baseline period (1970-1999) does not show a significant change trend, the analysis period does show a clear and significant increase. This suggests that there is a higher level of extreme variation in the meteorological indicators relative to the reference period. The absolute value index shows an even steeper trend, with a peak value of nearly 50% of indicators either above the 90th or below 10th percentile in 2020.

While the trend is clear when aggregated across all airports, an individual airport may not show as clear of a trend. Table 6.1describes the trends calculated for the extreme index. While all sites have a positive value for change, only Binghamton, Newark, and Scranton have a significant trend with a p-value less than 0.05.

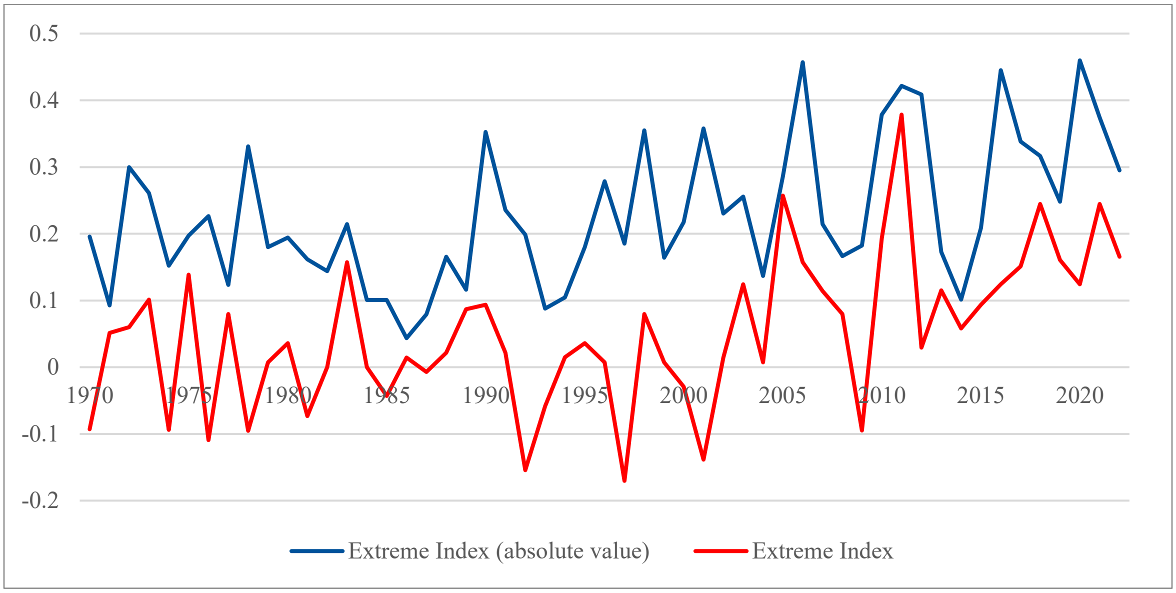


Figure 6.4 Meteorology extreme index results averaged across all airport locations.

Hydrology Index: The hydrology extreme index does not show significant trends during the analysis period, either at an aggregated level or at individual stream gages. Figure 6.5summarizes the extreme index for the average of all stream gages. The index does appear to stabilize at a higher overall level based on the absolute value index relative to the baseline period, with a peak value of 66% of indicators in extreme conditions. However, but it does not have a significant change trend during the period 2000-present. Because hydrologic conditions are more sensitive to antecedent conditions and other factors, there are additional biases introduced that may confound interpretation of hydrologic variables as direct indicators of climate change.

Table 6.1 Results of meteorology extreme index trends for all airport sites. Trend is only described for locations with a p-value < 0.05.

Analysis location	Trend	p-value	Tau	Change per year
All Airports	increasing	0.0095	0.391304	0.0081
Albany	no trend	0.71	0.059289	0.00065
Binghamton	increasing	0.029	0.328063	0.01
Burlington	no trend	0.052	0.29249	0.0079
Hartford	no trend	0.084	0.26087	0.0079
Newark	increasing	0.049	0.296443	0.0102
Scranton	increasing	0.012	0.375494	0.0115
White Plains	no trend	0.299	0.158103	0.00433

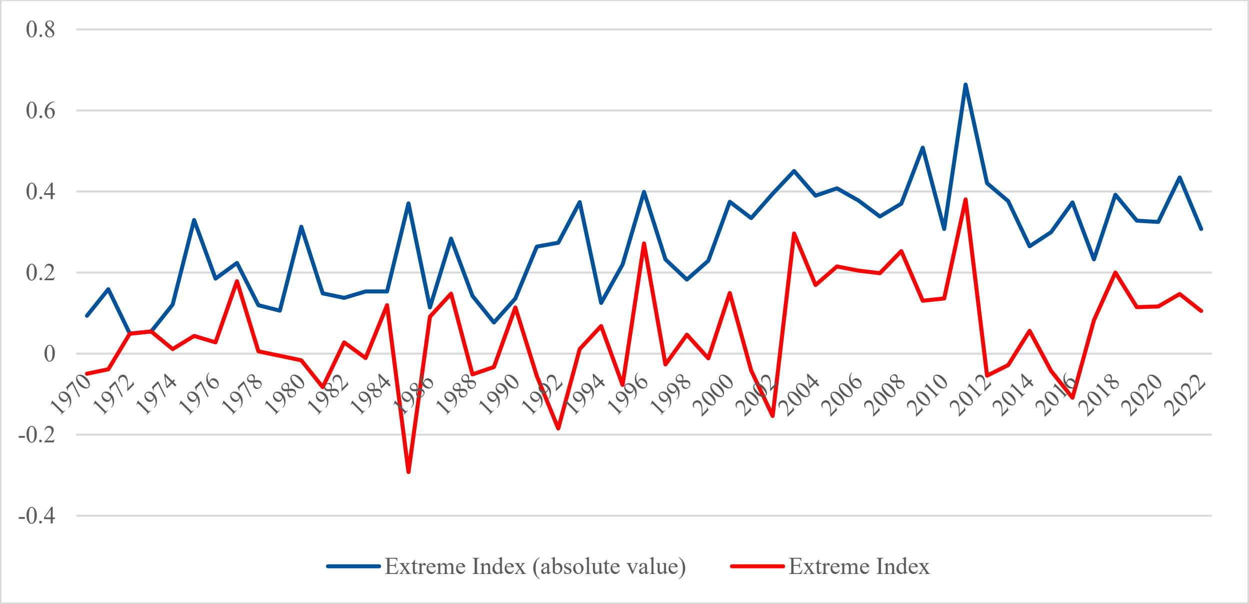


Figure 6.5. Hydrology extreme index results averaged across all stream gages at reservoir inflows.

6.3 Development of Extreme Climate Scenarios

During 2022 we continued to develop improved multiyear hydrological extreme scenarios for NYC Water Supply System resiliency studies. Extreme scenarios include both droughts and pluvials. The use of GCMs for water supply system impact, vulnerability, and resiliency studies typically requires corrections for precipitation biases at sub-grid spatial scales, and at daily through annual time scales. However, despite the underestimation of multiyear precipitation extremes by GCMs over many regions of the world, including the Catskill Mountains, bias corrections at these longer time scales are rarely employed.

In our 2022 publication in the Journal of Hydrometeorology (Frei et al. 2022), we develop a bias correction method applied to precipitation for multi-year extremes. Subsequent to the 2022 publication we have been applying this method to the WOH basins, developing regional-mean bias correction factors for the six WOH basins simultaneously, and comparing these methods to two other methods. The steps in the analysis include:

1. Evaluate observed multiyear variability for durations between 1 and 20 years from stations in the region (completed).
2. Evaluate downscaled and high-frequency bias corrected GCM results for multiyear variability at the same regional locations as stations (completed).
3. Compare observed (step 1) and modeled (step 2) multiyear variability and calculate bias correction factors at each station / duration (completed).
4. Calculate regional mean bias correction factors for each duration (completed).

5. Apply the bias correction factors for each duration to model precipitation simulations over all basins and evaluate results for the impact on extreme hydrologic events in the WOH watersheds (in progress; completed for only Ashokan Basin).
6. Compare this method to two other methods: bias-uncorrected GCM results; and analog extremes taken from observations during the historical period (in progress; completed for only Esopus Basin).
7. Submit one or more articles summarizing our work for peer-reviewed publication (in progress)

Results comparing the bias correction to two other methods (step 6 and Figure 6.6) demonstrate their impact on precipitation magnitude scenarios for the Ashokan Basin. The two other methods include bias-uncorrected GCM results and analog extremes taken from observations during the historical period. During the historical period (not shown here) bias-uncorrected GCM simulations do not simulate pluvial magnitudes as wet as observed pluvials for most durations. However, because GCM future simulations suggest an increasing trend in both mean precipitation and in multiyear variability, future simulations suggest wetter pluvials and wetter droughts in comparison to historical model simulations. Figure 6.6shows that bias-uncorrected GCM future simulations suggest pluvial magnitudes comparable to those observed historically. Bias-corrected GCM simulations show wetter pluvials, which we believe to be more realistic. Similarly, GCM drought magnitudes under future un-bias-corrected simulations are not nearly as dry as observed historical droughts. Corrected GCM future drought simulations are closer to observed historical drought magnitudes.

The plan for 2023 is to extend this analysis in two different ways. First, we will apply the regional bias correction factors already calculated to each of the six WOH basins to evaluate extreme scenarios for the entire WOH system simultaneously. Second, we will apply this method to the Cannonsville Basin individually based on basin-specific (rather than regional-mean) bias correction factors, allowing us to further evaluate the usefulness of this method. These scenarios will be used as input into our suite of water system models to evaluate the resiliency of the water supply system to potential future hydrologic extremes, including both drought and pluvial scenarios.

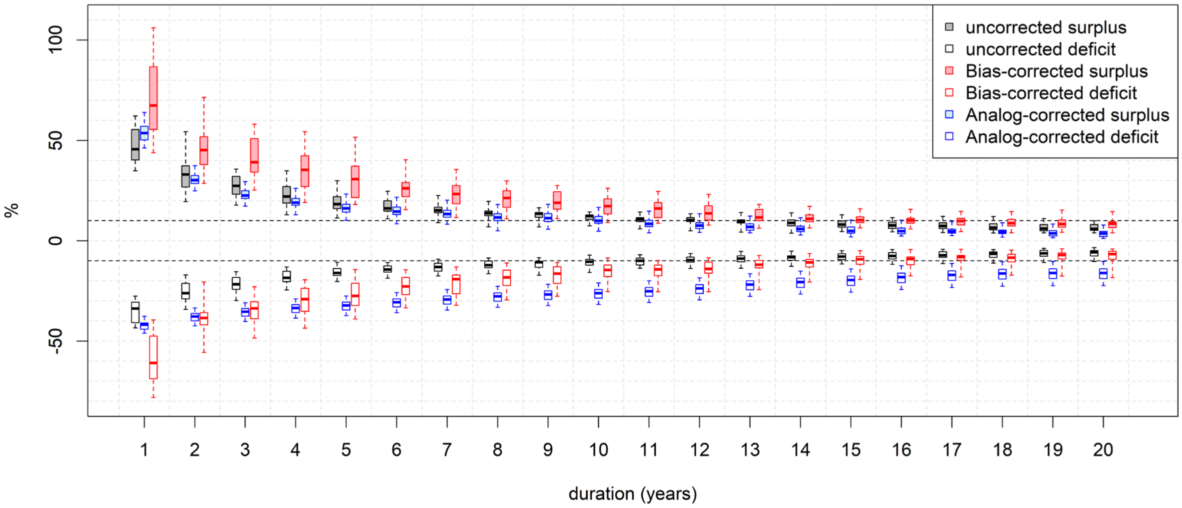


Figure 6.6 Drought deficit and pluvial surplus scenarios (2017-2099) for the Esopus Basin based on three methods, as discussed in text. Boxplots represent results from 20 GCMs.

6.4 DOC Modeling in the Neversink Watershed

Dissolved organic carbon (DOC) in surface water impacts the global carbon cycle, ecosystem productivity, and water quality in potable water supply systems. High levels of DOC can impact surface water supplies through its role as a precursor for disinfection byproducts (DBPs) during water treatment, where it combines with chlorine to form carcinogenic compounds (Chowdhury et al. 2009). Few physically based watershed models can simulate carbon cycling and predict DOC in surface waters under the influence of natural and anthropogenic drivers. This work transforms the Soil and Water Assessment (SWAT) model to simulate DOC from variable source runoff areas in humid forested watersheds.

6.4.1 Modeling Objectives

In this work, we adapted the SWAT-Carbon (C) model in the humid forested Neversink watershed (Figure 6.7) in the northeastern U.S. with spatial heterogeneity in topography, soils, and precipitation, where saturation excess runoff from variable source areas (VSAs) is the dominant runoff generation mechanism (Steenhuis et al. 1995). Incorporating VSA hydrology is important for DOC modeling in these watersheds to correctly predict the spatial location of DOC source areas. Specific objectives of this study are:

- To develop a model capable of simulating runoff and DOC export from watersheds with variable source areas that produce surface runoff.

- Use remotely sensed observations of the dynamic vegetation phenology (forest growth) and evapotranspiration amounts to calibrate SWAT for related parameters.
- Evaluate the model's capability to predict DOC fluxes from the main outlet of the watershed and five tributary sites using measured DOC and streamflow data and perform a sensitivity analysis on simulated DOC fluxes as a function of rainfall and temperature.

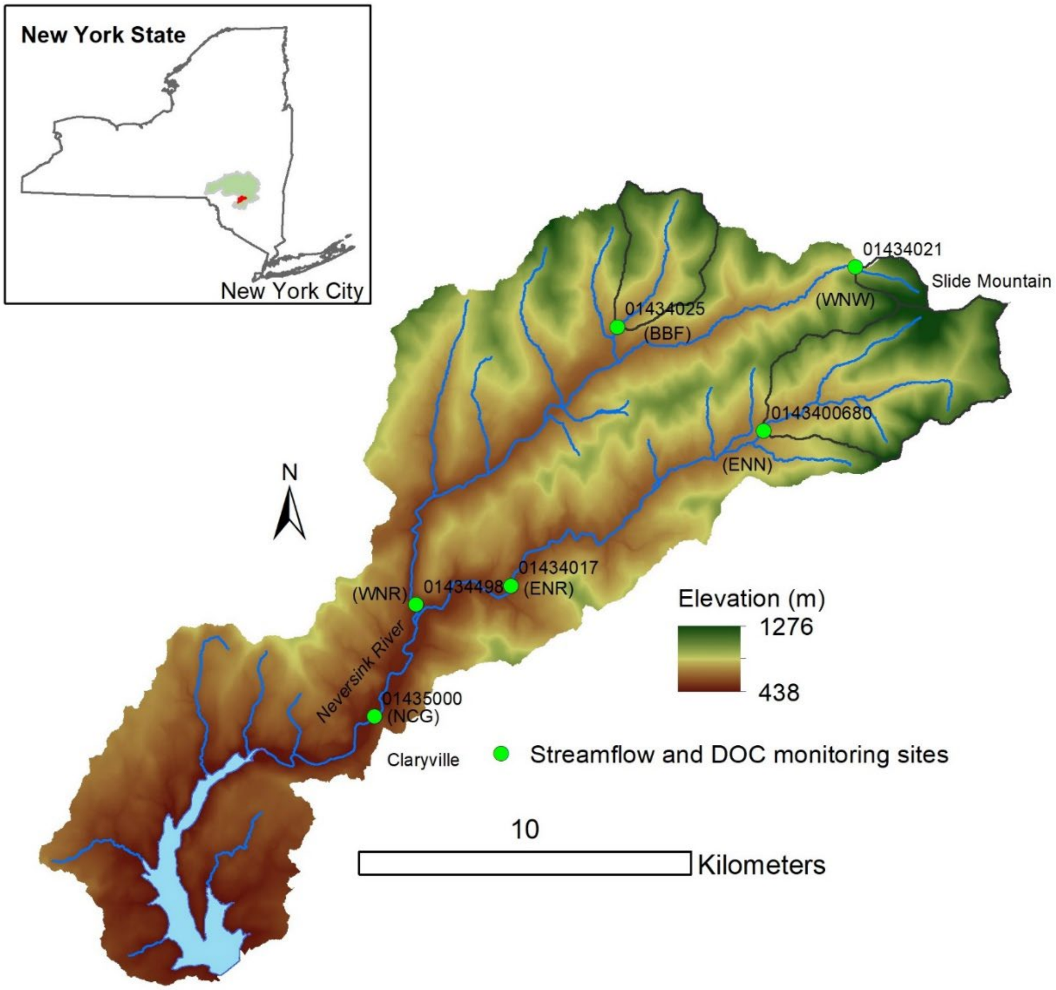


Figure 6.7 Location of the Neversink watershed, one of six West of Hudson New York City source watersheds (inset) in New York State. The Biscuit Brook sub basin (BBF) is one of the three headwater sites.

6.4.2 Description of SWAT-C

The SWAT model has been recently enhanced with a dynamic soil organic carbon pool based on the CENTURY carbon model, known as SWAT-C (Zhang et al. 2013). Yang and Zhang (2016) successfully tested the ability of SWAT-C to simulate evapotranspiration, net primary productivity, net ecosystem exchange, and biomass production in forested ecosystems. Du et al. (2019) integrated terrestrial and aquatic processes into SWAT-C for watershed-scale modeling of DOC in streams. Terrestrial DOC processes involve DOC production in soil layers and transport to streams through various pathways, such as surface runoff, lateral flow, percolation, and groundwater recharge, using widely used solute transport algorithms in SWAT (Neitsch et al. 2011). Overall, the SWAT-C model represents an important advancement in modeling the coupled terrestrial and aquatic carbon cycle at the watershed scale, with potential applications in various ecological studies.

6.4.3 Transforming SWAT-C into a Variable Source Area Runoff Model

By default, the SWAT-C model predicts runoff (Q) using the Natural Resources Conservation Service (formerly Soil Conservation Service) runoff-curve number equation (USDA 1972):

$$Q = \frac{P^2}{P+S} \tag{6.1}$$

where P is the effective rainfall (observed rainfall minus initial abstraction), and S is the average storage in the watershed before runoff occurs. Since Q varies with the antecedent moisture condition for a given amount of rainfall, S also depends on the antecedent moisture condition. Steenhuis et al. (1995) showed that the SCS curve number equation could be interpreted as a saturation excess runoff routine in which the spatially distributed storage in the soil needs to be filled up before overland flow occurs. This approach has been used to adapt curve number-based watershed models from infiltration excess to saturation excess models capable of simulating variable source area (VSA) hydrology as in VSLF (Schneiderman et al. 2007) and in SWAT-VSA (Easton et al. 2008).

Saturated areas (percent) in a watershed, A_s for a given runoff event with an effective rainfall, P can be derived by differentiating the discharge Q in Equation (1.1) with respect to P (Steenhuis et al. 1995).

$$A_s = 1 - \frac{S^2}{(P+S)^2} \tag{6.2}$$

The available local storage σ, before the soil profile becomes saturated can be expressed as a function of the area saturated, A_s (Schneiderman et al. 2007):

$$\sigma = S\left(\sqrt{\frac{1}{1-A_s}}-1\right) \tag{6.3}$$

For the SWAT-C model to simulate VSA hydrology, the determination of runoff from Hydrologic Response Units (HRUs) is based on soil wetness classes delineated from a Topographic Wetness Index (TWI) that classifies areas of the watershed based on soil-water storage, and the likelihood of becoming saturated and generating saturation excess runoff. TWI was derived from the fraction of upslope contributing area per unit contour length and the local surface topographic slope, both calculated using a 10 m DEM of the watershed. The Neversink watershed was discretized into 10 equal area wetness classes. Hence $A_s = 0$ for the wettest areas with the highest TWI that saturates first and $A_s = 1$ for the driest areas with the lowest TWI that saturates last.

The relationship between S (in cm) and curve number (CN) is:

$$S = 2.54\left(\frac{1000}{\overline{CN}}-10\right) \tag{6.4}$$

where $\overline{CN}$ is the average curve number of the watershed. Curve numbers vary with land use, ranging from near zero for a dry, vegetated, permeable surface to near 100 for an impervious surface as found in The National Engineering Handbook (NRCS 2004).

The runoff curve number for each wetness class was derived as:

$$CN = \left(\frac{1000}{\left(\frac{1000}{\overline{CN}}-10\right)\left(\sqrt{\frac{1}{1-A_s}}-1\right)+10}\right) \tag{6.5}$$

As in VSLF (Schneiderman et al. 2007) and in SWAT-VSA (Easton et al. 2008), SWAT-C as a VSA model predicts runoff q_i from an area as:

$$q_i = P - \sigma \quad \text{for } P > \sigma \tag{6.6}$$

For $P \leq \sigma$, $q_i = 0$, indicating that the portion of the watershed is not saturated.

Table 6.2 lists the sources of data that was used for watershed model setup and parameterization, including weather data used to drive the model, and streamflow and water quality data used for developing concentration-discharge relations and model calibration.

Table 6.2 Data used in the study, period of availability, and sources.

	Data	Description	Source
1	Digital Elevation Model (DEM)	10 m spatial resolution	NYC DEP
2	Land Use map	Derived from 2009 LiDAR and orthoimagery	NYC DEP
3	Soil data	SSURGO soils database	USDA-NRCS
4	Daily precipitation (cm), minimum and maximum air temperature (ºC)	4 km grids available from 1981-present	PRISM (https://prism.oregonstate.edu/)
5	Leaf Area Index (LAI)	Remotely sensed, 8-day interval, 500 m spatial resolution, 2003-2019	NASA Moderate Resolution Imaging Spectroradiometer (MODIS) product MCD15A2H
6	Evapotranspiration (ET, mm)	Remotely sensed, 8-day total, 500 m spatial resolution, 2001-2019	NASA Moderate Resolution Imaging Spectroradiometer (MODIS) product M*D16A2
7	Streamflow ($m^3 s^{-1}$) data at USGS sites described below	Daily average data for the period below	USGS
8	Dissolved organic carbon ($mg L^{-1}$) at USGS sites (drainage area):	Number of samples by site:	USGS
	#01434021 (2.1 km^2)	N=1589	
	#01434025 (9.59 km^2)	N=2903	
	#0143400680 (23.4 km^2)	N=1505	
	#01434017 (59.5 km^2)	N= 160	
	#01434498 (87.8 km^2)	N=152	
	#01435000 (172.5 km^2)	N=1350	

Site names and three-letter site abbreviations are West Br. Neversink River at Winnisook (#01434021, WNW), Biscuit Brook at Frost Valley (#01434025, BBF), East Br. Neversink River Northeast of Denning (#0143400680, ENN), East Br. Neversink River near Claryville (#01434017, ENR), West Br. Neversink River at Claryville (#01434498, WNR), and Neversink River near Claryville (#01435000, NCG).

6.4.4 Results: DOC Flux Calculation

Daily concentration (C) - discharge (Q) regressions using a power function ($C = aQ^b$) show that headwater stream reaches (BBF, WNW, ENN) contributed more DOC per unit streamflow than downstream reaches (ENR, WNR, NCG; Figure 6.8). The C-Q relationships also indicate a transport-limited condition particularly for the headwater stream sites where DOC increased with an increase in streamflow. The coefficient a in the regression equation represents DOC concentrations at unit streamflow and allows comparison of sites for their relative importance as DOC sources.

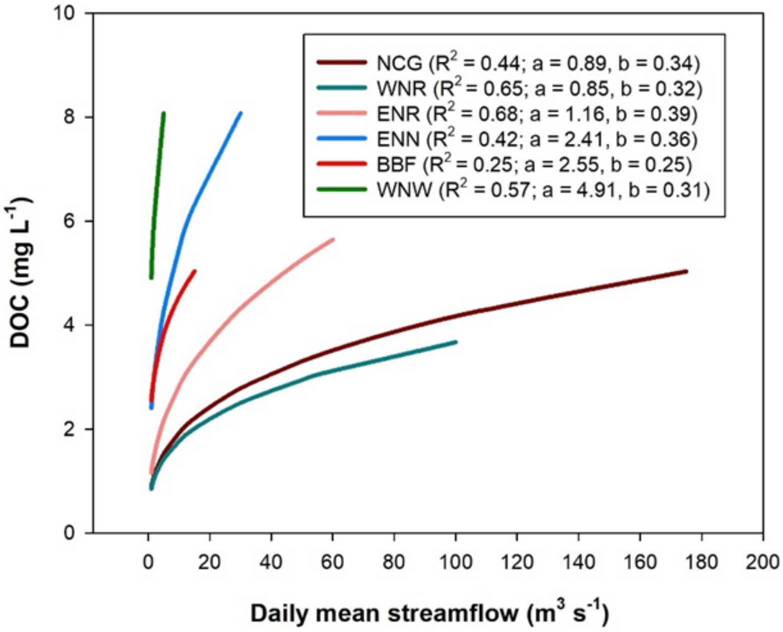


Figure 6.8 Power function relationships between DOC and streamflow.

6.4.5 Results: Forest Growth and Evapotranspiration

Forest growth parameters in SWAT found in the literature and comparison of simulated LAI with MODIS data determined the final values used for plant growth parameters. The model predicted monthly LAI correlated well ($R^2 = 0.78$) with both the timing and magnitude of average values based on MODIS for the watershed. The highest correlation was for evergreen forests ($R^2 = 0.82$) whose LAI was the highest during the dormant season (Figure 6.9). There was good correlation ($R^2 = 0.89$) between simulated monthly ET and MODIS based ET regarding the timing although MODIS overpredicted ET for the watershed. MODIS predictions of average annual ET were closer to the higher end of the range predicted by the model for different HRUs (Figure 6.10).

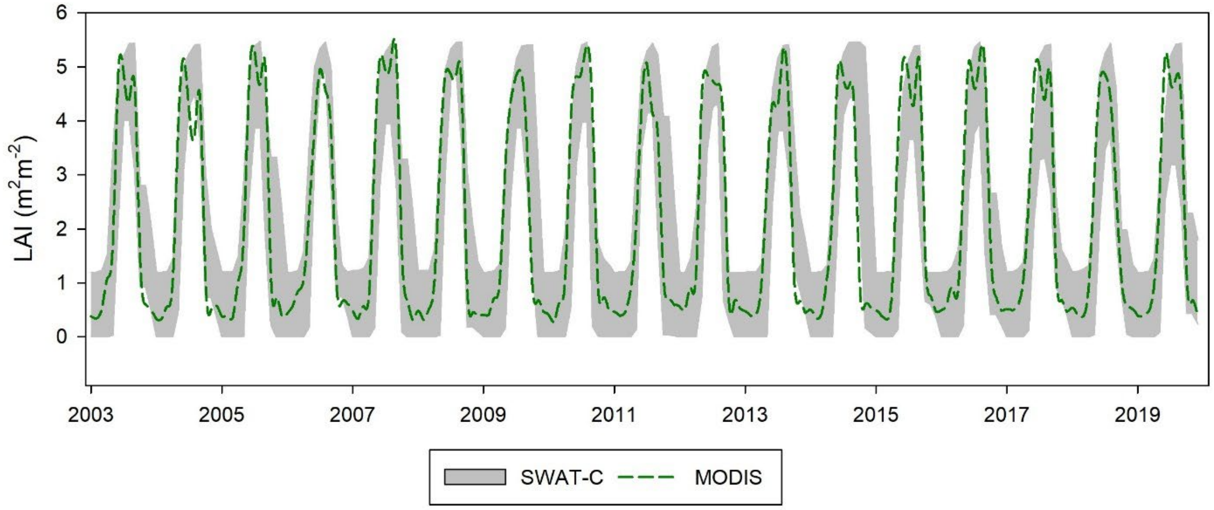


Figure 6.9 Comparison of SWAT-C simulated leaf area index (LAI) with MODIS dataset for the period 2003-2019. Simulated range (gray) are for 30 selected HRUs above site ENN (Figure 6.7) and includes all ten wetness classes and three forest types.

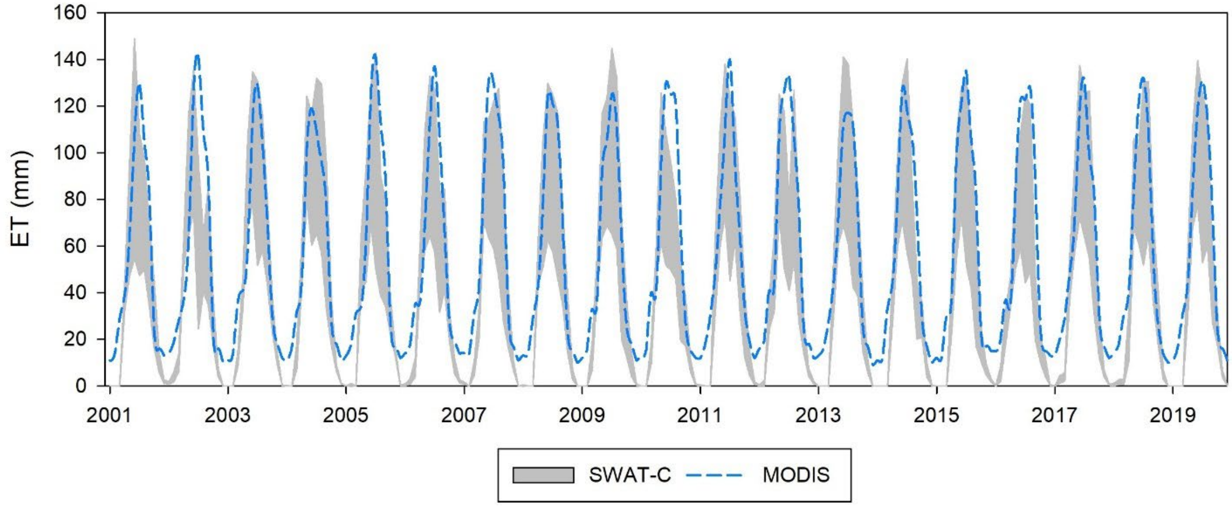


Figure 6.10 Comparison of SWAT-C simulated evapotranspiration (ET) with MODIS dataset for the period 2001-2019. Simulated range (gray) are for 30 selected HRUs above site ENN and includes all 10 wetness classes and three forest types.

6.4.6 Results: Streamflow and Dissolved Organic Carbon

A curve number value for each wetness class was estimated using an average curve number of 70 estimated from observed runoff-rainfall relationship for the watershed, and the runoff contributing saturated area (Equation 1.5). The estimated average curve number values for the Neversink watershed using this approach ranged between 40.2 for wetness class 10 (driest) and 98.9 for wetness class 1 (wettest). As per model evaluation guidelines (Moriasi et al. 2007), the performance of the model can be rated as good to very good based on Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) values in most cases for both streamflow and DOC flux predictions (Table 6.3). The mean simulated streamflow and DOC flux were close to the observations in most cases except for DOC flux at site ENN. Overall performance of the model was better at sites near the outlet of the watershed compared to headwater tributaries. A comparison of predicted and observed timeseries of streamflow and DOC flux at the watershed outlet indicates that the model could capture the temporal pattern in streamflow and DOC flux during both calibration and validation periods (Figure 6.11).

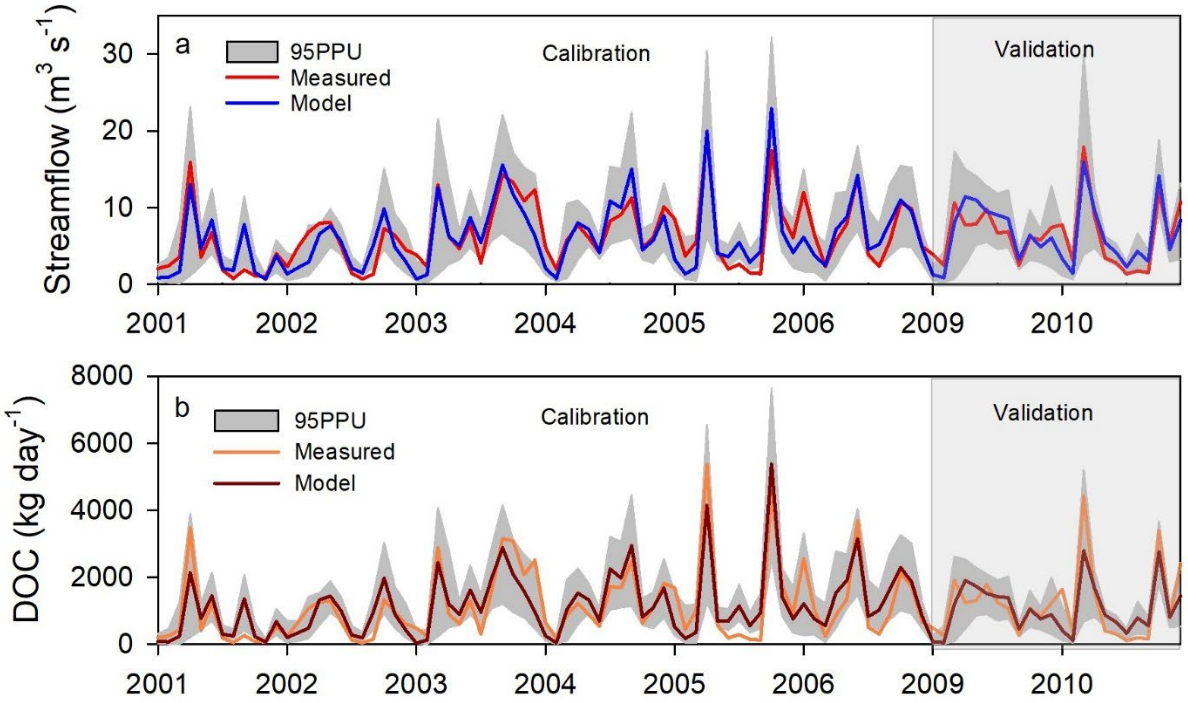


Figure 6.11 Comparison of SWAT-C simulated and measured streamflow (a) and DOC flux (b) at the outlet of the Neversink watershed (site NCG). Gray areas indicate uncertainty bounds.

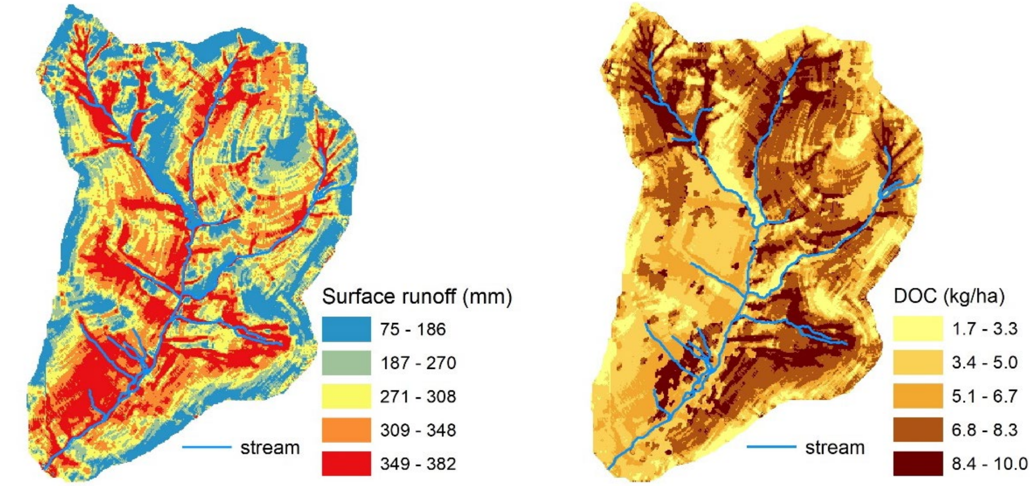
Uncertainty in monthly streamflow and DOC flux based on p-factor (fraction of measured data bracketed by the credible simulation interval) shows that the model was able to capture 73-75% of the observed streamflow values and 64-65% of the observed DOC flux values within the bounds of uncertainty. Model calibration and uncertainty analysis without the use of MODIS data was able to capture only 66% of the streamflow values and 54-56% of the observed DOC flux values within the bounds of uncertainty.

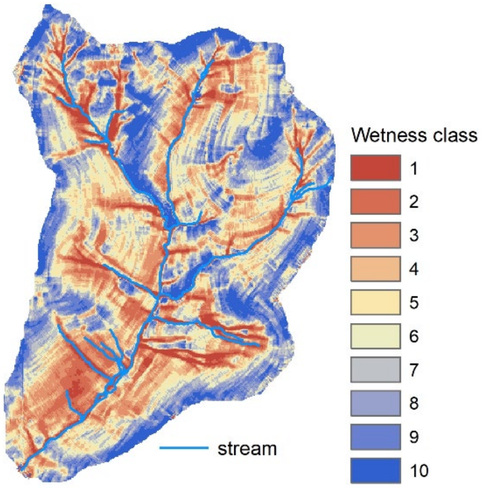
Table 6.3 Summary of model performance for monthly streamflow and DOC flux.

Variable/Site	**R^2**	**NSE**	**KGE**	**PBIAS**	**Mean simulated (observed)**	**p-factor**
Streamflow		*Calibration period*			$m^3\ s^{-1}$	
WNW	0.79	0.78	0.89	-1.6	0.09 (0.09)	0.62
BBF	0.69	0.66	0.83	-5.2	0.35 (0.33)	0.64
ENN	0.79	0.74	0.85	-1.8	1.01 (0.99)	0.74
ENR	0.78	0.73	0.83	-3.7	2.29 (2.21)	0.79
WNR	0.74	0.70	0.81	11.2	2.98 (3.35)	0.82
NCG	0.75	0.71	0.85	1.5	6.14 (6.23)	0.78
DOC flux		*Calibration period*			$kg\ day^{-1}$	
WNW	0.77	0.73	0.68	12.1	22 (25)	0.47
BBF	0.60	0.60	0.72	-3	70 (68)	0.56
ENN	0.81	0.78	0.71	11.3	247 (278)	0.60
ENR	0.81	0.79	0.81	-14.5	466 (407)	0.75
WNR	0.74	0.72	0.80	-12.5	529 (470)	0.75
NCG	0.75	0.75	0.82	-3	1168 (1134)	0.68
Streamflow		*Validation period*			$m^3\ s^{-1}$	
WNW	0.59	0.32	0.63	-16.2	0.09 (0.08)	0.63
BBF	0.77	0.76	0.87	-5	0.36 (0.34)	0.75
ENN	0.72	0.62	0.78	-0.4	1.05 (1.04)	0.67
ENR	0.73	0.65	0.81	-6.7	2.38 (2.23)	0.83
WNR	0.72	0.69	0.76	9.4	3.29 (3.64)	0.83
NCG	0.74	0.72	0.86	-1.5	6.57 (6.47)	0.79
DOC flux		*Validation period*			$kg\ day^{-1}$	
WNW	0.60	0.56	0.59	18.8	18 (22)	0.58
BBF	0.80	0.68	0.58	21	57 (72)	0.67
ENN	0.71	0.52	0.46	32.7	207 (307)	0.58
ENR	0.70	0.69	0.68	6.4	394 (422)	0.71
WNR	0.72	0.72	0.72	1.4	509 (516)	0.71
NCG	0.72	0.68	0.66	9.9	1079 (1198)	0.67

6.4.7 Results: DOC Export from Variable Source Areas

A sequence of rainfall events in October 2005 resulted in total precipitation as high as 520 mm in parts of the Neversink watershed. The SWAT-C VSA model was able to predict high runoff DOC source areas that in general coincided with the predicted surface runoff areas. The spatial pattern of surface runoff and DOC export followed VSA hydrology in general with highest runoff for wetness class 1 and lowest runoff for wetness class 10. This is illustrated in Figure 6.12 using the Biscuit Brook subbasin above site BBF as an example.



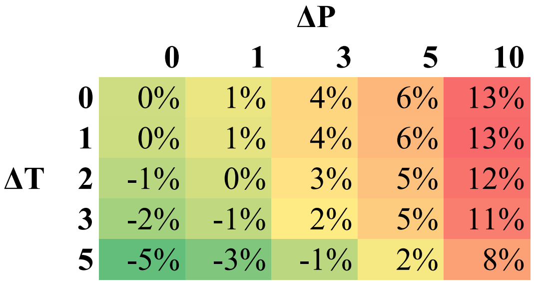


Wetness class	TWI max	CNII	Runoff (mm)	DOC (kg ha^{-1})
1	25.4	98.9	381	8.86
2	10.8	96.5	372	9.42
3	10.0	93.8	355	9.47
4	9.61	90.7	334	8.29
5	9.26	87.0	317	7.96
6	8.98	82.6	298	7.53
7	8.71	77.2	279	7.07
8	8.41	70.0	240	6.01
9	8.10	59.6	182	4.46
10	7.65	40.2	87	2.04

Figure 6.12 Spatial distribution of runoff (top left) and DOC export (top right) from the Biscuit Brook sub-basin above site BBF during October 2005 predicted by the SWAT-C VSA model. Wetness class map for the subbasin is also shown (bottom left). For each wetness class the maximum topographic wetness index (TWI max), average curve number (CNII), and average simulated runoff and DOC export during October 2005 is shown in the table.

6.4.8 Results: Climate Sensitivity of DOC Flux

A warmer and wetter future climate is projected for the study region, which could change the DOC flux in the future. SWAT-C simulations indicate a decrease in annual DOC flux in response to rising temperatures and an increase in response to higher precipitation amounts. A combination of increasing air temperature and precipitation indicated a net change in DOC flux between -5% to 13% (Figure 6.13). Such responses are indicative of streamflow responses by the watershed to changing climate and the resulting changes in DOC flux. These results are consistent with other studies in the region on DOC export from watersheds under climate change (Sebestyen et al. 2009).



ΔT \ ΔP	0	1	3	5	10
0	0%	1%	4%	6%	13%
1	0%	1%	4%	6%	13%
2	-1%	0%	3%	5%	12%
3	-2%	-1%	2%	5%	11%
5	-5%	-3%	-1%	2%	8%

Figure 6.13 Sensitivity of annual DOC flux to changes in precipitation (ΔP) and air temperature (ΔT) as percent change relative to the baseline scenario (ΔP=0, ΔT=0).

6.4.9 Summary and Conclusions

The SWAT-C model as a variable source area (VSA) model was tested for its ability to predict streamflow and DOC fluxes in the predominantly forested Neversink watershed. Remotely sensed leaf area index and evapotranspiration data were used to parameterize the model and reduce uncertainty in streamflow and DOC flux predictions. The calibrated model could predict DOC fluxes from the main outlet of the watershed and five tributary sites with good accuracy. The spatial pattern of DOC export from the watershed followed VSA hydrology. Sensitivity analysis of DOC flux to possible future climate scenarios indicate greater sensitivity to precipitation than temperature changes. The methodology presented in this study, including model parameterization for simulating forest growth and DOC export, may be used in other forested watersheds in regions where runoff from variable source areas is important. Overall, the results show that the application of the SWAT-C VSA model is a promising tool to study water quality issues related to DOC (such as disinfection byproducts formation potential) in the context of watershed management and climate change in the New York City Water Supply System and other regions of concern.

6.5 SWAT Model Setup for EOH Watersheds

Including variable source area (VSA) in hydrological modeling provides a better estimation of surface runoff and the ability to predict the location of saturated areas, both of which are key elements in transferring substances from upland areas to the valley bottom and eventually to the receiving waterbody. A conceptual wetness map can be developed based on topographic characteristics of the watershed to incorporate VSA in the Soil and Water Assessment Tool (SWAT) water quantity and quality simulations.

East of Hudson (EOH) watersheds provide 10% of NYC’s drinking water and have a combined surface area of 1004 km^2. Elevations in these watersheds range from 13 m to 408 m, and 93% of the area is comprised of land, while around 7% is water, in the form of more than 80 individual water bodies and reservoirs. EOH is divided into 15 watersheds defined by DEP that are shown in Figure 6.14. Our objective is to setup SWAT models for water quantity and water quality simulations, starting with the five watersheds of Amawalk, Boyd Corners, Cross River, East Branch, and Titicus, and then expand the modeling to the rest of the watersheds based on the findings from these five.

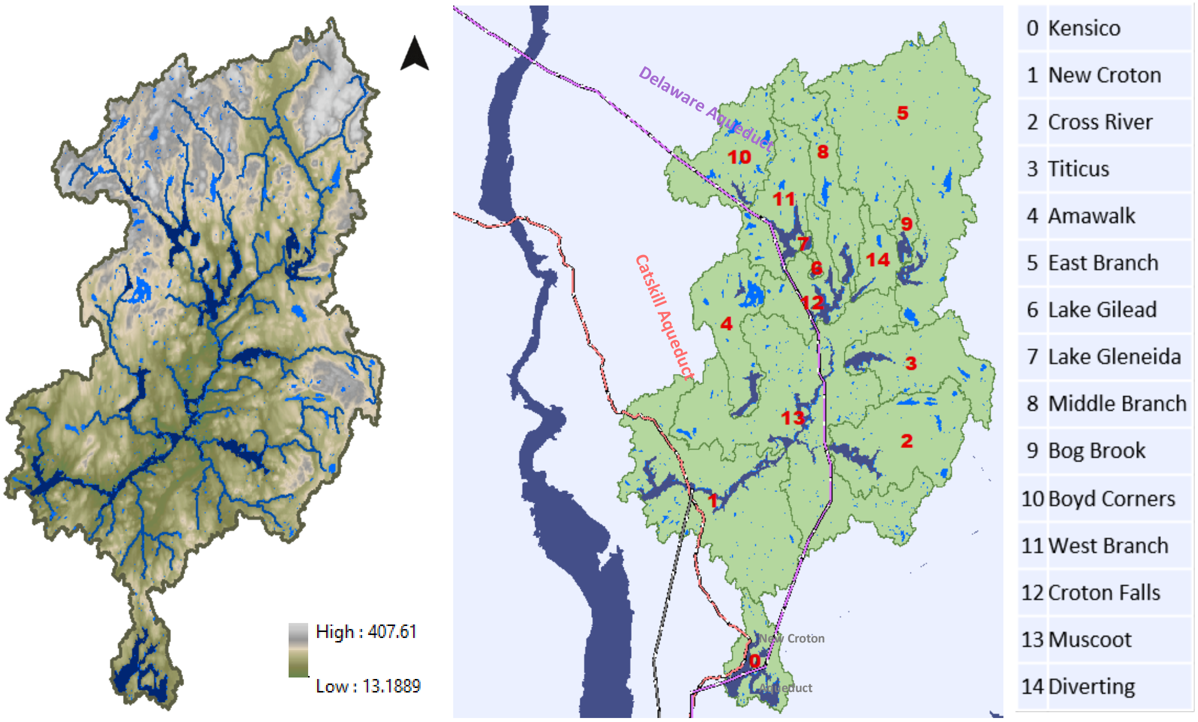


Figure 6.14 EOH topographic map (left) and EOH reservoir watersheds (right).

6.5.1 Data Preparation for East of Hudson Watersheds

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

6.5.2 Land Use and Land Cover Map

The land use and land cover (LULC) map of EOH was derived from DEP's classified 2009 aerial photography data. The LULC classifications of this map were simplified and adjusted based on the standardized classification provided in the SWAT model specifications. The main classifications have nine categories including different types of forests, agricultural lands, rangeland, pastures, urban areas, and water. The map on the left in Figure 6.15 shows the distribution of different land cover over EOH basins.

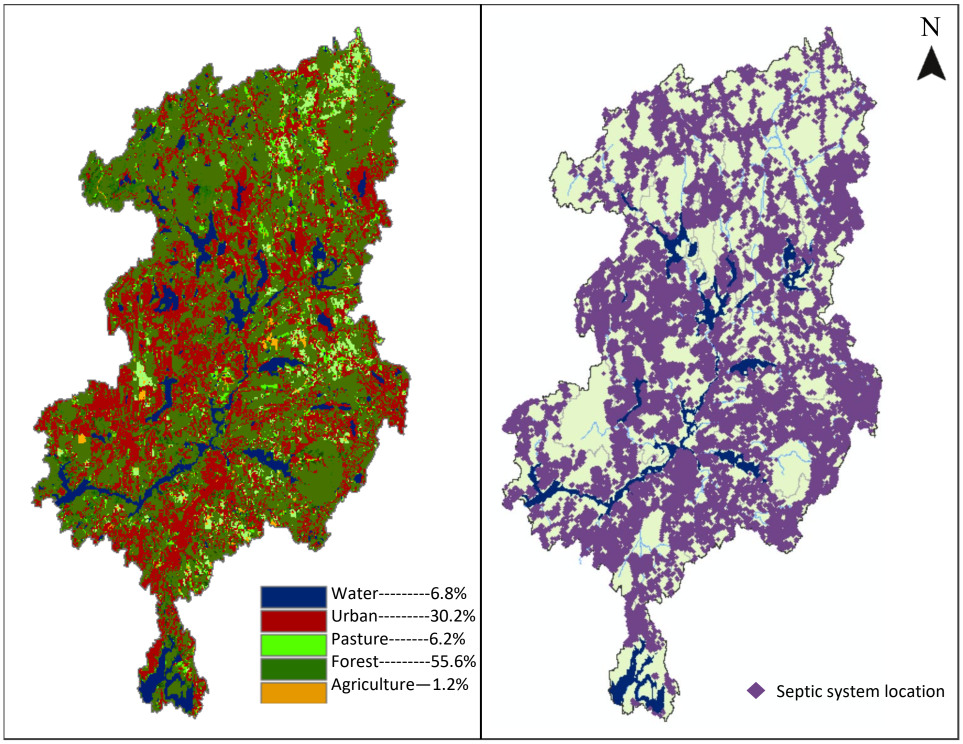


Figure 6.15 EOH LULC map (left) and septic system locations (right).

It can be observed from this figure that the two dominant LULC types in EOH are forest, encompassing more than 50% of the land cover, and urban, with around 30%. In urban dominated basins, septic systems are the cause of significant non-point source pollution, which must be considered in water quality modeling. SWAT has a biozone algorithm to take such calculations into account, for which LULC maps must be modified to include septic units over the surface of the basin. The septic system map used for this purpose is created by DEP based on approximate building locations as a proxy for septic system locations. The data points from this map were filtered based on the wastewater map which resulted in removal of 554 septic system units overlaying with wastewater shapefiles. This procedure resulted in extracting 43,360 septic system units for EOH, with the density of around 43 unit/km^2, which is seven times more that of WOH (6 unit/km^2). An area of 10 by 10 meters was considered for each septic system unit and was added to the LULC map. Figure 6.15 visualizes the LULC map before incorporating septic systems (on the left) and the septic system locations for EOH (on the right).

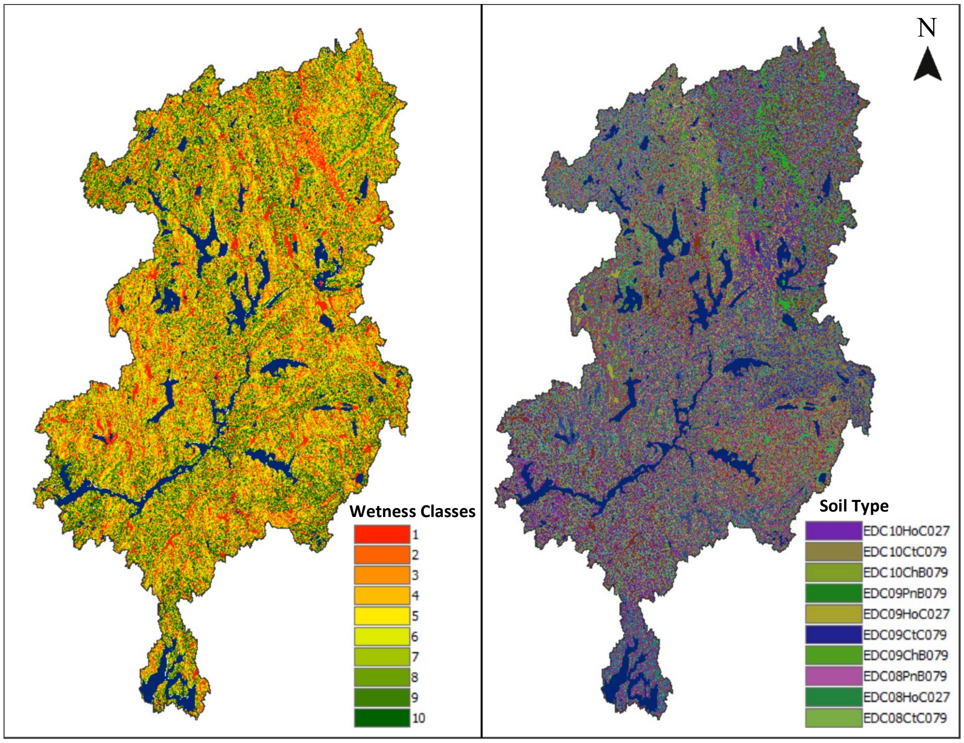


Figure 6.16 EOH wetness class map (left) and soil type map (right).

6.5.3 Soil and Wetness Class Map

Other inputs to SWAT are a soil map and a wetness class map, which must be combined before they are used in the model. The wetness map is a conceptual map dividing the watershed based on increasing soil-water-storage capacity, from downslope to upslope regions, and the likelihood of getting saturated. This specification of hillslope improves the simulation of lateral and surface runoff from upslope ("drier" wetness classes) to downslope ("wetter" wetness classes). Topographic Wetness Index (TWI) is the technique used to delineate wetness classes. The TWI takes into account the slope and contributing area of each cell in a DEM to determine the wetness potential. The slope represents the rate of change in elevation, while the contributing area represents the upslope area that contributes water flow to a particular cell. We calculated TWI using the 10-meter DEM that was resampled from the 1-meter DEM.

EOH watersheds were classified into 10 equal wetness classes, which were then combined with the soil map. The EOH soil map was extracted from the Soil Survey Geographic (SSURGO) database (USDA-NRCS 2012). The soil map was overlaid with the wetness map and watershed map to create a new soil map with the dominant soil for each wetness class within a watershed of the basin. Through this procedure, 121 different soil types were created for EOH. Figure 6.16shows both the wetness map with 10 equal classes created for EOH and the dominant soil selected for each watershed across each wetness class. Note that the legend of the soil wetness map in Figure 6.16shows only a few samples of created soil types and not all.

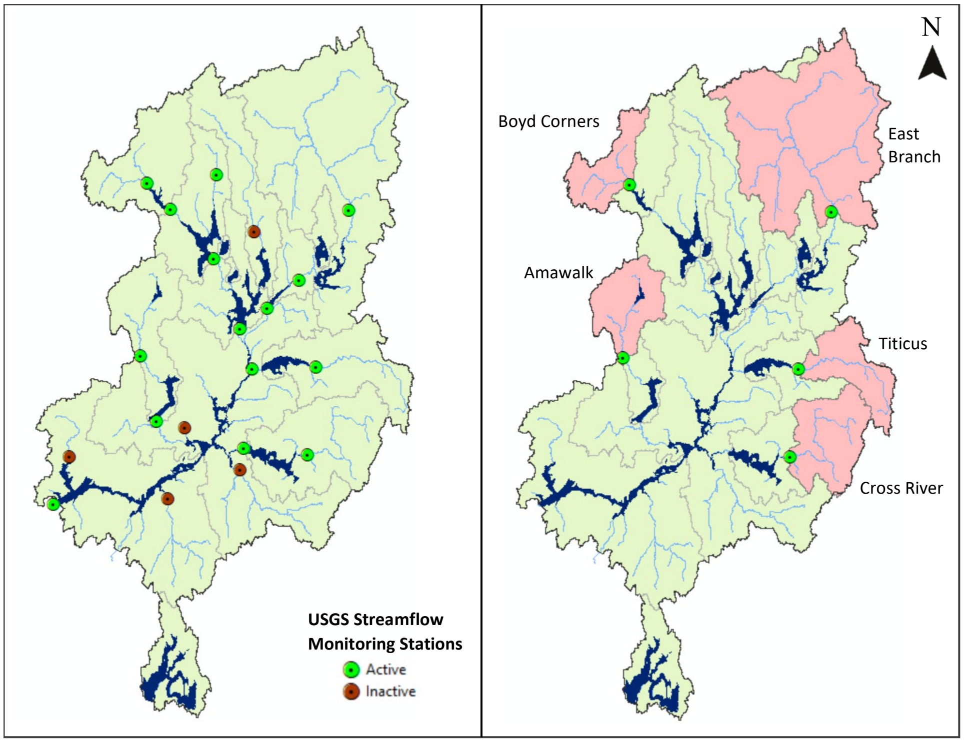


Figure 6.17 USGS streamflow monitoring stations (left) and selected EOH watersheds for SWAT modeling (right).

6.5.4 Model Setup

Throughout EOH basins there exist 20 active and inactive USGS gauging stations, with streamflow data available for more than 10 years (Figure 6.17). Nine of these stations are located on streams with regulated flow and 11 are on streams with natural inflow. Initially, DEP will set up SWAT models for five of the watersheds with active stations and natural inflows. These watersheds are Amawalk, Boyd Corners, Cross River, East Branch and Titicus (Figure 6.17). These watersheds have long-term records of daily discharge measurements (Table 6.4) at their outlets. A summary of LULC proportions and septic system counts within these watersheds is presented in Table 6.5. We plan to complete the model setup in 2023, and then begin calibration/validation of the model for hydrology.

Table 6.4 USGS streamflow monitoring stations in five East of Hudson watersheds

Basin	USGS station location	USGS ID	Drainage area at the station location (km^2)	Average daily streamflow (m^3/s)	Data availability (year)
Amawalk	Muscoot River at Baldwin Place NY	1374930	35.05	0.59	27
Boyd Corners	West Branch Croton River at Richardsville NY	1374559	28.8	0.82	27
Cross River	Cross River near Cross River NY	1374890	44.55	1.08	27
East Branch	East Branch Croton River near Putnam Lake NY	137449480	157.5	0.91	27
Titicus	Titicus River Below June Road at Salem Center NY	1374781	33.47	6.97	16

Table 6.5 Specification of East of Hudson watersheds' Land Cover/Land Use over the drainage area at the location of USGS stations

Basin	**Urban (%)**	**Agriculture (%)**	**Pasture (%)**	**Forest (%)**	**Water (%)**	**Septic System (unit)**	**Septic System Density (unit/km2)**
Amawalk	46.8	0.4	3.4	39.8	9.7	3,225	92
Boyd Corners	7.7	0.6	2.4	84.9	4.4	315	11
Cross River	30.5	0.7	3.8	60.6	4.4	2,139	48
East Branch	20.4	1.7	12.2	63.6	2.1	5,435	35
Titicus	42.4	1.2	13.8	40.3	2.3	1,884	56

6.6 West Branch Reservoir Turbidity Model

The objective of this work was to build a water quality model to guide short-term as well as long-term reservoir operations while optimizing water quantity and quality. Specifically, it was aimed to address: (i) hydrothermal regime of the reservoir, and (ii) fate and transport of turbidity. The model will also serve as a transport framework for simulating other water quality constituents, e.g., UV254, in the future.

We adopted CE-QUAL-W2 (W2), a two-dimensional hydrothermal and water quality model developed by US Army Corps of Engineers (Cole and Wells 2013) as the provider of the transport framework. The turbidity submodel included in it is the same as previously tested turbidity models for other NYC reservoirs. Model testing (calibration-validation) was performed for 2013-2021 (nine years), the period of most complete available data. W2 setup for West Branch Reservoir with model segments and locations of inflows, outflows, in-stream and in-reservoir routine water quality monitoring sites is depicted in Figure 6.18. The reservoir was configured into a computational grid of two branches, 23 longitudinal segments [including four boundary (non-active) segments], and 20 vertical layers [including two boundary (non-active) layers]. The two branches are separated by culverts below Carmel-Kent Cliffs Road. The culverts are not considered explicitly in the model. The model may be integrated into Operations Support Tool (OST) in the future.

Inputs required for the model include inflows, outflows, inflow temperatures, inflow turbidities, the light attenuation coefficient for downwelling irradiance, and meteorological conditions (air temperature, dewpoint temperature, wind speed and direction, and solar radiation or cloud cover; hourly time step). Inflows from the two minor tributaries Long Pond and Gypsy Trail Brook and from the rest of the ungaged portion of the watershed were estimated from a flow budget calculation and were specified in the model as distributed inflow around the perimeter of the reservoir. Difference between the gaged flow below the dam at USGS site WESTBRR, and the spill estimated from the rating curve was attributed to conservation release from the reservoir.

Inflow temperature for Horse Pound Brook was estimated from a polynomial fitted to observations from tributaries of Kensico Reservoir. A flow-turbidity relationship was also developed for Horse Pound Brook to estimate turbidity on days when observations were not available:

$$\log_{10} Tn_{HPB} = 0.3811082 + 0.2526081 \log_{10} Q_{HPB} \qquad (6.7)$$

Where, Tn_{HPB} = Horse Pound Brook inflow turbidity (NTU), and Q_{HPB} = Horse Pound Brook inflow (m^3 s^{-1}).

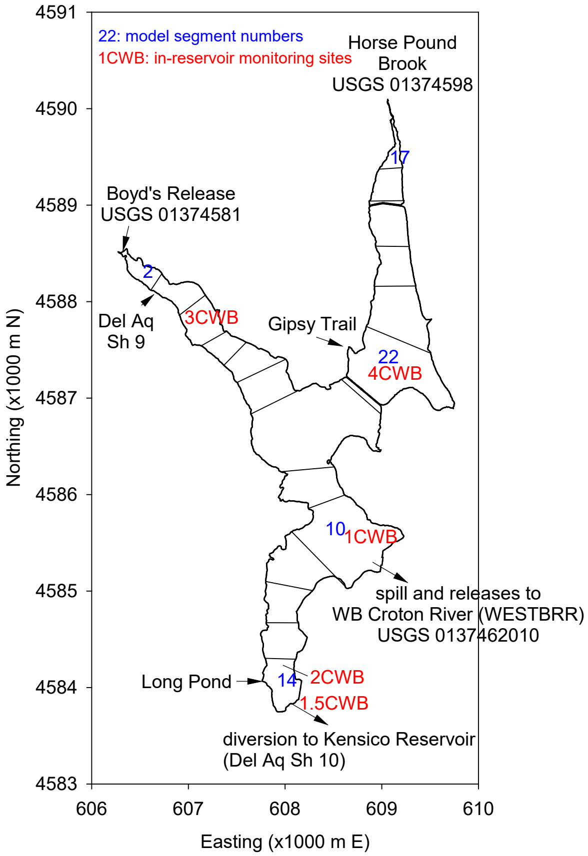


Figure 6.18 West Branch Reservoir: Inflows, outflows, in-stream and in-reservoir routine water quality monitoring locations, and W2 model segments. Selected model segments are also numbered according to the numbering scheme of W2.

All model drivers are interpolated at the timestep of calculation. The value of light extinction coefficient (k_d; 0.3–2.3 m^{-1}) was based on photic zone (1% light level; z; m) depth data collected during 1987–2021.

Model performance: The model performed well in tracking the seasonal stratification dynamics of the reservoir for 2013–2021, as represented in the patterns of volume-weighted average temperatures in selected water layers at deep-water site 1 (Figure 6.19). This location has maximum depth of 15.5 m. The root mean square error (RMSE) was 1.4 °C for 0–5 m, 1.3 °C for 5–10 m, and 1.3 °C for 10 m – bottom layers. Maximum temperatures as observed and predicted in 0–5 m and 5–10 m layers during mid-summers of 2019–2021 were lower than in other years. During these years, West Branch was mostly in 'reservoir' mode and relatively cooler DEL9 Aqueduct water entering the reservoir caused lower water temperatures in the surface and mid-depth layers.

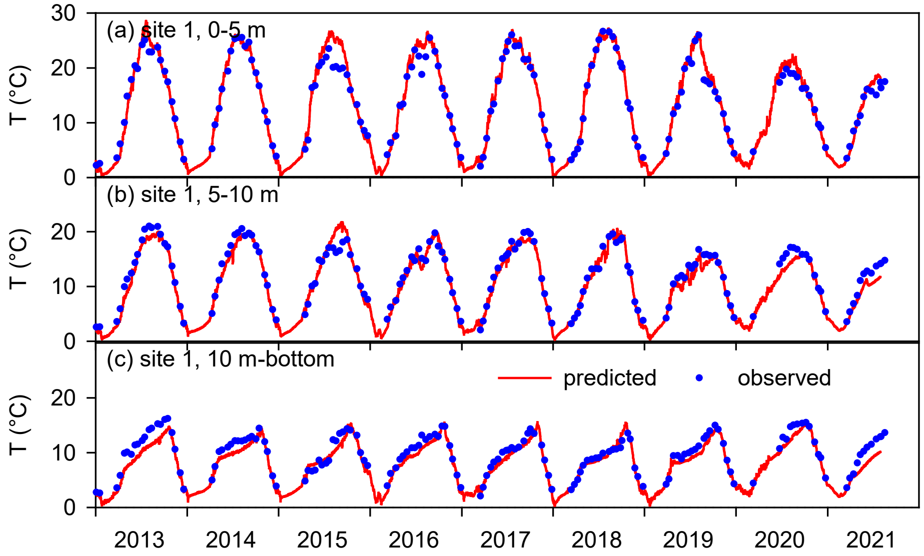


Figure 6.19 Comparison of the observed and predicted values of volume-weighted average temperatures in selected layers of water at site 1CWB in West Branch Reservoir, 2013-2021: (a) 0-5 m, (b) 5-10 m, and (c) 10 m-bottom.

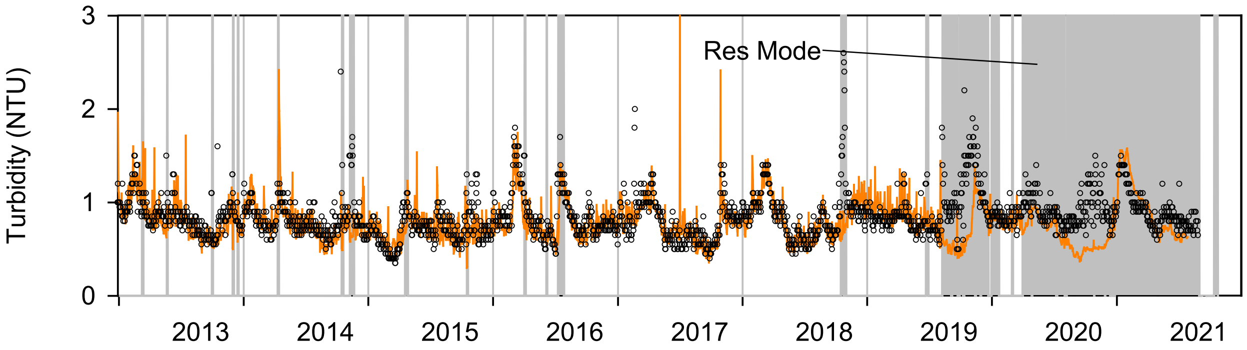


Figure 6.20 Performance of the model for West Branch Reservoir presented as comparison of observed and predicted time series of withdrawal turbidities, 2013-2021. Observations are recorded at site DEL17 at the point of discharge into Kensico Reservoir. Shaded region indicates ‘reservoir’ mode, clear region is ‘float’ or bypass’ mode.

Good performance is also indicated for the diversion turbidity as shown in Figure 6.20. RMSE was 0.3 NTU during 2019-2021 when the reservoir was mostly operated in reservoir mode. Diversion turbidity is reflective of the Delaware water (DEL9) in bypass/float modes as no or little (~ 15%) of the reservoir water is added to the aqueduct (DEL10), but also indirectly in the reservoir mode because Delaware water is first discharged into the reservoir causing dilution of the reservoir water and then diverted at DEL10.

6.7 DBP Monitoring During Runoff Events

University of Massachusetts, under contract with City University of New York and DEP, sampled two storm events in the Neversink watershed (site NCG) in 2022. Some of the analytes measured were UV-Visible absorbance, organic carbon, organic nitrogen, chemical oxygen demand, fluorescence, THMFP, and HAAFP. Preliminary conclusions of this study are: (i) storm events show large increases in concentration and loading of all organic parameters except bromine incorporation, (ii) hysteresis effects are evident when comparing organics concentrations in the rising and falling limb of the hydrograph, and such effects are likely dependent upon the antecedent conditions, (iii) The base flow natural organic matter (NOM) is low in DBP precursor content (especially THAA precursors) indicating less fresh hydrophobic organic matter, and (iv) the topographic index [$TI = \ln(\alpha/\tan \beta)$; α = basin area and β = surface slope; Wolock et al. 1997] may be a useful predictor of baseflow NOM concentrations. The detailed data, methods, and findings of this study are available in a report by Reckhow et al. (2023).

6.8 DBP Modeling with UV254

DEP is continuing to work on a multi-year project to develop DBP formation potential (DBPFP) models for source water streams, fate and transport models for DBP precursors in reservoirs, and a DBP model for the City's distribution system. Here we present a conceptual framework and a proof of concept for modeling of DBPs from the source water to the tap. We discuss the modeling environment from streams to reservoirs to distribution system, model state variables, and considerations for model complexity. The proposed source-to-tap linked model will allow testing of strategies such as selective withdrawals from different reservoirs, mode of operation, and optimization of water treatment (e.g., chlorine dosing) – all under a wide range of normal and extreme weather conditions.

6.8.1 Overall Framework

Based on measurements from 2016-2022 from selected inflow and outflow points in the NYC water supply system (NYCWSS), we established that UV254 measurement is a good proxy for DBPFP and DBPs. UV254 is an inherent optical property of water; it measures absorbance of ultraviolet light at 254 nm wavelength by water and dissolved organic matter (DOM) present in water. Building a UV254 and DBP model for the entire NYCWSS – from source to tap – requires considerations of the components of the system – the watershed, stream network, aqueducts, and distribution system. Each of the component environment is unique in terms of (i) sources and sinks, and reactivity of DOM that causes UV254 absorbance, (ii) transport and transformation processes, and (iii) optimum model complexity as governed by spatial and temporal scales of interest. The guiding principle in developing the modeling strategy was that it must allow tracking of UV254 through the entire system, especially during runoff events, as well as allow us to evaluate operational and treatment alternatives for managing DBPs in the water distribution environment.

Fate and transport of UV254 in the reservoir environment are the key components of this framework (Figure 6.21). It needs to accommodate the primary features of spatial distribution of UV254 in reservoirs at a daily time scale. Furthermore, the framework must scale up to the full system of reservoirs with ability to select source reservoirs as well as location of withdrawal within the source reservoirs. DEP already uses its Operations Support Tool (OST) routinely to manage NYC's complex system of cascading reservoirs within the constraints of overall water availability, demand requirements, and source water quality (turbidity). The UV254 modeling framework proposed here could be easily integrated into OST.

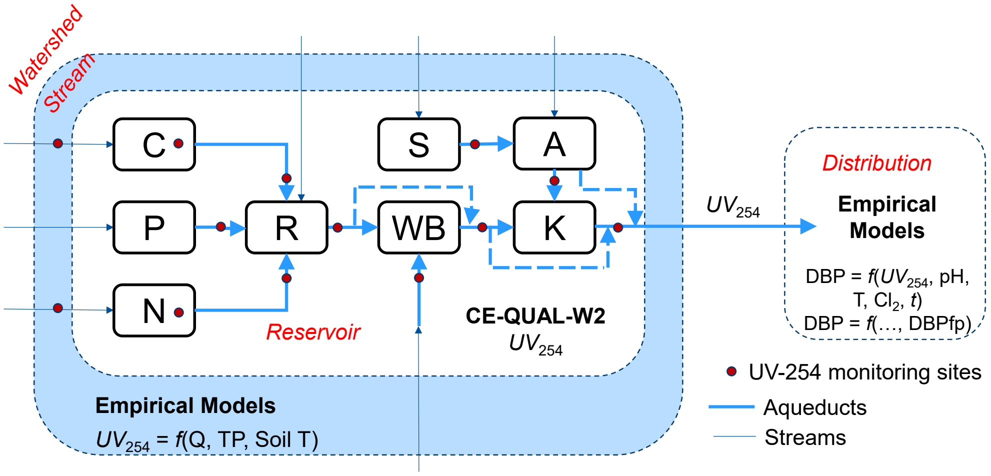


Figure 6.21 A conceptual framework for predicting disinfection byproducts in the NYC distribution system. UV254 is the primary state variable for the stream and reservoir environments models. For the distribution system, UV254 is one of the predictor variables and DBP is a predictand. Reservoirs included are Cannonsville (C), Pepacton (P), Neversink (N), Rondout (R), Schoharie (S), Ashokan (A), West Branch (WB), and Kensico (K) reservoirs. Dashed arrows indicate alternate diversion paths.

Consistent with the goals outlined above, for reservoir models, we selected mechanistic, dynamic two-dimensional (vertical and longitudinal structure) hydrothermal/transport model CE-QUAL-W2 (W2; Cole and Wells 2013), which has been previously shown to perform well in simulating the seasonal density stratification and plunging inflows and spatial distribution of turbidity in NYC reservoirs (Gelda and Effler 2007; Gelda et al. 1998, 2009). In addition, W2 is already a component of OST's water quality simulation module. UV254 in W2 will be modeled as a generic constituent with kinetics represented by a "lumped" first-order process that is adjusted for temperature (Arrhenius equation) and very low UV254 levels (inverse Monod equation). Both adjustments are commonly made for biochemical processes in aquatic environments. We will add photolysis as an explicit mechanism if supported by data in future work.

During the development and testing phase, each reservoir model will be calibrated and validated independently. For example, the accuracy of the Rondout Reservoir model will not be dependent on the performance of the three upstream reservoirs models. Later during the application phase, we will test the reservoir models as interconnected models where predictions from upstream reservoirs become input to the downstream reservoirs.

Source water from the watershed reservoirs is chlorinated before entering the distribution system. In the proposed framework, an empirical, predictive model of DBPs will be developed based on terminal levels of source water UV254, along with pH, temperature, chlorine dose, and contact time. Watershed modeling of organic carbon precursors would provide a linkage to the inflow UV254 for the NYC reservoirs, which would be necessary for understanding the effects of climate change and long-term management of DBPs.

6.8.2 Stream Environment Models

In 2022, DEP proposed and validated a two-component, simple statistical approach to predict HAA5FP and TTHMFP in inflows to Cannonsville and Neversink reservoirs using environmental variables (streamflow, total phosphorus, and soil temperature) and an optical proxy measurement (UV254 measured in the laboratory). The first component of the model predicts UV254 from streamflow, soil temperature, and total phosphorus; the second component then predicts HAA5FP and TTHMFP from UV254. The resulting models are presented in Table 6.6.

Table 6.6 Empirical models for predicting UV254 (abs cm^{-1}), HAA5FP ($\mu\mathrm{g\ L}^{-1}$), and TTHMFP ($\mu\mathrm{g\ L}^{-1}$) in West Branch Delaware (site CBS) and Neversink (site NCG) rivers.

Q = streamflow ($\mathrm{m}^3\ \mathrm{s}^{-1}$), TP = total phosphorus ($\mu\mathrm{g\ L}^{-1}$), $T_{s,50}$ = soil temperature at 50 cm depth (°C).

West Branch Delaware River at Beerston	Neversink River near Claryville
$\ln(UV_{254}) = -5.054 + 0.284\log(Q) + 0.294\log(TP) + 0.043\,T_{s,50}$	$\ln(UV_{254}) = -4.719 + 0.550\log(Q) + 0.220\log(TP) + 0.021\,T_{s,50}$
$\ln(HAA5fp) = 8.902 + 1.236\log(UV_{254})$	$\ln(HAA5fp) = 8.204 + 0.992\log(UV_{254})$
$\ln(TTHMfp) = 8.179 + 1.103\log(UV_{254})$	$\ln(TTHMfp) = 7.671 + 0.922\log(UV_{254})$

These models, in combination with routine monitoring of UV254, will allow us to generate improved ‘loading’ information of UV254 for reservoir models. In addition, these models will also estimate UV254 and DBPFP for long-term historic conditions and help us understand seasonality, extremes, and provide an opportunity for validating reservoir models for a wide range of hydrologic conditions.

We will develop such empirical models for other major tributaries in WOH basins in the future, as we continue to expand UV254 monitoring across the watershed. For minor, unmonitored inflows, we will assume that the ratio of UV254 flux to the contributing watershed area is equal to that of the monitored inflow of the respective watershed.

6.8.3 Reservoir Environment Models

In 2022, we began testing of a two-dimensional hydrothermal and water quality model CE-QUAL-W2 (W2; Cole and Wells 2013) for predicting UV254 in Cannonsville and Neversink reservoirs. We previously reported calibration and validation of W2 for predicting temperature and turbidity in these reservoirs in 2017 and 2021 (DEP 2017, 2021). UV254, as a model state variable, is not explicitly available in W2, but it can be modeled as a generic water quality constituent. We modeled it with first-order decay kinetics, where the net loss rate is temperature and concentration dependent:

$$\frac{dc}{dt} = -k\theta^{(T-20)}\frac{c}{c+k_s}c \tag{6.8}$$

where, c = UV254 concentration (cm^{-1}), t = time (sec), k = first-order net loss rate (sec^{-1}), θ = temperature correction multiplier (dimensionless), T = water temperature (°C), k_s = half-saturation constant (cm^{-1}). Photodegradation of UV254 is not included in the model at present, but we may consider it in future work if we have necessary observations for calibrating the photolysis process and we find that the simple model does not an adequately explain the observed vertical gradients in UV254. The first-order net loss rate coefficient, k was determined to be 0.0025 d^{-1} and 0.0 d^{-1} for Cannonsville and Neversink reservoirs, respectively; θ was set to 1.024 (a typical value for biological processes used in water quality models, Chapra et al. 1997), and k_s was set to a low (relative to typical in-reservoir levels) value of 0.001 abs cm^{-1} for both the reservoirs.

Cannonsville Reservoir UV254 model: W2 setup for Cannonsville Reservoir with model segments and locations of inflows, outflows, in-stream and in-reservoir routine water quality monitoring sites is depicted in Figure 6.22. The reservoir was configured into a computational grid of two branches, 52 longitudinal segments, and 45 vertical layers. Model testing (calibration-validation) was performed for 2011-2021 (11 years), the longest period of available UV254 data in the diverted water. Input data required by the model included bathymetry, hourly meteorology (air temperature, dew point, wind, and solar radiation), inflows, outflows, water surface elevation, inflow temperatures and inflow UV254. Model testing data consisted of in-reservoir and outflow temperatures and UV254. Selected data used in the model development and testing are presented in Figure 6.23.

DEP started monitoring UV254 at keypoint CR2 since 2011; however, monitoring at the primary lacustrine site 4WDC and at the inflow site CBS did not start until 2015 and 2016, respectively. The model requires that a value of UV254 for all inflows is specified for each day of simulation. We used the stream model, as discussed above, to estimate continuous daily input for 2011–2015, and to gap-fill observed records for 2016-2021. Substantial variability induced primarily by hydrology (coefficient of variation 48%) in stream UV254 is evident, with peak levels exceeding 0.2 abs cm^{-1}, while the average level is ~ 0.05 abs cm^{-1} (Figure 6.23b). Once the underlying organic matter is discharged into the reservoir, hydrodynamic, thermal, and biological processes regulate the fate and transport, resulting in more modulated variability and peak levels of UV254 (Figure 6.23c and Figure 6.23d). The attenuation of inflowing UV254 in the reservoir for 2021 is clearly seen in Figure 6.24.

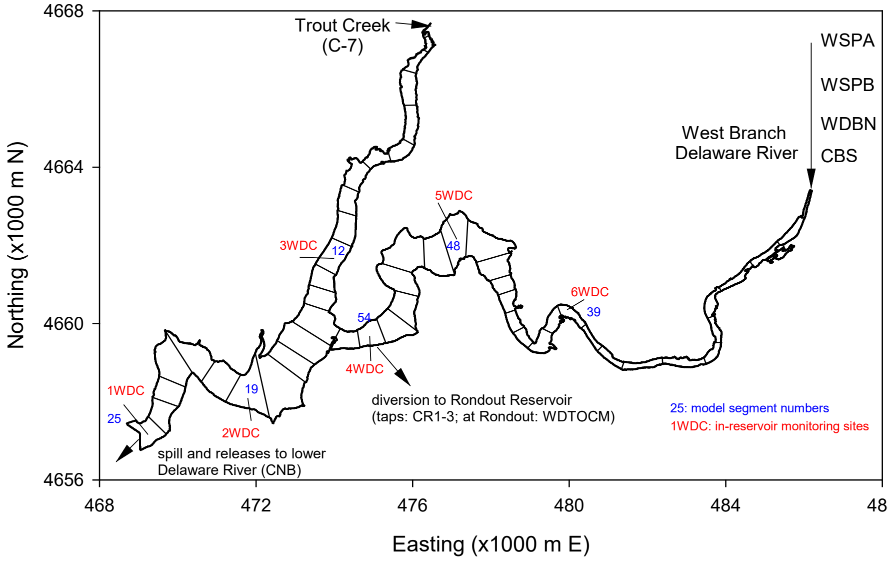


Figure 6.22 Cannonsville Reservoir: Inflows, outflows, in-stream and in-reservoir routine water quality monitoring locations, and W2 model segments. Selected model segments are also numbered according to the numbering scheme of W2.

For Trout Creek (Figure 6.22), currently unmonitored for UV254, we computed UV254 from:

$$\frac{Q_{TC}c_{TC}}{Q_{WBDR}c_{WBDR}} = \frac{A_{TC}}{A_{WBDR}} \tag{6.9}$$

Where, Q = streamflow (m^3 s^{-1}), c = UV254 (abs cm^{-1}), A = watershed area (m^2), and subscripts TC and $WBDR$ indicate Trout Creek and West Branch Delaware River inflow sites, respectively.

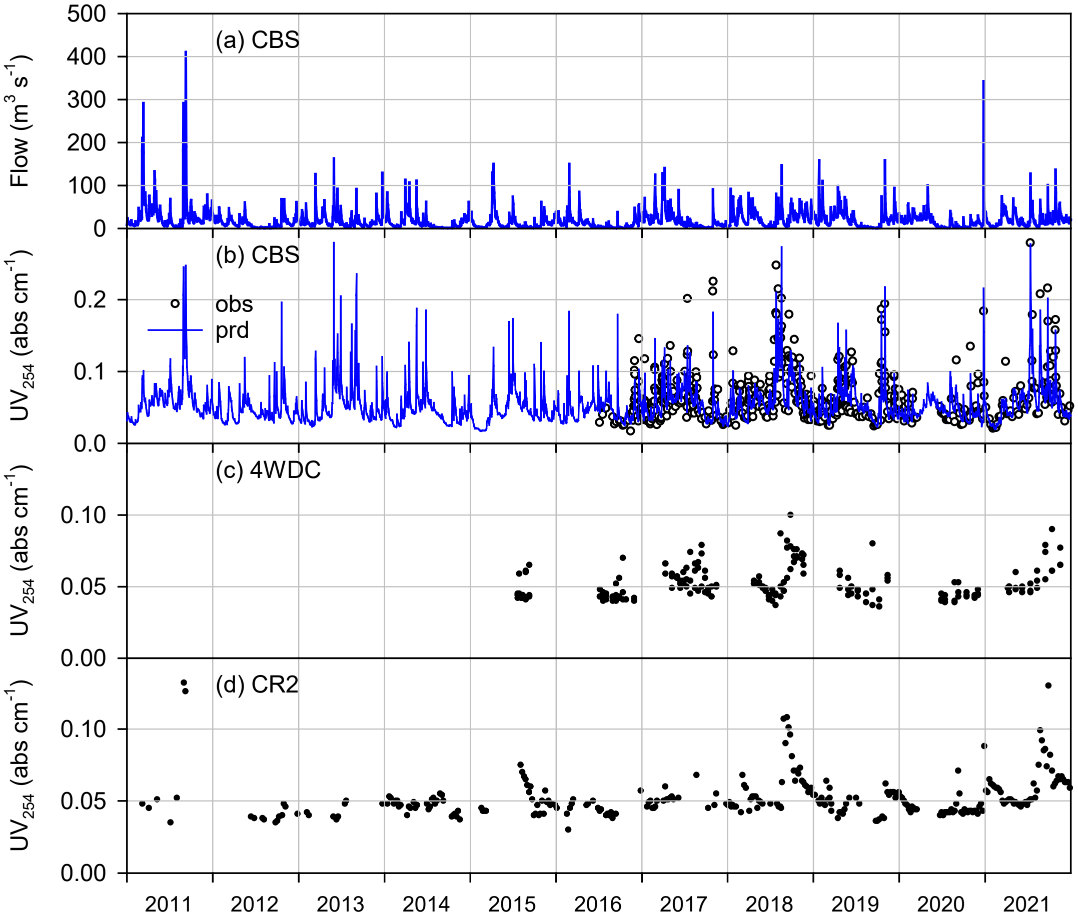


Figure 6.23 Time series of inflow and UV254 data for Cannonsville Reservoir, 2011–2021: (a) inflow from West Branch Delaware River at CBS, (b) observed and modeled inflow concentration of UV254 at CBS, (c) UV254 at in-reservoir site 4WDC, and (d) UV254 at another in-reservoir site CR2 known as elevation tap, which corresponds to the elevation of the mid-level intake.

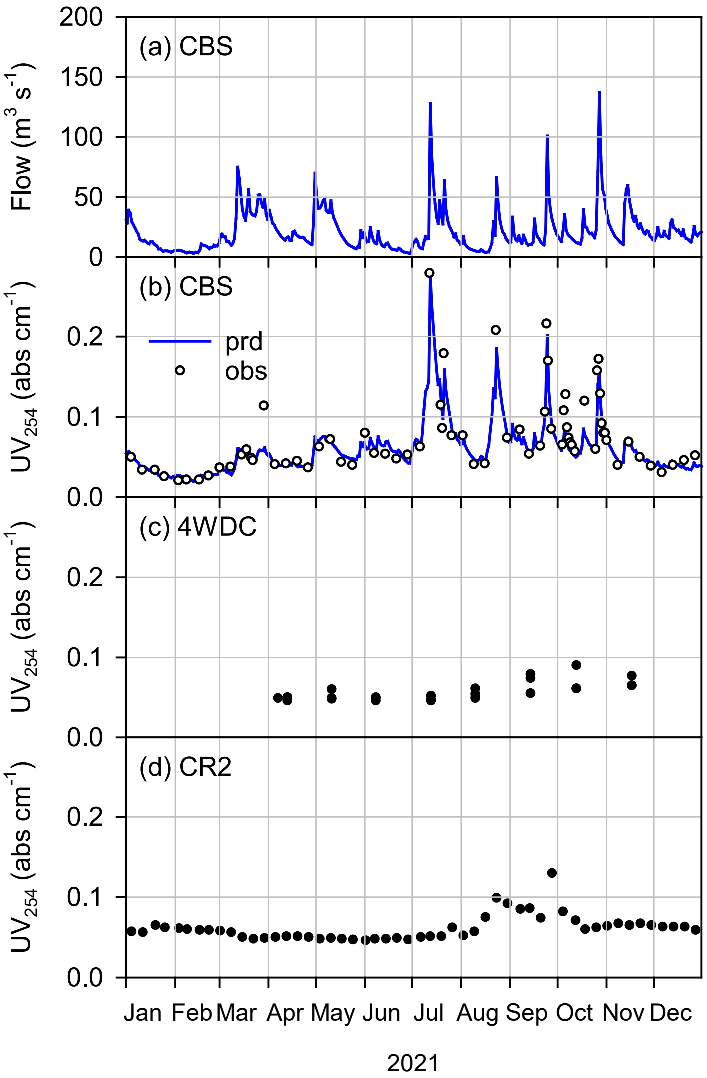


Figure 6.24 Time series of inflow and UV254 data for Cannonsville Reservoir, 2021: (a) inflow from West Branch Delaware River at CBS, (b) observed and modeled inflow concentration of UV254 at CBS, (c) UV254 at in-reservoir site 4WDC, and (d) UV254 at another in-reservoir site CR2 known as elevation tap, which corresponds to the mid-level intake.

Cannonsville Reservoir UV254 Model performance: The ability of the model to reproduce observed behavior of UV254 was evaluated by comparing observations with the predictions in two formats: (a) depth-profiles at site 4WDC for 2017–2021 (Figure 6.25), and (b) timeseries at keypoints CR1-CR3 and WDTOCM for 2011–2021 (Figure 6.26). At site 4WDC, the observations from three depths probably did not adequately resolve the vertical gradient and suggested that UV254 was vertically uniform (Figure 6.25). The predictions matched these observations well, but the model also predicted subsurface maxima during the runoff events of mid-August 2018 and mid-July 2021. These subsurface maxima are attributed to density-driven interflow of WBDR. The mean absolute error (MAE) range was 0.0011 abs cm^{-1} – 0.024 abs cm^{-1}, and the RMSE range was 0.0013 abs cm^{-1} – 0.028 abs cm^{-1}.

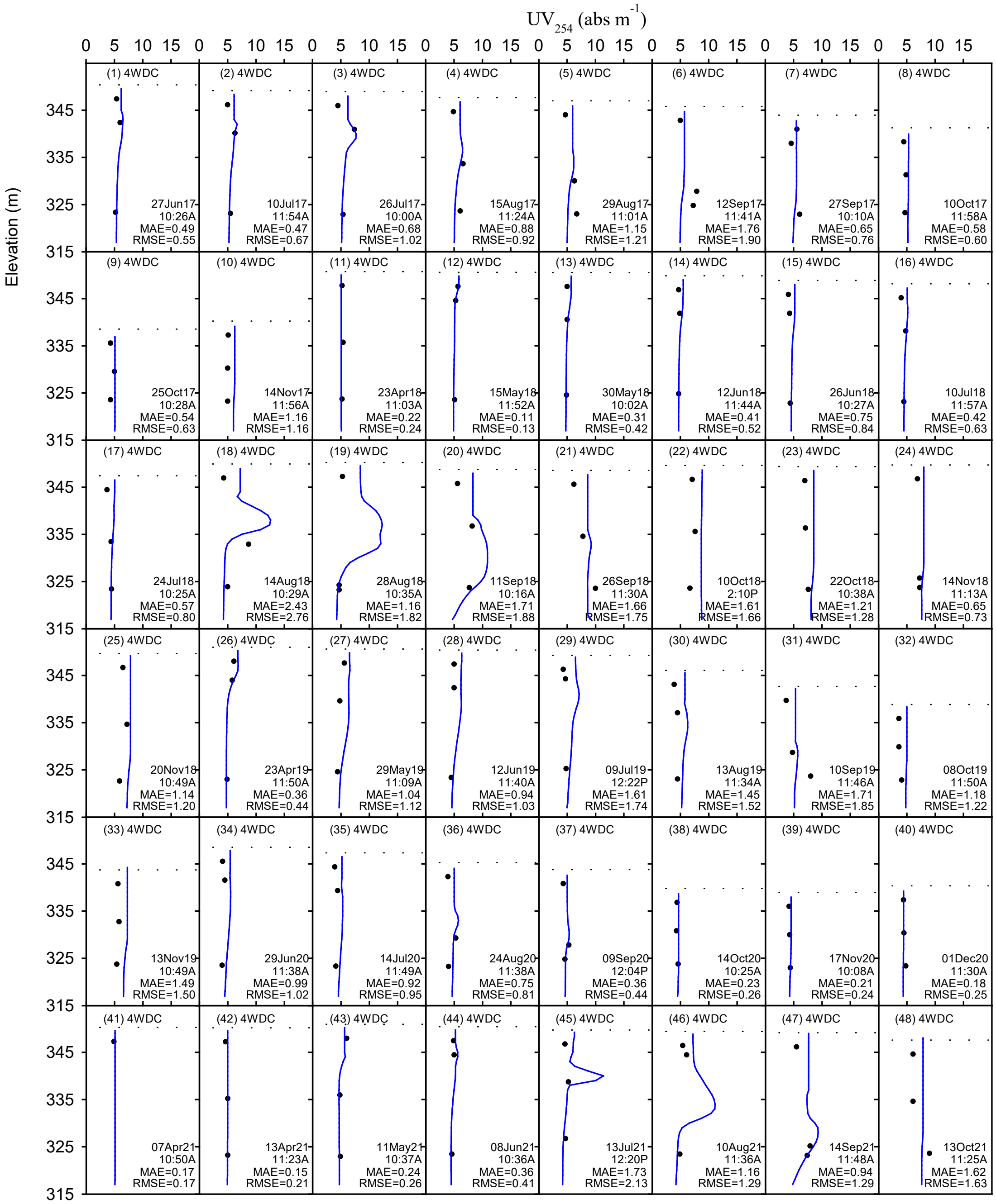


Figure 6.25 Performance of Cannonsville Reservoir UV254 model, presented as comparison of observed and predicted vertical depth profiles of UV254 at site 4WDC for selected days, 2017-2021. MAE and RMSE indicate mean absolute and root mean square errors (m^{-1}), respectively.

Performance of the model regarding withdrawal UV254 is shown in Figure 6.26. The model generally predicted well the seasonal dynamics, peak response, and subsequent attenuation of UV254 levels. The performance is particularly good for 2016–2021 (RMSE = 0.008 abs cm^{-1}), for which we were able to define loading of UV254 from WBDR more accurately, largely from the observed data. For the earlier period, uncertainty in the specification of loading remains high causing overprediction (e.g., during 2011–2012 following Hurricane Irene in August 2011).

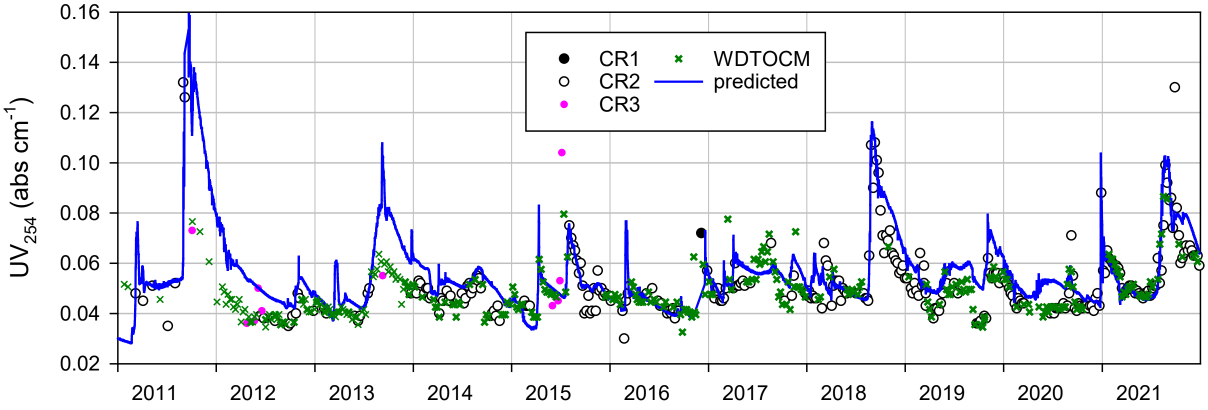


Figure 6.26 Performance of Cannonsville Reservoir UV254 model, presented as comparison of observed and predicted withdrawal UV254, 2011-2021.

Neversink Reservoir UV254 model: W2 for Neversink Reservoir was configured into a computational grid of one branch, 21 longitudinal segments, and 52 vertical layers (Figure 6.27). Model testing (calibration-validation) was performed for 2011-2021 (11 years), the longest period of available UV254 data in the diverted water. Input data required by the model included bathymetry, hourly meteorology (air temperature, dew point, wind, and solar radiation), inflows, outflows, water surface elevation, inflow temperatures and inflow UV254. Model testing data consisted of in-reservoir and outflow temperatures and UV254. Selected data used in the model development and testing are presented in Figure 6.28.

DEP started monitoring UV254 at keypoint NR2 since 2011; however, monitoring at the primary lacustrine site 1.5NN and at the inflow site NCG did not start until 2016. The model requires that a value of UV254 for all inflows is specified for each day of simulation. We used the stream model, as discussed above, to estimate continuous daily input for 2011–2015, and to gap-fill observed records for 2016-2021. Substantial variability induced primarily by hydrology in stream UV254 is evident (coefficient of variation 87%), with peak levels of 0.3 abs cm^{-1}, while the average level is ~ 0.05 abs cm^{-1} (Figure 6.28b). There is no other major inflow to Neversink Reservoir. UV254 in the distributed inflow (computed from a flow budget calculation) was assumed to be the same as in Neversink River at NCG.

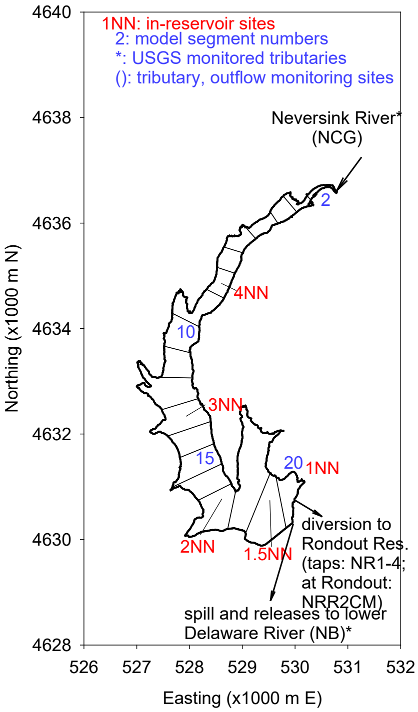


Figure 6.27 Neversink Reservoir: Inflows, outflows, in-stream and in-reservoir routine water quality monitoring locations, and W2 model segments. Selected model segments are also numbered according to the numbering scheme of W2.

Once the underlying organic matter is discharged into the reservoir, hydrodynamic, thermal, and biological processes regulate the fate and transport, resulting in more modulated variability and peak levels of UV254 (Figure 6.28cand Figure 6.28d). The attenuation of inflowing UV254 in the reservoir and withdrawal for 2021 is clearly seen in Figure 6.29.

Neversink Reservoir UV254 Model performance: Similar to Cannonsville Reservoir model, the model to reproduce observed behavior of UV254 was evaluated by comparing observations with the predictions in two formats: (a) depth-profiles at site 1.5NN for 2016–2021 (Figure 6.30), and (b) timeseries at keypoints NR2 and NRR2CM for 2011–2021 (Figure 6.31). At site 1.5NN, the observations from 3–4 depths occasionally indicated presence of a vertical gradient in UV254 (Figure 6.30) due to density-driven inflows. The predictions matched these observations well. The mean absolute error (MAE) range was 0.0007 abs cm^{-1} – 0.017 abs cm^{-1}, and the RMSE range was 0.0009 abs cm^{-1} – 0.022 abs cm^{-1}.

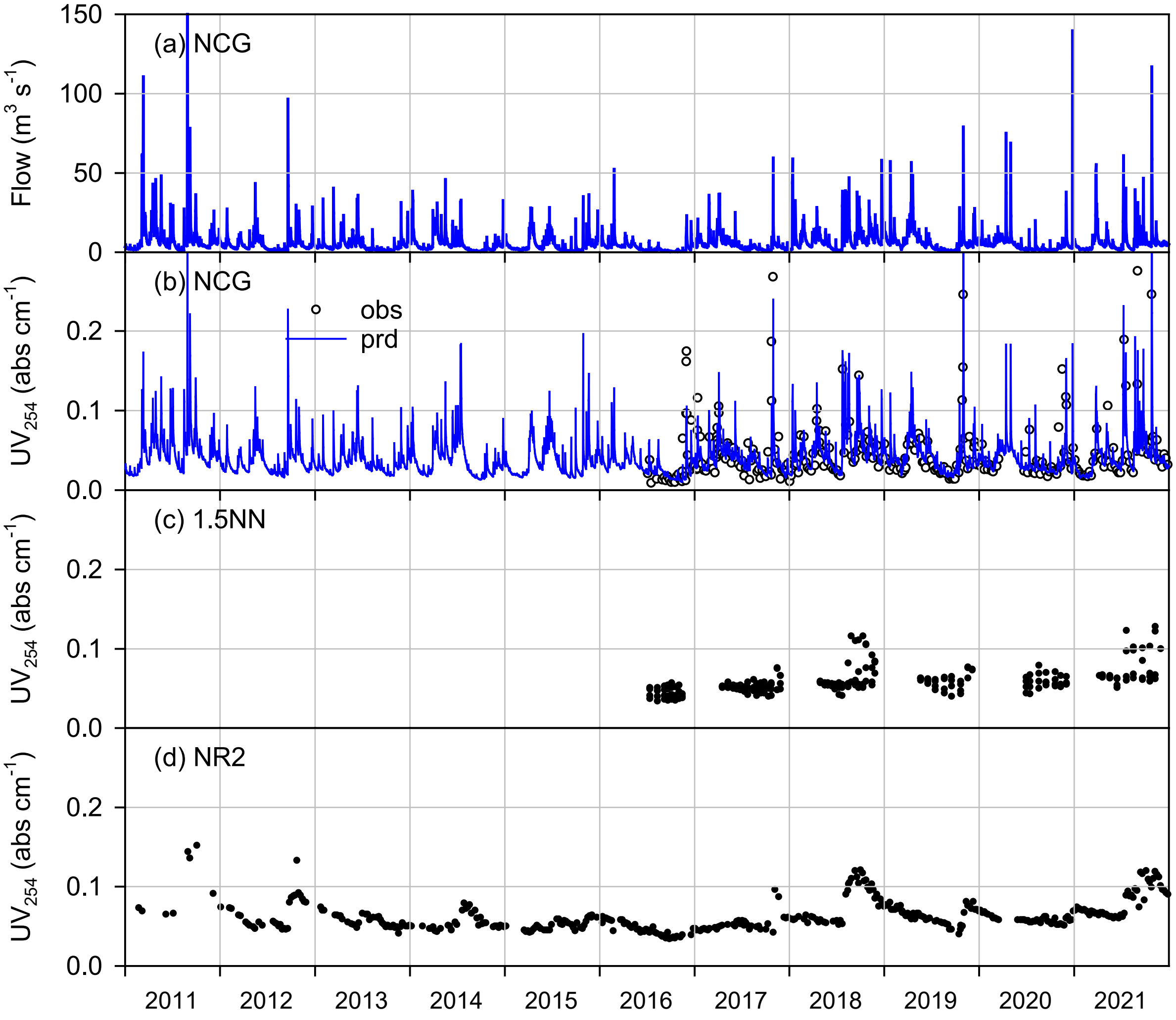


Figure 6.28 Time series of inflow and UV254 data for Neversink Reservoir, 2011–2021: (a) inflow from Neversink River at NCG, (b) observed and modeled inflow concentration of UV254 at NCG, (c) UV254 at in-reservoir site 1.5NN, and (d) UV254 at another in-reservoir site NR2 known as elevation tap, which corresponds to the elevation of the 2nd-level intake.

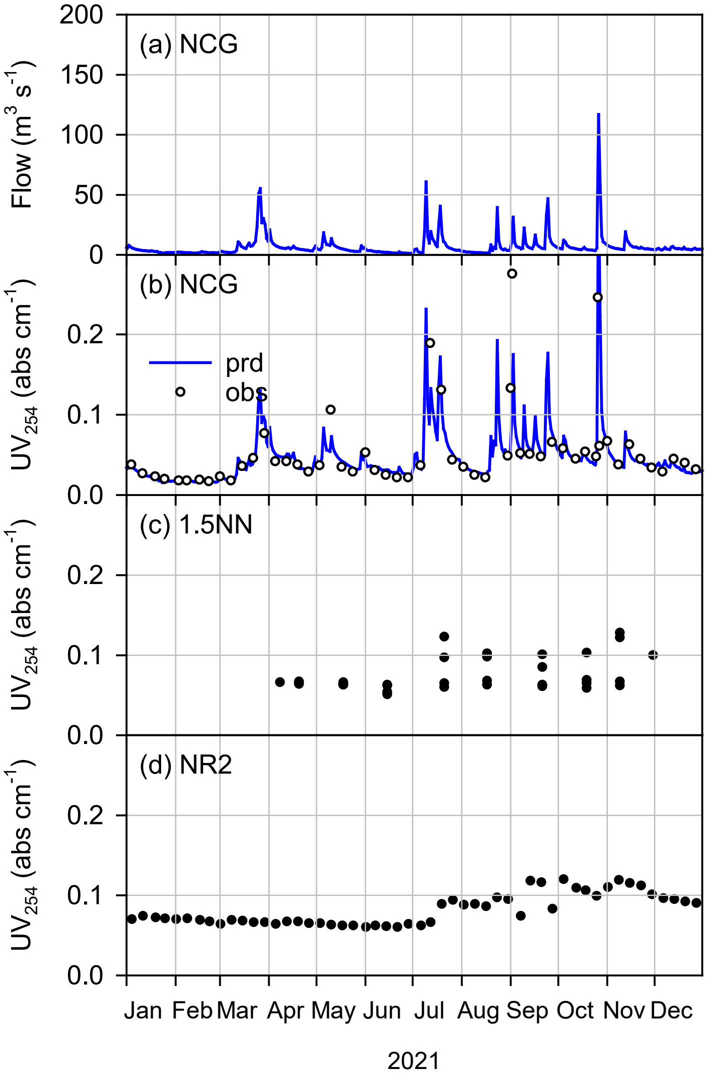


Figure 6.29 Time series of inflow and UV254 data for Neversink Reservoir, 2021: (a) inflow from Neversink River at NCG, (b) observed and modeled inflow concentration of UV254 at NCG, (c) UV254 at in-reservoir site 1.5NN, and (d) UV254 at another in-reservoir site NR2 known as elevation tap, which corresponds to the elevation of the 2nd-level intake.

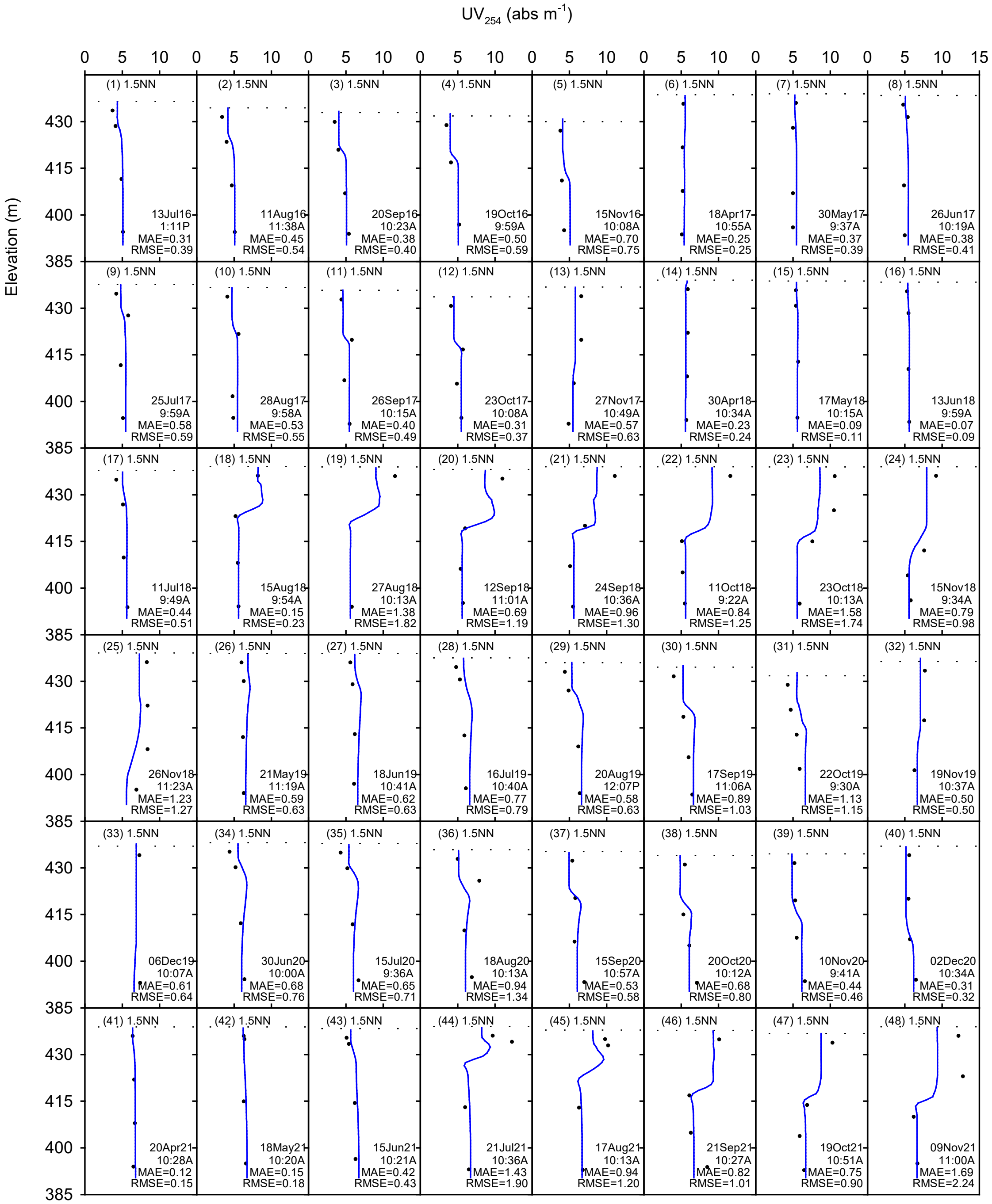


Figure 6.30 Performance of Neversink Reservoir UV254 model, presented as comparison of observed and predicted vertical depth profiles of UV254 at site 1.5NN for selected days, 2016-2021. MAE and RMSE indicate mean absolute, and root mean square errors (m^{-1}), respectively.

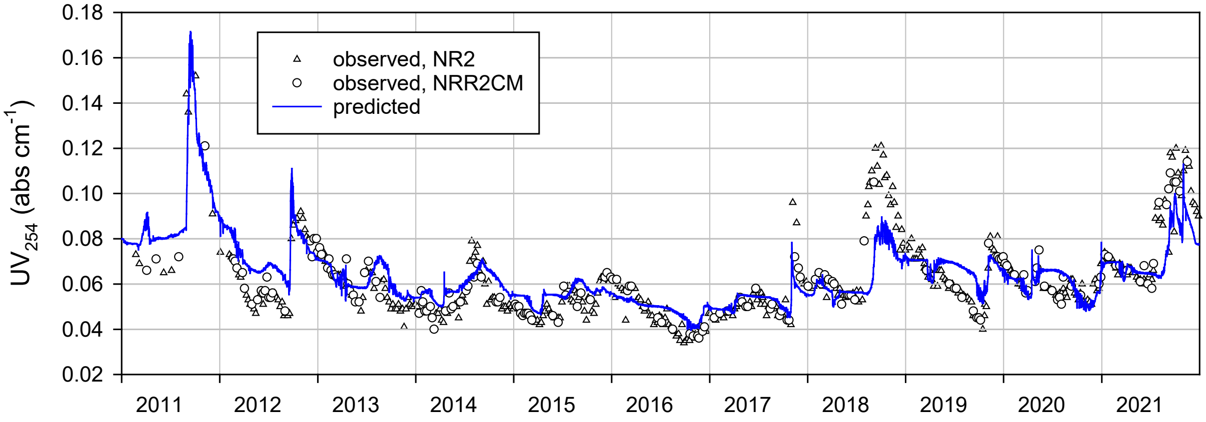


Figure 6.31 Performance of Neversink Reservoir UV254 model, presented as comparison of observed and predicted withdrawal UV254, 2011-2021.

Performance of the Neversink Reservoir model regarding withdrawal UV254 is shown in Figure 6.31. The model generally predicted well the seasonal dynamics, peak response, and subsequent attenuation of UV254 levels; however, withdrawal UV254 during the wet period of late-July–September 2018 was underpredicted (Figure 6.31). One likely source of uncertainty is the representativeness of observations from NR2 – the observations are expected to correspond to hypolimnetic levels (NR2 is in the hypolimnion during stratified conditions); however, observed UV254 magnitude suggests that some epilimnetic water is also drawn, which may be possible only if stop-shutters at higher elevations (NR3 and NR4) are only partially blocking the entry way. Model simulations show that the envelope of withdrawal does not extend above thermocline into the epilimnion during the stratified period. Nevertheless, the overall level of performance of the model for 2011-2021 is satisfactory (RMSE = 0.01 abs cm^{-1}) and the model would be acceptable for making operational and planning decisions.

From the two successful applications of W2 presented above, we can conclude that: (i) UV254 can be modeled in the reservoir environment with a simple first-order kinetic model, (ii) autochthonous sources of dissolved constituents causing UV254 absorbance in both Cannonsville and Neversink reservoirs are negligible, and (iii) allochthonous sources of UV254 are largely refractory.

6.9 Data Analysis

DEP conducted operational availability demonstration (OAD) of alum addition into Catskill Aqueduct at inflow to Kensico Reservoir (CATALUM) during May 9 – May 23, and September 14 – September 21. During these two intervals, we also monitored effect of alum treatment on the removal of natural organic matter (NOM) – the treatment reduced UV254 by 37% and 11%, respectively.

6.10 Use of Models for Support of Operational Decisions

DEL10 chlorination study: To evaluate the effectiveness of chlorination at Delaware Shaft 10 (DEL10) in oxidizing NOM and therefore reducing disinfection byproducts in the distribution system, DEP conducted a pilot study in 2021-2022. We used a simple model based on mass balance equation for a continuously stirred tank reactor (CSTR) with first-order kinetics to evaluate the fate of DBPs in Kensico Reservoir. Upon chlorination of water at DEL10, DBPs (HAAs + THMs) would be formed and would be discharged into Kensico Reservoir at DEL17. The following scenarios were evaluated: Catskill Aqueduct inflow = 550 MGD, DBPs = 0 µg L^{-1}; Delaware Aqueduct inflow (DEL17) = 350 MGD, DBPs = 10, 20, 50 µg L^{-1}; and loss rate = 0, 0.01, 0.001 per day. For the scenario that was closest to the actual conditions (DEL17 DBPs = 10 µg L^{-1}), the model predicted accurately that DBPs at Shaft 18 would be < 2 µg L^{-1} during the first three weeks of the study.

OST-W2 runs: A major storm impacted water quality of the Catskill System on April 7, 2022 (E16I; Esopus Creek peak instantaneous flow = 15,900 CFS; turbidity > 1400 NTU). After the storm, we conducted several OST runs to guide operations of the Catskill Aqueduct and manage water quality. Three scenarios of Ashokan East Basin diversion flow rates of 575 MGD (Run A), 400 MGD (Run B), and 300 MGD (Run C) were considered. OST-W2 simulations projected that Kensico diversion turbidity would not exceed ~ 1.5 NTU at 50th percentile level in all the scenarios and the maximum of all scenarios at 90th percentile level would be ~ 1.8 NTU, about three weeks after the initial impact of the storm (Figure 6.32). Thus, Ashokan diversion was considered feasible without adversely affecting Kensico water quality. Accordingly, Ashokan diversion was planned and executed, while following the interim release protocol for Ashokan Release Channel operation.

6.11 Reservoir Operations Modeling and OST

We performed 615 OST simulations in 2022, supporting daily reservoir operations as well as long-term planning activities, including: (1) Mock outage runs, i.e., testing the model for the 2023 Rondout West Branch Tunnel (RWBT) shutdown by using 2022 hydrological conditions and subsequently briefing BWS management monthly in terms of RWBT go/no-go decision risk level, (2) Croton outage, (3) Shandaken Tunnel Intake Chamber outage, (4) Catskill air monitoring project, (5) Catskill Alum Plant operates-as-designed testing, (6) New Croton drawdown and inspection, (7) Full Delaware power generation outage (bypass flows), (8) 1st Catskill Aqueduct pressure tunnel remotely operated vehicle (ROV) inspection, (9) RWBT 2nd shutdown – valve and flowmeter work, (10) 2nd Catskill Aqueduct (Wallkill) pressure tunnel ROV inspection, (11) RWBT dewatering exercise, and (12) Catskill shutdown to support Kiryas Joel Community new Catskill Aqueduct connection.

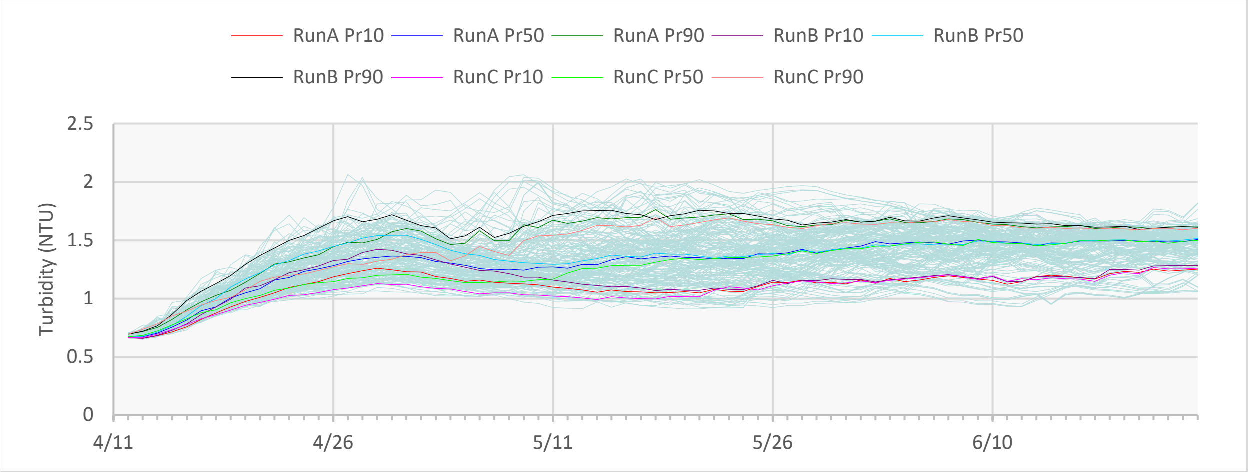


Figure 6.32 Projections of Kensico diversion turbidity for a range of operating conditions of Catskill Aqueduct (Pr10, Pr50, and Pr90 represent 10th, 50th, and 90th percentiles of the projected traces of turbidity).

During 2022, we continued enhancing OST so that it better reflected current system rules, infrastructure status and provided guidance for various infrastructure outage applications, e.g., the planned 2023 RWBT outage. Some of the enhancements are described next.

6.11.1 NWS Forecast Upgrades

In 2022, the NWS through its Middle Atlantic River Forecast center (MARFC) in collaboration with the NOAA's Office of Water Prediction (OWP) started recalibrating their hydrologic models in the upper Delaware River Basin (DRB) to replace the Continuous-API hydrological model with the Sacramento Soil Moisture Accounting Model (SAC-SMA) for generating daily ensemble inflow forecasts for all reservoirs and other forecast locations in the DRB represented in OST. This work is important and is in direct response to one of the National Academy of Science, Engineering and Medicine (NASEM) OST Expert Panel recommendations.

6.11.2 Multi-year Technical Support, Training and Knowledge Transfer Contracts

During 2022, DEP engaged in two long-term contracts: (1) DEL-444: Technical Support, Training and Knowledge Transfer, and Development for OST with Hazen and Sawyer, and (2) DEL-445: OST Technical Support Services, Training and Knowledge Transfer Needs for the OST Ensemble Forecast Post-Processor (EPP), diagnostic and verification tools, with the Research Triangle Institute (RTI) International. As part of DEL-444, OASIS Graphical User Interface (GUI) software was upgraded from version 5.4 to 6.1. The upgraded version provides the platform for new OST enhancements, such as moving certain OASISGUI functions to a plugin architecture. Three new plugins have been implemented in OST version 6.1, including forecast data, W2 data, and scheduled-variable input. Among these, the forecast data plugin was expanded with new capabilities, while the other two still offer the same capabilities; however, all plugins will be expanded with new functionalities during the duration of the contract. The new forecast data plugin expands the capabilities for DEP staff to make changes to EPP such as create a new mixed EPP that selectively applies different EPPs for different forecast locations or add a new forecast type for use to drive OST. Until now, such changes could only be implemented by Hazen and Sawyer specialists. Work under DEL-445 is just starting. This contact will provide the necessary support to develop new EPPs, new forecast types, as well as help enhance DEP's forecast diagnostic and verification tools. One very important goal for both contracts is training for, and knowledge transfer to, DEP staff. This will allow DEP to maintain, enhance, and develop OST in future.

6.11.3 Enhancements to OST Baseline Run

As part of DEL-444, Hazen and Sawyer performed QA/QC for a new OST baseline run that was developed by DEP staff through implementation of model enhancements and updates to better reflect operations and the existing operational flexibility in the Croton system, as well as a better simulation of the turbidity load from Cannonsville, Pepacton, and Neversink reservoirs into Rondout Reservoir using historical observations of reservoir turbidity. This new baseline run is being finalized to include the new USGS bathymetry for EOH reservoirs.

6.12 Water Quality Modeling: Publications and Presentations in 2022

Frei, A., Mukundan, R., Chen, J., Gelda, R., Owens, E. M., Gass, J., and Ravindranath, A. 2022. A cascading bias correction method for global climate model simulated multi-year precipitation variability. J. Hydrometeorol., 23(5), 697-713.

Gass, J. 2022. Identifying trends in climate change indicators for the NYC Water Supply Watershed. Paper presented at Catskill Environmental Research & Monitoring (CERM) Conference, Big Indian, NY, October 26-28, 2022.

Gass, J. 2022. Development of High-Resolution Bathymetry for the East of Hudson Reservoirs. Paper presented at NYC Watershed Science and Technical Conference (WSTC), Tomkins Cove, NY, September 21, 2022.

Gelda, R.K. 2022. Hydroclimatology of the Catskills: 2070s and beyond. Paper presented at Catskill Environmental Research & Monitoring (CERM) Conference, Big Indian, NY, October 26-28, 2022.

Gelda, R., Mukundan, R., Wang, K. 2022. An innovative approach to modeling disinfection byproducts (DBPs) in water supply: From source to tap. Paper presented at NYC Watershed Science and Technical Conference (WSTC), Tomkins Cove, NY, September 21, 2022.

Mukundan, R. 2022. Carbon, nutrient, and sediment export from NYC watersheds under a changing climate. Paper presented at Catskill Environmental Research & Monitoring (CERM) Conference, Big Indian, NY, October 26-28, 2022.

Mukundan, R., Gelda, R. Moknatian, M., Meshesha, T. 2022. Modeling and analysis of carbon, nitrogen and phosphorus export from New York City watersheds. Paper presented at NYC Watershed Science and Technical Conference (WSTC), Tomkins Cove, NY, September 21, 2022.

Wang, K. 2022. Evaluating suspended sediment and turbidity reduction from stream restoration projects. Paper presented at Catskill Environmental Research & Monitoring (CERM) Conference, Big Indian, NY, October 26-28, 2022.

6.13 Contract updates

6.13.1 CUNY

The CUNY post-doctoral contract WQ-MODEL-19 was extended to September 30, 2024. David Reckhow, Professor (University of Massachusetts, Amherst) and his team continued a DBP monitoring program in the Neversink watershed to characterize natural organic matter (NOM) precursors, and disinfection byproducts formation potential.

6.13.2 USGS

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

7. Innovation and Research

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

7.1 Research Inventory

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

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

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

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

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

As of December 2022, BWS had 54 active or planned research projects. Across the core subjects, the Research Inventory includes 15 research areas (Figure 7.1).

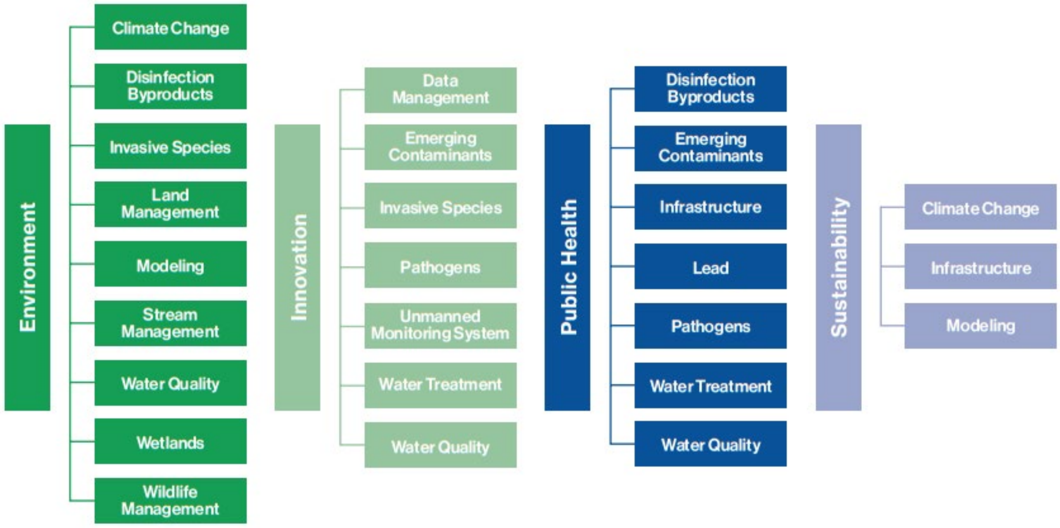


Figure 7.1 Research Inventory Research Areas.

7.1.1 Defining Research Areas

As the research inventory continues to grow, new and emerging issues have been identified. One current effort is to define each research area in use before clarifying and consolidating areas with significant overlap. This effort was initiated in 2022 and will continue into 2023.

BWS created the Research Advisory Council (RAC) to establish and manage a research process and act as a forum to communicate and support research initiatives. The RAC is a staff-level group with representation from all directorates. In this role, they are serving as the lead to develop definitions for over 30 research areas.

7.2 2022 BWS Conference

BWS holds an annual internal conference, inviting staff to present on critical research underway within the bureau. The theme of the May 17 – 18, 2022 conference was *Adaptation: What Comes Next?*

The conference program centered on the ways in which technology, climate, and regulatory changes sharpen our focus on how to manage NYC's water supply. The conference opened with a focus on the adaptive approach needed to operate the system as a result of climate change, infrastructure repairs and upgrades, and regulatory mandates. Staff presented on climate change, data modernization, Lead and Copper Rule Revisions and the Stage 2 Disinfection Byproducts Rule, Croton System taste and odor complaints, and invasive species.

In 2022, over 140 BWS staff participated in the two-day conference.

7.3 2022 BWS Webinars

In addition to the annual conference, BWS also highlights ongoing research or related activities with monthly “Thirsty Thursday” webinars. In 2022, 438 staff participated in five webinars (Table 7.1).

Table 7.1 2022 Thirsty Thursday Webinars

Month	Topic
February	Chloride Trends in the NYC Water Supply
March	An Innovative Approach for Modeling Disinfection Byproducts Formation Potential in Source Water
April	Riding the (Internal) Wave: Using Sensor Data and Computer Modeling to Understand Drivers of Lake Nutrient Loading and Harmful Algal Bloom Dynamics
October	The Water Quality Index
December	Using Open-Source R Software to Transform DEP’s Data into Information

7.4 Innovation in Research

7.4.1 Data Modernization

BWS collects millions of data points annually from various systems that monitor the water supply. Therefore, it is critical to optimize and review how information is stored, used, and shared. BWS manages over 100 applications and database systems across different business units. To facilitate centralized storage of critical datasets for decision support and long-term trends and analysis, a modern data warehouse is being developed in a cloud-based environment. This data warehouse can integrate numerous resources such as AI, machine learning, and analytics, including Power BI.

In 2022, data modernization efforts included integrating robotic monitoring data (reservoir buoys and stream monitoring) and laboratory and field results from the Watershed Water Quality Operations (WWQO) Laboratory Information Management System (LIMS). Additionally, work commenced on integrating reservoir operations data into the data warehouse. Late in 2022, planning began to review and design a strategy to clean sensor data using statistical or machine learning methods, which would remove anomalous spikes or outliers from both Early Warning and Remote Monitoring (EWRM) and robotic monitoring data. Development and testing also commenced on an EWRM field application that would allow EWRM staff to digitally record QA/QC data, including maintenance, calibration, and meter adjustments, and apply these back to the data warehouse to remove erroneous data from online sensor trends.

BWS's data modernization effort also includes its data governance program, which continued to document datasets in a shared data catalog, refine, or contribute to the database and application inventories, and develop data-driven business process models. During 2022, the data governance program focused on drafting a set of BWS data management policies and a framework document outlining the program and resources/policies available to BWS staff.

7.5 Working Groups

7.5.1 Enhanced Treatment Working Group

The Enhanced Treatment Working Group consists of staff from multiple directorates with diverse scientific and professional expertise. In 2022, the objective of the working group was to better understand the causes and potential mitigations for taste and odor events which are primarily a challenge in the Croton System. Initially, the group focused on developing enhanced monitoring plans and evaluating treatment alternatives. The goals were group expanded to include collaboration to other subject areas including: (1) evaluating multiple treatment techniques, (2) evaluating multiple technologies and methods, (3) collaborating externally with other water utilities and research experts, and (4) traveling to various locations to visualize real world applications.

7.5.2 Drone Working Group

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

7.5.3 Salinity Task Force

Formed in 2020, the BWS Salinity Task Force (STF) concluded meetings in 2022 and developed a draft Salinity Management Strategy. This initiative was intended to better understand the drivers of salinity increase in the City’s watersheds, and to identify recommendations to work towards a regional approach to salinity management. The STF was comprised of staff appointed by the various directorates in BWS. The task force's goal was to examine, measure, and understand the trends of salinity for the NYC watersheds and water supply, and to develop a strategy to monitor and reduce salinity. While the STF found a sustained increase in chloride concentrations in all NYC reservoirs, the highest increases were in the EOH watersheds. These increases ranged in magnitude and the causes for observed increases are primarily connected to the use of road deicers in winter.

7.5.4 R Data Analysis Group

The overarching goal of the R Data Analysis Group (RDAG) is to continue to develop the DEP's internal data analysis and management skill sets for scientific reporting. This internal working group serves to improve legacy knowledge transfer to the next generation of data analysts/scientists using the open-source R statistical software for statistical analysis and data visualization. During 2022, seven RDAGs were held covering the topics of data importing, data wrangling, basic statistics, exploratory data analysis, outlier detection, and two sessions on plotting data. Each RDAG session was conducted via Microsoft Teams and the members were provided with a complete copy of the R scripts that were to be discussed. Each session was recorded, allowing colleagues to rewatch a specific portion or view the session if they were unable to attend it live. While the goal had been monthly sessions, holidays and competing deadlines interfered with meeting each month. To help encourage interest in R, the group subject matter expert created an internal presentation titled "Using Open-Source R Software to Transform DEP's Data into Information". For 2023, the plan topics will include exploring working with date and time, side by side comparisons, basic multivariate statistics, and topics requested by members of the group.

7.6 Water Research Foundation

The Water Research Foundation (WRF, www.waterrf.org) is "the leading research organization advancing the science of all things water to meet the evolving needs of its subscribers and the water sector. WRF is a 501(c)(3) nonprofit, educational organization that funds, manages, and publishes research on the technology, operation, and management of drinking water, wastewater, reuse, and stormwater systems—all in pursuit of ensuring water quality and improving water services to the public." DEP has been a subscriber and participant in the research conducted under the WRF since the early 1990s, both as project advisory committee (PAC) members and as a participating utility (PU), to remain current with cutting-edge research for the benefit of the City's drinking water.

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

7.6.1 Metrics

BWS tracks involvement with The Water Research Foundation year-over-year to measure engagement and identify areas or opportunities for growth (Table 7.2). Webinar participation has declined for several reasons: the foundation held fewer webinars in 2022 and, of those webinars, most focused on wastewater resource recovery facility treatment of nutrients. In addition, staffing shortages have placed increased demands on staff time and many webinars are scheduled when staff are no longer in the office. BWS is working with the foundation to help increase participation for 2023.

Table 7.2 Water Research Foundation Projects 2019 – 2021.

Metric	**2019**	**2020**	**2021**	**2022**
New Staff Accounts	18	32	1	15
External Organizations included in DEP's Subscription	5	5	5	5
Staff Serving on WRF Planning/Research Bodies	17	24	32	45
Webinar Participation	65	215	287	24

7.6.2 WRF Workshop – Taste and Odor

WRF organized a Taste and Odor (T&O) Expert Panel Workshop on behalf of BWS on May 24 and 25, 2022. The goals of the workshop were fivefold: (1) review water quality monitoring data to identify causes, (2) review current monitoring and treatment strategies and identify opportunities for improvement, (3) propose an integrated process to investigate MIB formation and its fate and transport through the treatment process to distribution, (4) identify next steps along with the human, capital, and technological resources needed to study and remedy these issues in the Croton System, and (5) identify emerging technologies for pilot testing.

Five subject matter experts participated in the workshop (Table 7.3). The panel recommended DEP to first focus on identifying sources of T&O events, using this information to build upon reservoir dynamics and develop predictive models for future events. Proactive and near-term plans for T&O response and control should also be developed, with effective public communication as a critical component.

Table 7.3 Taste and Odor Expert Panel Workshop: Subject Matter Experts.

Expert Panelists	
J. Hunter Adams Environmental Laboratory Supervisor, City of Wichita Falls, TX	Dr. Rupert Perkins Reader, School of Earth and Environmental Sciences, Cardiff University, UK
Dr. Justin Brookes Professor, School of Biological Sciences, University of Adelaide, Australia	Dr. Fred Lubnow Senior Technical Director, Ecological Services, Princeton Hydro
Gary Burlingame Consultant on Water Science and Aesthetics Management	

7.6.3 SEE IT Scholarship

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

BWS staff visited Colorado and Texas on September 13 – 15, 2022. Staff first visited Aurora Water in Aurora, CO, a suburban City of Denver, CO. The first stop was the Binney Water Purification Facility in Aurora, CO. The facility incorporates UV treatment with advanced oxidation, as well as biological activated carbon filtration and absorption, and this visit was helpful to discuss GAC specifications and experiences with carbon vendors. Next the group visited Denver Water's North Water Treatment Plant, which utilizes UV disinfection. Having an opportunity to see how Denver was constructing their plant provided an opportunity to see state of the art construction processes, as well as new technologies, as they were being built.

Finally, the BWS team travelled to Wylie, TX, to visit the North Texas Municipal Water District's Wylie Water Treatment Plant, the world's largest ozone facility. This facility can treat up to 840 MGD. In addition, this plant also uses chlorine dioxide to kill off zebra mussels and for iron and manganese control in raw water.

In December, eight staff from DEP's Bureau of Wastewater Treatment visited four WRRFs in the Hampton Roads Sanitation District. The goal of this trip was to access the lessons learned from a leading-edge utility, so that they can be utilized to meet NYC's future stringent environmental stewardship goals, whether driven by regulatory requirements or social imperatives. Hampton Roads Sanitation District incorporates several technologies at the forefront of this goal: deammonification technologies, Sustainable Water Initiative for Tomorrow potable water reuse full scale demonstration, Ostara Pearl struvite recovery, multiple aeration control strategies, Cambi thermal hydrolysis, laboratory information system, and utility/academic partnership model.

7.6.4 WRF Project Participation

Table 7.4 summarizes all WRF project participation in 2022.

Table 7.4 2022 WRF Project Participation.

Title	Description	Participation[1]
PFAS in Water	PFAS One Water Risk Communication Messaging for Water Sector Professionals (5124) - This project is focused on developing plug-and-play tools and communication materials that water utilities across the United States can use to communicate their PFAS risk and solutions to their customers. The effort thus far is focused on creating universal tools for traditional communications, social media, bill inserts, websites, and presentations. All of this will be done ahead of UCMR5 results so that water utilities will have the tools they need to communicate their results and talk about it with their elected leaders and customers.	PAC
Emerging Disinfection Byproducts	Technologies and Approaches to Minimize Brominated and Iodinated DBPs in Distribution Systems - This project aims to develop creative and novel techniques and approaches to minimize the formation of currently unregulated brominated and iodinated disinfection byproducts (DBPs) in the distribution system considering practical applicability and economic feasibility in the operation of existing treatment systems.	PU
Cyanobacterial Blooms & Cyanotoxins	Assessment of molecular techniques to detect and predict cyanotoxin-producing blooms.	PAC
Lead & Copper Management	Using phosphate-based corrosion inhibitors and sequestrants to meet multiple water treatment objectives.	PAC
Defining Exposures of Microplastics/ Fibers (MPs) in Treated Waters and Wastewaters: Occurrence, Monitoring, and Management Strategies	Project Objectives: • Characterize typical MP numbers, types and sizes in secondary and tertiary treated wastewater, recycled water, drinking water supplies (ambient waters) and treated drinking water. • Develop reliable monitoring and sampling guidelines, based on MP sizes and source media. • If needed, develop a decision-making framework for MP reduction strategies from the whole water supply cycle. • Describe the relative effectiveness of various technologies and legislation to mitigate sources and pathways of MPs.	PAC

Title	Description	Participation[1]
Impact of a Haloacetic Acid MCL Revision on DBP Exposure and Health Risk Reduction	The objectives of this project are to develop: • A holistic assessment of the potential impacts of potential new regulatory levels for HAA5, HAA6Br, or HAA9. • A defensible database and analysis available to water systems for discussion with regulatory authorities. • An understanding of the benefits of compliance technologies for a future rule, which will allow water systems to make preliminary evaluations of water treatment improvements they may have to incorporate after the regulations are revised. • Guidance to water systems and regulators on consequences of implementing changes to respond to a revised maximum contaminant level (MCL) for haloacetic acids (HAAs).	PU
Advancing Low-Energy Biological Nitrogen and Phosphorus Removal	The main objective of this project is to conduct research needed to advance the most promising intensive and efficient low-energy nutrient treatment process(es) and innovative process control approach(es) that utilities can employ and reliably operate at their facilities with a balance of cost-effective investments and appropriate levels of process control complexity. While the scope of this project is open to all low-energy biological nutrient removal intensification processes, we encourage proposers to consider the processes and research topics listed in the research approach of the RFP.	PU
Investigation of Alternative Management Strategies to Prevent PFAS From Entering Drinking Water Supplies and Wastewater	Project Objectives: • Identify potential point sources. • Identify effective pre-treatment and mitigation measures such as BMPs and permitting at point sources. • Investigate impacts of wastewater effluent PFAs on drinking water utilities. Develop a roadmap of multiple strategies to mitigate PFAS at point source or prior to entry to drinking water and wastewater treatment facilities.	PAC
Guidance for Using Pipe Loops to Inform Lead and Copper Corrosion Control Treatment Decisions	Project Objectives: To provide “fit for purpose” guidance for corrosion control pipe loop construction, operation, sampling, and data interpretation to inform pipe loop implementation for corrosion control studies.	PU

Title	Description	Participation[1]
Assessment of Vulnerability of Source Waters to Toxic Cyanobacterial Outbreaks	Project Objectives: • Develop a risk assessment for the prediction of the occurrence of different types of cyanobacteria and the progress toward bloom development. • Develop a model that uses the conventional understanding of the major factors triggering and supporting the growth of cyanobacteria • Calibrate and validate the model with data from a variety of source waters, geographical area, and environmental factors.	PAC/PU
Analysis of Corrosion Control Treatment for Lead and Copper Control **Completed in 2021**	Project Objectives: • Evaluate analysis tools for and risks from changing and/or implementing corrosion control treatment (CCT). • Explore the potential impact of various source water or treatment changes to CCT. • Develop a framework for how to assess current CCT and under what circumstances CCT should be reevaluated. • Explore the impacts to both lead and copper.	PU
Sampling and Monitoring Strategies for Opportunistic Pathogens in Drinking Water Distribution Systems	The goal of this project is to establish an optimized sampling and monitoring protocol providing a practical guideline for drinking water utilities to manage the detection of opportunistic pathogens in distribution systems.	PAC
Evaluating Key Factors that Affect the Accumulation and Release of Lead from Galvanized Pipes **Completed in 2021**	The objective of this project is to better understand the scenarios where Galvanized pipes can contribute to lead at the tap, the magnitude of lead release from galvanized pipes, and factors that can impact accumulation and lead release from galvanized pipes.	PAC

Title	Description	Participation[1]
Designing Sensor Networks and Locations on an Urban Sewershed Scale with Big Data Management and Artificial Intelligence Applications	The water sector is undergoing a transformation to digital where data and data management are driving every aspect of a utility's work. To address this new way of conducting business, this project will consolidate insights gained from the WRF projects *Designing Sensor Networks and Locations on an Urban Sewershed Scale* (4835) and *Leveraging Other Industries - Big Data Management* (4836) into demonstration projects at multiple facilities. The demonstrations are designed to validate sensor-based, real-time monitoring/metering and models/decision support systems on sewershed/sub-sewershed scales, including the application of analytics to solve sewershed network management issues. Based on the insights gained from the demonstrations, a sensor-based network and data management framework will be developed. The framework will provide a clear architectural roadmap and guidance for advancing data and information management, practices, automation of quality assurance/quality control, data use mapping, database management, and data integration for the water sector. The framework will incorporate new and emerging monitoring/metering technologies for real-time decision-making.	PAC
Opportunistic Pathogens (OPs) in Premise Plumbing	This project aims to develop methods for accurately detecting and quantifying bacterial and protozoan OPs in drinking water systems, with a particular focus on *L. pneumophila, P. aeruginosa*, nontuberculous mycobacteria, and *Acanthamoeba* spp. These four OPs represent the greatest health and economic burden posed among those occurring in premise plumbing.	PAC
Long Term Water Demand Forecasting Practices for Water Resources and Infrastructure Planning	This project aims to describe models, methods and practices currently used to forecast long-term demand in support of water resources and infrastructure planning and management. To the extent possible, the project deliverables will discuss how current practices have evolved over time. The research team will consider the accuracy of different forecasting approaches by comparing actual with model-estimated demands and comment on the relative effectiveness of different approaches. The team will also identify the extent to which forecasting models, methods, practices, and communications influence decisions about utility plans and actions. Finally, this project will develop recommendations to help improve the role and effectiveness of demand forecasting practices and different types of communication strategies on water resource and infrastructure planning and decision-making.	PU

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

7.7 American Water Works Association (AWWA)

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

7.7.1 Technical Advisory Workgroups (TAWs)

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

Table 7.5 AWWA Technical Advisory Working Groups in 2022.

AWWA Committees	
Committee Name	**Participant**
Disinfection By-Products	Lori Emery, Director, Water Quality & Innovation, Bureau of Water Supply
Microbial/Disinfection By-Products Rule	Salome Freud, First Deputy Director, Distribution Water Quality and Operations, Water Quality & Innovation, Bureau of Water Supply
Lead and Copper Rule	Salome Freud, First Deputy Director, Distribution Water Quality and Operations, Water Quality & Innovation, Bureau of Water Supply
Microbiological Contaminants Research	Kerri Alderisio, Research Microbiologist, Distribution Water Quality Operations, Water Quality & Innovation, Bureau of Water Supply
Organisms in Water	Kerri Alderisio, Research Microbiologist, Distribution Water Quality Operations, Water Quality & Innovation, Bureau of Water Supply
UV Disinfection for Wastewater	Matthew Burd, Advisor for Process, Wastewater Resource Recovery Operations, Source Water Operations, Bureau of Water Supply
Water Resources and Source Water Protection	Jeffrey Graff, Section Chief, City Land Stewardship, Watershed Protection Programs, Bureau of Water Supply
AWWA Water Utility Council	Paul V. Rush, Deputy Commissioner, Bureau of Water Supply
NYSAWWA Water Utility Council	Salome Freud, First Deputy Director, Water Quality & Innovation, Bureau of Water Supply

7.8 Town+Gown

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

7.8.1 Hemlock Woolly Adelgid

The hemlock woolly adelgid is an invasive, aphid-like insect that attacks North American hemlocks, and has been identified in much of the City's watershed. BWS contracted with Cornell University in 2022 to determine how effective predatory insect species from the Pacific Northwest can be when used as biocontrol agents to control hemlock woolly adelgid populations. In 2022, DEP continued collaborating on the Cornell Hemlock Initiative to establish populations of *Laricobius nigrinus* (beetle) and *Leucopis* spp. (silver fly) at several experimental release sites in both the East and West of Hudson watersheds. Populations are being monitored for signs of successful reproduction.

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

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

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

In 2022, BWS developed an RFP to address these goals, with a plan to finalize and issue the RFP in 2023.

7.9 Research Partners

7.9.1 Cary Institute of Ecosystem Studies

BWS has developed a partnership with the Cary Institute of Ecosystem Studies in 2022. In particular, the bureau is seeking to formalize the administration of the Catskill Science Collaborative, a program designed to promote scientific research and environmental monitoring in the Catskill region. This year three research projects were accepted through this program: 1) monitoring geomorphic change using pole-mounted cameras; 2) field investigation to study dissolved organic carbon sources in the Neversink watershed; and 3) effects of cover crop decay on dissolved phosphorus release from soils.

7.9.2 Virginia Tech

BWS is coordinating with Virginia Tech on several research projects including a Smart One Water program through the National Science Foundation, data governance, and a Future of Water summit. The goal of the proposed Smart One Water Engineering Research Center is to advance measurement and decision support technologies for adaptive management of engineered and natural water systems driven by societal needs for resilience, sustainability, and social justice. Recent natural disasters, cyber-security breaches, and aging infrastructure failures are a reminder that natural, technological, and anthropogenic hazards have great impacts on our society and economy. Smart One Water seeks to create a system of systems approach to integrate cyber-social-environmental components of water resources management. As part of the next phase of this program, Virginia Tech is using the Delaware River Basin as a test bed, along with Biscayne Bay in Florida and the Upper Colorado River Basin states. In 2022, BWS staff participated in the two-day Future of Water Summit, which brought together utility managers, engineers, data experts, and federal officials in furtherance of a Smart One Water paradigm.

7.9.3 Cardiff University

In 2022, BWS continued to build a collaboration with researchers from Cardiff University who have been helping water utilities in the United Kingdom (UK) study taste and odor issues. Cardiff University has been developing genomic methods of analysis that determine not only the presence of algal species, but also their ability to produce certain taste and odor compounds. BWS and Cardiff University held multiple discussions throughout 2022, which focused on a specific type of field analysis using eDNA filters that is coupled with two types of analysis. The first analysis uses next generation sequencing (NGS) to determine relative abundance of species presence to track changes in the algal communities over time. An additional analysis that uses RNA determines what portion of the cells present can produce the taste and odor compounds geosmin and 2-methylisoborneol.

In 2022, Cardiff University was awarded an Engineering and Physical Sciences Research Council grant and four Cardiff University researchers visited DEP and to demonstrate both field and lab eDNA analyses to BWS staff.

The results of this eDNA analysis will describe the relative abundance of bacterial species present in the samples collected at eight locations across New Croton and Muscoot reservoirs. Their findings will hopefully allow BWS to understand and implement appropriate source water and treatment actions to mitigate or prevent future taste and odor episodes.

7.9.4 Global Lake Ecological Observatory Network

The overall mission of the Global Lake Ecological Observatory Network (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. Additionally, GLEON offers online webinars and interactive training sessions each year. In November 2022, DEP staff participated in an interactive workshop using a simple model of lake primary productivity to generate forecasts. The workshop included exploration of how the use of different types of data at different temporal frequencies (e.g., daily, weekly) affects forecast accuracy. The material covered was from one of the Macrosystems EDDIE (Environmental Data-Driven Inquiry and Exploration) training modules. Information about GLEON research can be found at http://gleon.org/research/projects/.

7.9.5 Wadsworth Center for Laboratories and Research

Scientists from the DEP Water Quality & Innovation Directorate initiated collaboration with scientists at the NYSDOH Wadsworth Center for Laboratories and Research (NYSDOH) to further examine stool samples that had been submitted from NYC residents diagnosed with cryptosporidiosis. The goal was to identify the species, and genotypes where possible, in stool specimens from 2015 - 2018 and compare them to previous research on species and genotypes from watershed samples. Final data analysis was completed on the 547 specimens and a collaborative presentation was provided for the 2022 interagency annual Pathogen Technical Working Group meeting. Additionally, this research was submitted for publication to the American Society of Microbiology's Microbiology Spectrum journal in September 2022 and accepted in December – Identification and Evaluation of *Cryptosporidium* Species from New York City Cases of Cryptosporidiosis (2015-2018): a Watershed Perspective, K. Alderisio, K. Mergan, H. Moesner, S. Madison Antenucci (Alderisio et al. 2023).

References

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.

Alderisio, K. A., K. Mergan, H. Moesner, S. Madison Antenucci. 2023. Identification and Evaluation of *Cryptosporidium* Species from New York City Cases of Cryptosporidiosis (2015-2018): A Watershed Perspective. Microbiol. Spectr. 11(1). https://doi.org/10.1128/spectrum.03921-22

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 6/21/2021).

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

Chapra, S. C. 1997. Surface water-quality modeling, McGraw-Hill, New York.

Chowdhury, S., Champagne, P., McLellan, P.J. 2009. Models for predicting disinfection byproduct (DBP) formation in drinking waters: a chronological review. Sci. Tot. Environ., 407(14): 4189-4206.

Cole, T. M., and Wells, S. A. 2013. "CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.71." Department of Civil and Environmental Engineering, Portland State University, Portland, Oregon.

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

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

DEP. 2017. 2016 Watershed Water Quality Annual Report. New York City Department of Environmental Protection, Bureau of Water Supply, Valhalla, NY. 213 p.

DEP. 2018. 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. 2019. New York City Watershed Rules and Regulations. 1997, amended November 29, 2019. 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. https://www1.nyc.gov/assets/dep/downloads/pdf/watershed-protection/regulations/rules-and-regulations-of-the-nyc-water-supply.pdf

DEP. 2021. 2020 Watershed Water Quality Annual Report. New York City Department of Environmental Protection, Bureau of Water Supply, Valhalla, NY. 213 p.

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

Easton, Z.M. et al., 2008. Re-conceptualizing the soil and water assessment tool (SWAT) model to predict runoff from variable source areas. J. Hydrol., 348(3-4): 279-291.

Frei, A., R. Mukundan, J. Chen, R. Gelda, E. Owens, J. Gass, A. Ravindranath 2022. “A cascading bias correction method for global climate model simulated multi-year precipitation variability” Journal of Hydrometeorology 23(5): 697-713, DOI: 10.1175/JHM-D-21-0148.1

Gelda, R. K., and Effler, S. W. 2007. "Modeling Turbidity in a Water Supply Reservoir: Advancements and Issues." J. Environ. Eng., 133(2), 139-148.

Gelda, R. K., Effler, S. W., Peng, F., Owens, E. M., and Pierson, D. C. 2009. "Turbidity model for Ashokan Reservoir, New York: Case Study." J. Environ. Eng., 135(9), 885-895.

Gelda, R. K., Owens, E. M., and Effler, S. W. 1998. "Calibration, verification, and an application of a two-dimensional hydrothermal model [CE-QUAL-W2(t)] for Cannonsville Reservoir." Lake Reserv. Manage., 14(2-3), 186-196.

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

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.

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

Mayfield, J. and R. Van Dreason. 2019. Chloride Trends in West of Hudson Streams. Presented at NYC Watershed Science and Technical Conference, September 12, 2019. Saugerties, NY.

Moriasi, D.N. et al., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. Asabe, 50(3): 885-900.

National Academies of Sciences, Engineering, and Medicine (NASEM), 2020. *Review of the New York City Watershed Protection Program.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25851.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and water assessment tool theoretical documentation version 2009, Texas Water Resources Institute.

NRCS. 2004. National Engineering Handbook: Part 630—Hydrology. Chapter 9: Hydrologic Soil-Cover Complexes. United States Department of Agriculture-Natural Resources Conservation Service.

NYSDEC [New York State Department of Environmental Conservation]. 2019. Standard Operating Procedure: Biological Monitoring of Surface Waters in New York State. Division of Water. NYSDEC SOP-208_V21-1 Stream Biomonitoring 04/05/21. 159 p.

NYSDEC [New York State Department of Environmental Conservation]. 2022. 2022 Archived HABs Notices. https://www.dec.ny.gov/docs/water_pdf/habsarchive2022.pdf (accessed 5/10/2023).

Reckhow, D. A., C. D. Guzman, and M. Shakhawat (2023). "Report on Year 2 Field Studies - UMass-DEP Collaboration." Prepared by University of Massachusetts, Amherst.

Schneiderman, E.M. et al., 2007. Incorporating variable source area hydrology into a curve-number-based watershed model. Hydrol. Processes, 21(25): 3420-3430. DOI:10.1002/hyp.6556

Sebestyen, S.D., Boyer, E.W., Shanley, J.B., 2009. Responses of stream nitrate and dissolved organic carbon loadings to hydrological forcing and climate change in an upland forest of the northeast USA. J. Geophys. Res., 114(G2).

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 67(2):99.

Steenhuis, T.S., Winchell, M., Rossing, J., Zollweg, J.A., Walter, M.F., 1995. SCS runoff equation revisited for variable-source runoff areas. J. Irrigat. Drain. Eng., 121(3): 234-238.

Stoddard, J.L., D.S. Jeffries, A. Lukewille, T.A. Clair, P.J. Dillon, C.T. Driscoll, M. Forsius, M. Johannessen, J.S. Kahl, J.H. Kellogg, A. Kamp, D.T. Mannio, P.S. Murdoch, S. Patrick, A. Rebsdorf, B.L. Skjelkvale, M.P. Stainton, T. Traaen, K.E. Webster, J. Weiting, & A. Wilander. 1999. Regional trends in aquatic recovery from acidification in North America and Europe. Nature 401:575-578.

USDA. 1972. National engineering handbook, section 4: Hydrology. Washington, DC.

USDA- NRCS. 2012. Soil Survey Geographic (SSURGO) Database. Soil Survey Geographic Database (SSURGO) | Natural Resources Conservation Service (usda.gov) (accessed 7/10/23).

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]. 2006. Long Term 2 Enhanced Surface Water Treatment Rule. EPAHQ-2002-0039. Washington, D.C. http://www.federalregister.gov/a/06-4 (accessed 6/13/23).

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

Van Dreason, R. 2022. Salt (i.e., Chloride) Trends in the Croton System of the New York City Water Supply. Presented at NYC Watershed Science and Technical Conference, September 21, 2022. Tomkins Cove, NY.

Wolock, D. M., J. Fan and G. B. Lawrence, 1997. "Effects of basin size on low-flow stream chemistry and subsurface contact time in the Neversink River Watershed, New York." Hydrological Processes 11(9): 1273-1286.

Yang, Q., Zhang, X., 2016. Improving SWAT for simulating water and carbon fluxes of forest ecosystems. Sci. Tot. Environ., 569: 1478-1488.

Zhang, X., Izaurralde, R.C., Arnold, J.G., Williams, J.R., Srinivasan, R., 2013. Modifying the soil and water assessment tool to simulate cropland carbon flux: model development and initial evaluation. Sci. Tot. Environ., 463: 810-822.

Appendix A. 2022 Robotic Monitoring – Locations and Types

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

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

[1] Parameter codes: Temp = temperature; SpCon = Specific conductivity; Turb = Turbidity; Chl *a* = chlorophyll *a* fluorescence; BGA = blue green algae fluorescence.

Appendix B. Watershed Water Quality Operations Early Warning Remote Monitoring (EWRM) Sites

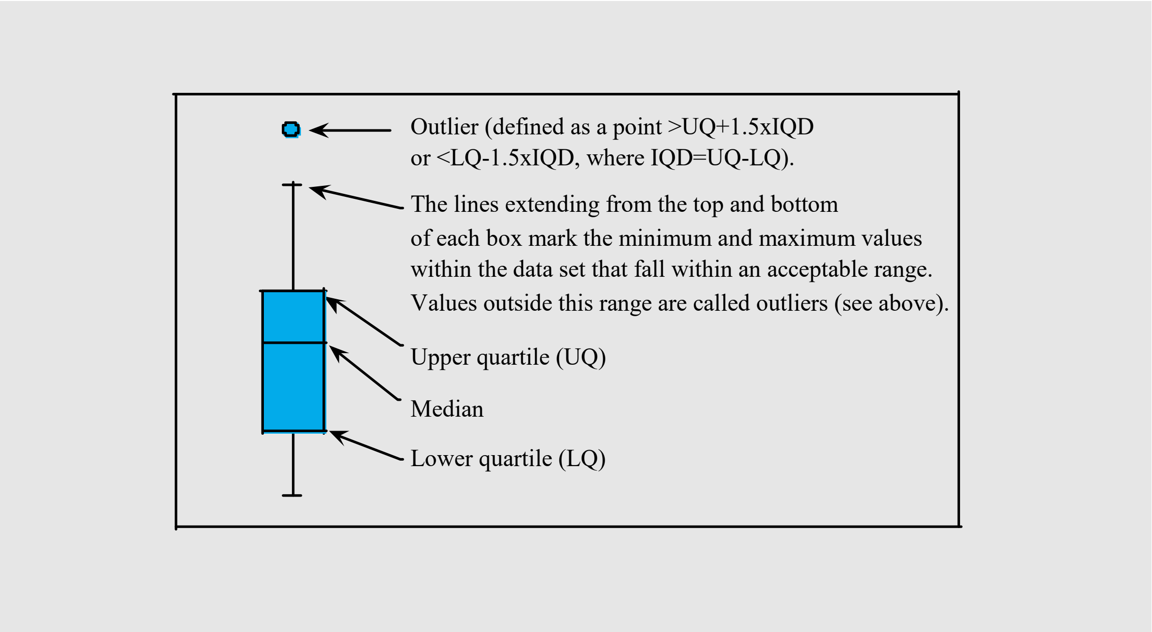
Site	Location	System	Water Type	Parameters
SRR1CM	Schoharie Intake Chamber	Catskill	Raw	Turbidity, pH, Temperature, Specific conductivity
SRR2CM	Shandaken Tunnel Outlet (STO)	Catskill	Raw	Turbidity, pH, Temperature, Specific conductivity
EARCM	Catskill Aqueduct	Catskill	Raw	Turbidity, pH, Temperature, Specific conductivity
EARATF	Catskill Aqueduct	Catskill	Raw/ Treated	Turbidity, pH, Temperature, Specific conductivity, Chlorine dioxide, Total Chlorine Residual
M-1	Ashokan Release Channel	Catskill	Raw	Turbidity
AEAP	Esopus Creek Upstream STO	Catskill	Raw	Turbidity
RDRRCM	Delaware Aqueduct at Rondout Effluent Chamber (REC)	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity
NRR2CM	Neversink Tunnel Outlet	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity
PRR2CM	East Delaware Tunnel Outlet	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity
WDTOCM	West Delaware Tunnel Outlet	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity
RR1-RR4	REC Elevation Taps	Delaware	Raw	Turbidity
CDIS4-DEL	Cat/Del Interconnect at Shaft 4 (Delaware)	Delaware	Raw	Turbidity
CDIS4-CAT	Cat/Del Interconnect at Shaft 4 (Catskill)	Catskill	Raw	Turbidity, pH, Temperature, Specific conductivity, Chlorine Dioxide, Total Chlorine Residual
CDIS4- Combined	Cat/Del Interconnect at Shaft 4 (Catskill)	Catskill	Raw	Chlorine Dioxide
CWB1.5	West Branch Reservoir	Delaware	Raw	Pump used to collect grab samples.

Site	Location	System	Water Type	Parameters
DEL9	Delaware Shaft 9	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity, Total Chlorine Residual[1], Dechlorination analyzer[1], Dissolved oxygen[1]
DEL10	Delaware Shaft 10	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity, Elevation
DEL17	Delaware Shaft 17	Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity, Total Chlorine Residual[1], Dechlorination analyzer[1], Dissolved oxygen[1]
DEL18DT	Delaware Shaft 18 Downtake	Catskill/ Delaware	Raw	Turbidity, pH, Temperature, Specific conductivity, Flow, Elevation, Fish biomonitoring system
DEL19LAB	Delaware Shaft 19 Lab	Catskill/ Delaware	Pre-Treated	Turbidity, pH, Temperature, Specific conductivity, Free Chlorine Residual, Fluoride Residual
DELSFBLAB	Delaware South Forebay Lab	Catskill/ Delaware	Pre-Treated	Turbidity, pH, Temperature, Specific conductivity, Free Chlorine Residual, Fluoride Residual
CCCLAB	Catskill Connection Chamber Lab	Catskill/ Delaware	Pre-Treated	Turbidity, pH, Temperature, Specific conductivity, Free Chlorine Residual, Fluoride Residual
CROFALLSVC	Croton Falls Valve Chamber	Croton	Raw	Turbidity
CROSSRVVC	Cross River Valve Chamber	Croton	Raw	Turbidity
CATALUM	Catskill Alum Plant	Catskill	Raw	Turbidity
CATIC	Catskill Influent Chamber	Catskill	Raw	pH, Temperature
CROGH	CLGH Raw Water	Croton	Raw	Turbidity, pH, Temperature, Specific conductivity, Dissolved oxygen, Fish biomonitoring system
CRO1T	New Croton Dam	Croton	Raw	Turbidity, pH, Temperature, Specific conductivity, Dissolved oxygen
CRO1B	New Croton Dam	Croton	Raw	Turbidity, pH, Temperature, Specific conductivity, Dissolved oxygen
CRO183	Croton Lake Gatehouse	Croton	Raw	Turbidity, pH, Temperature, Specific conductivity, Dissolved oxygen
CRO163	Croton Lake Gatehouse	Croton	Raw	Turbidity, pH, Temperature, Specific conductivity, Dissolved oxygen

Site	Location	System	Water Type	Parameters
CRO143	Croton Lake Gatehouse	Croton	Raw	Turbidity, pH, Temperature, Specific conductivity, Dissolved oxygen

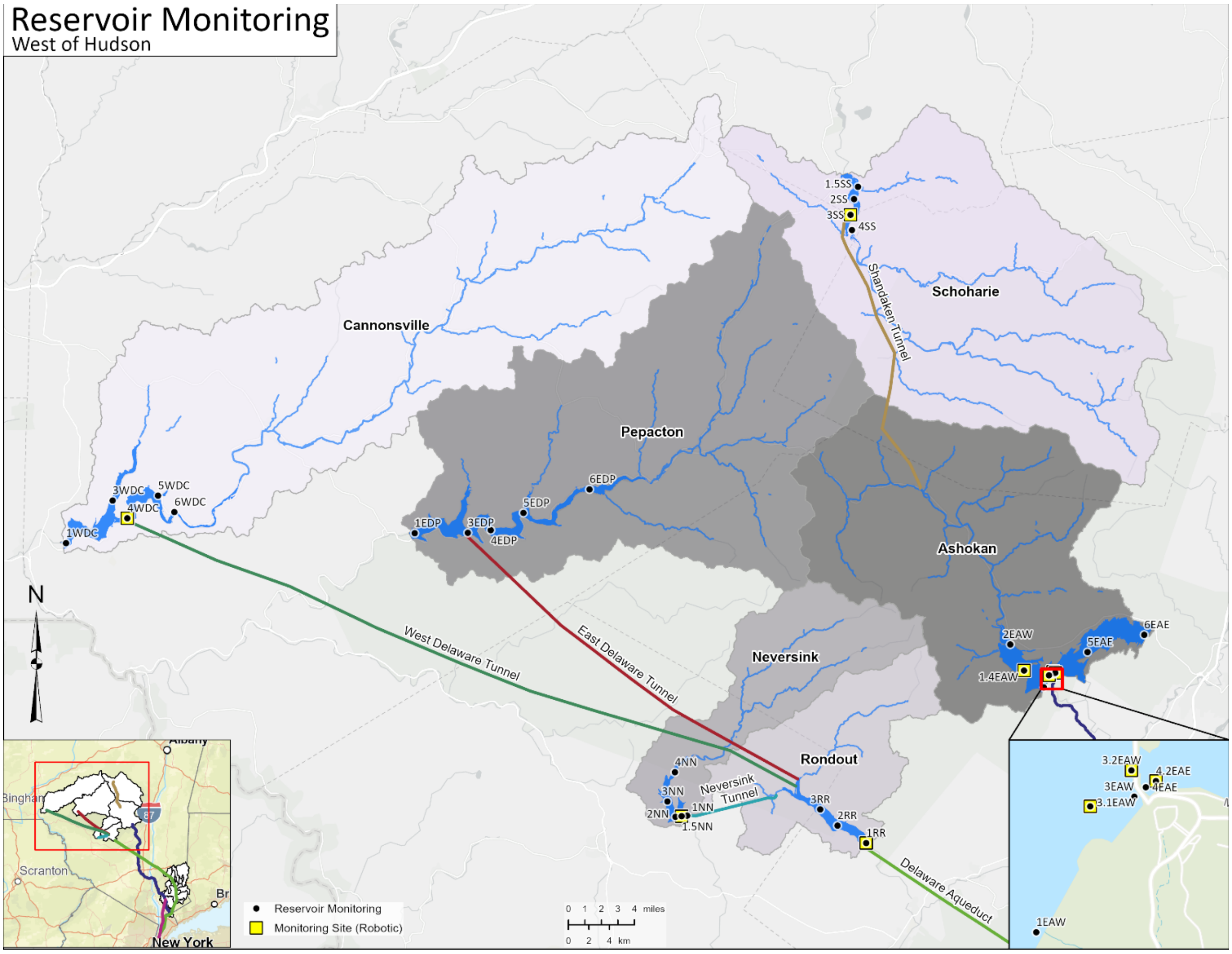
[1] Only operational during chlorine treatment.

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

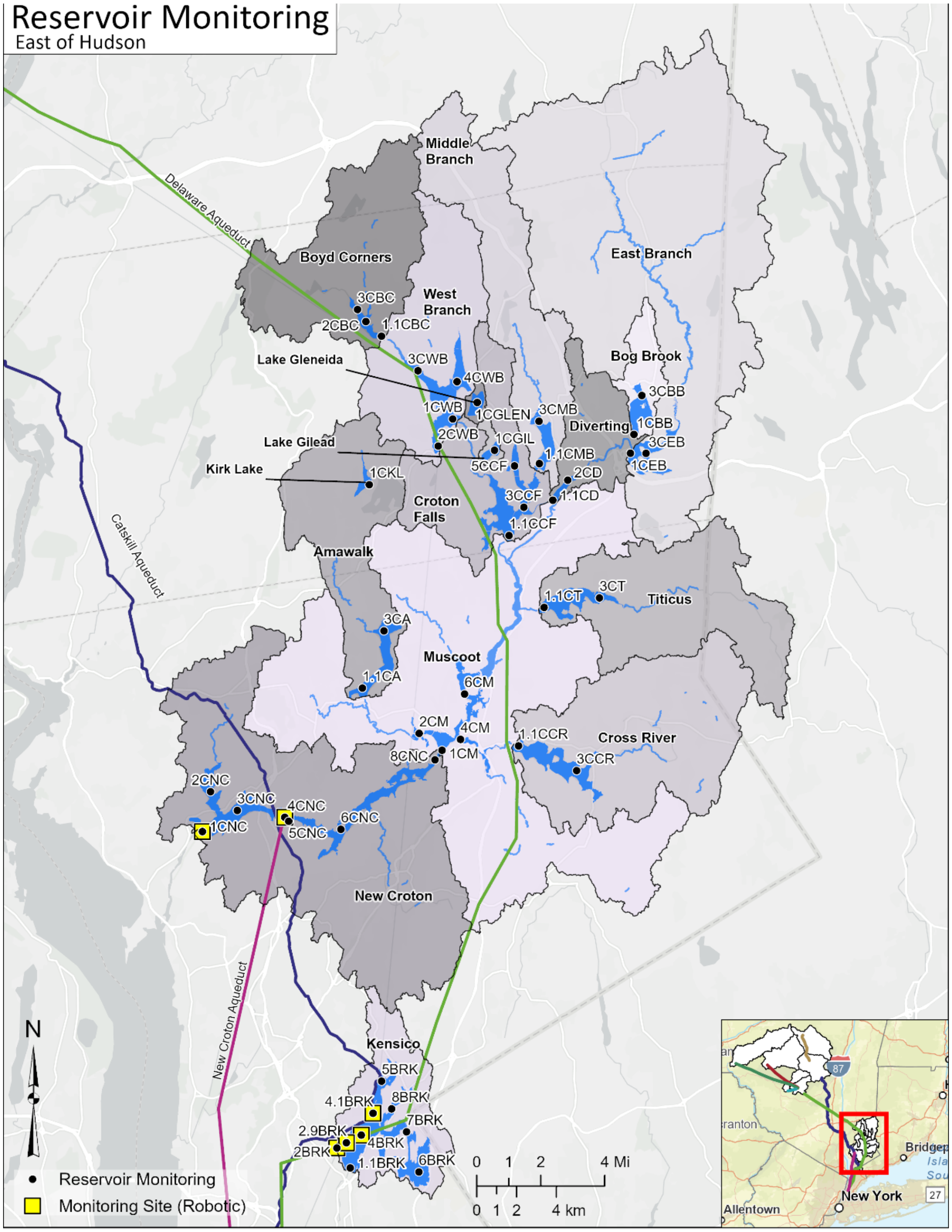


Water quality data are often left-censored in that many analytical results occur below the instrument's detection limit. Substituting some value for the detection limit results, and then using parametric measures such as means and standard deviations, will often produce erroneous estimates. In this report 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.

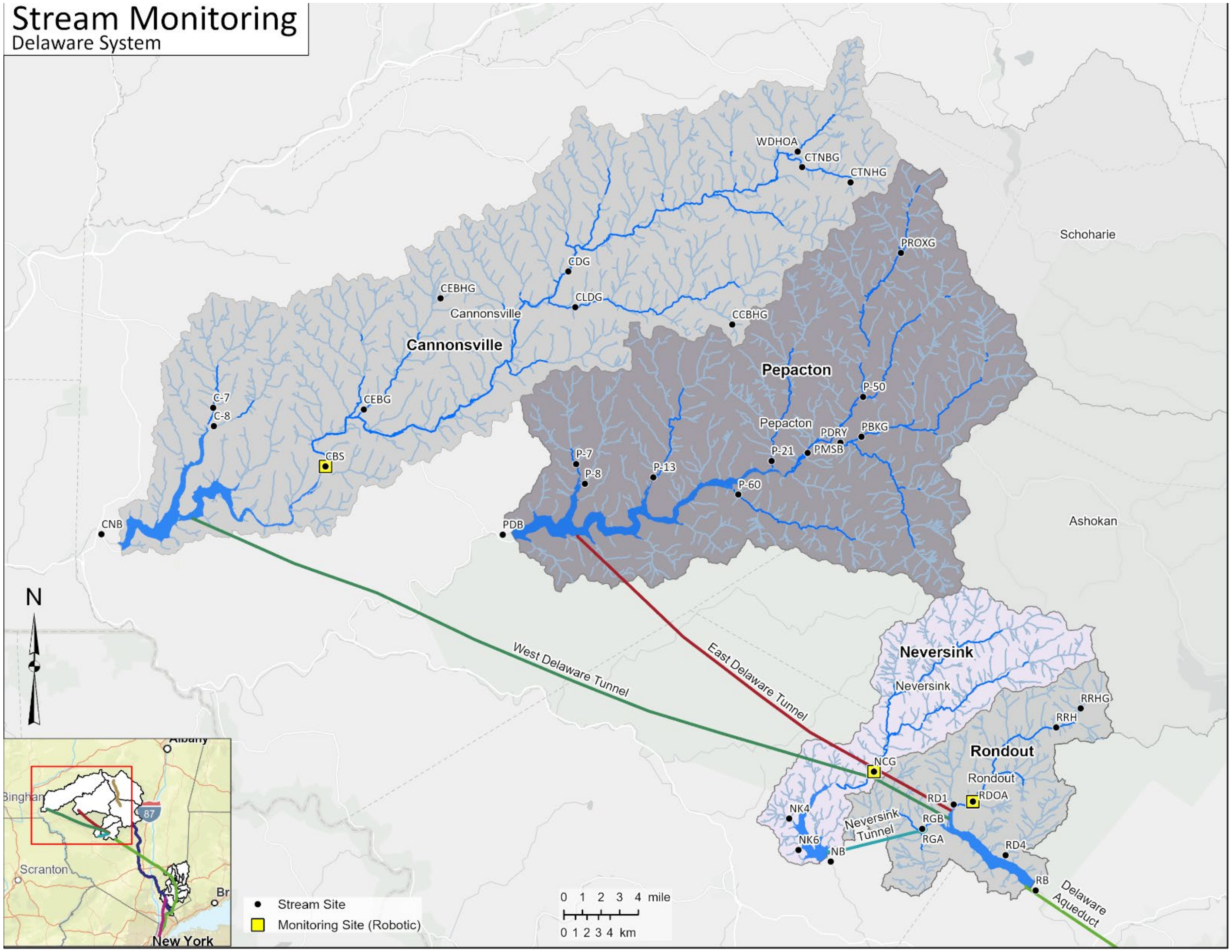
Appendix D. Sampling Locations



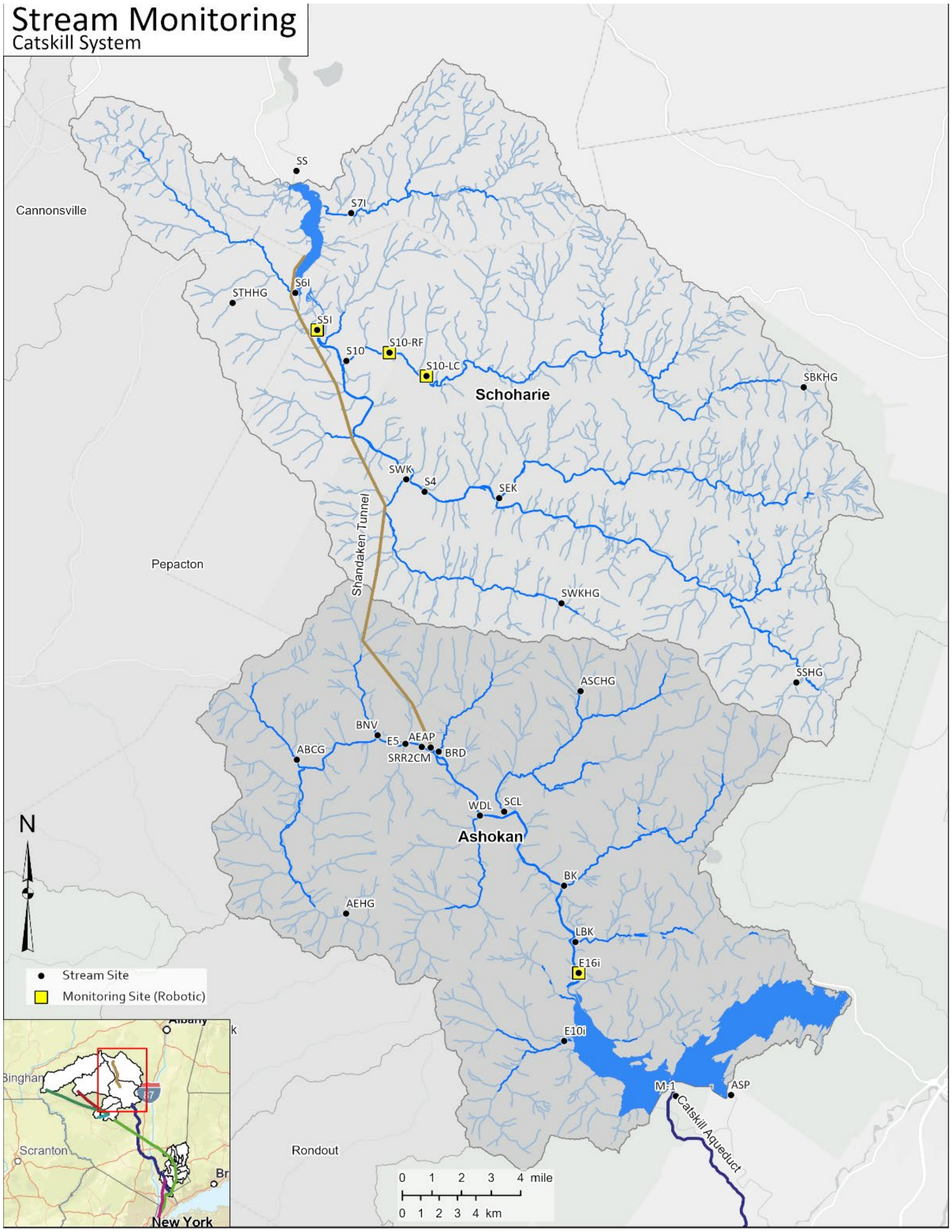
Appendix Figure 1 WOH reservoir monitoring sites.



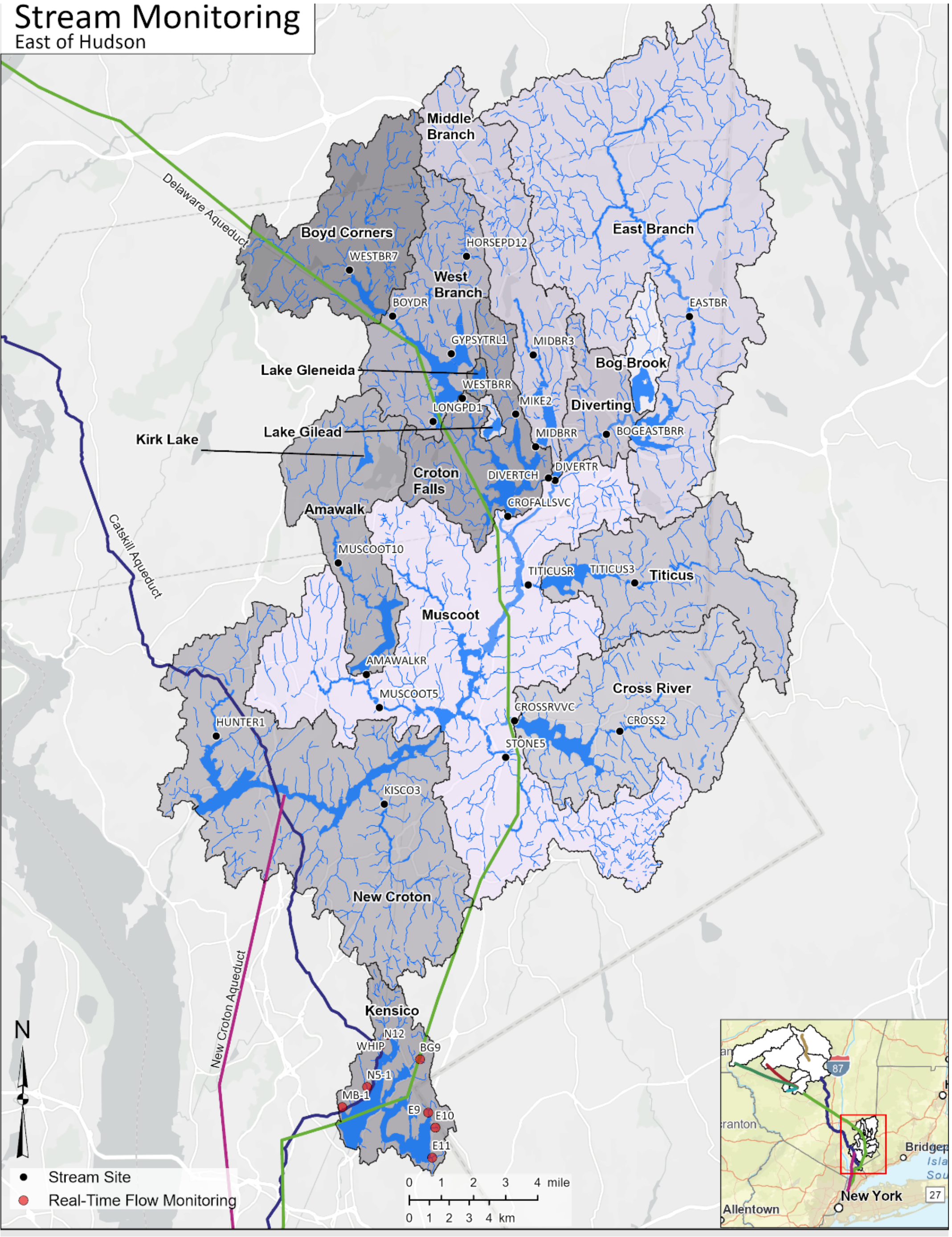
Appendix Figure 2 EOH reservoir monitoring sites.



Appendix Figure 3 Delaware System stream monitoring sites.

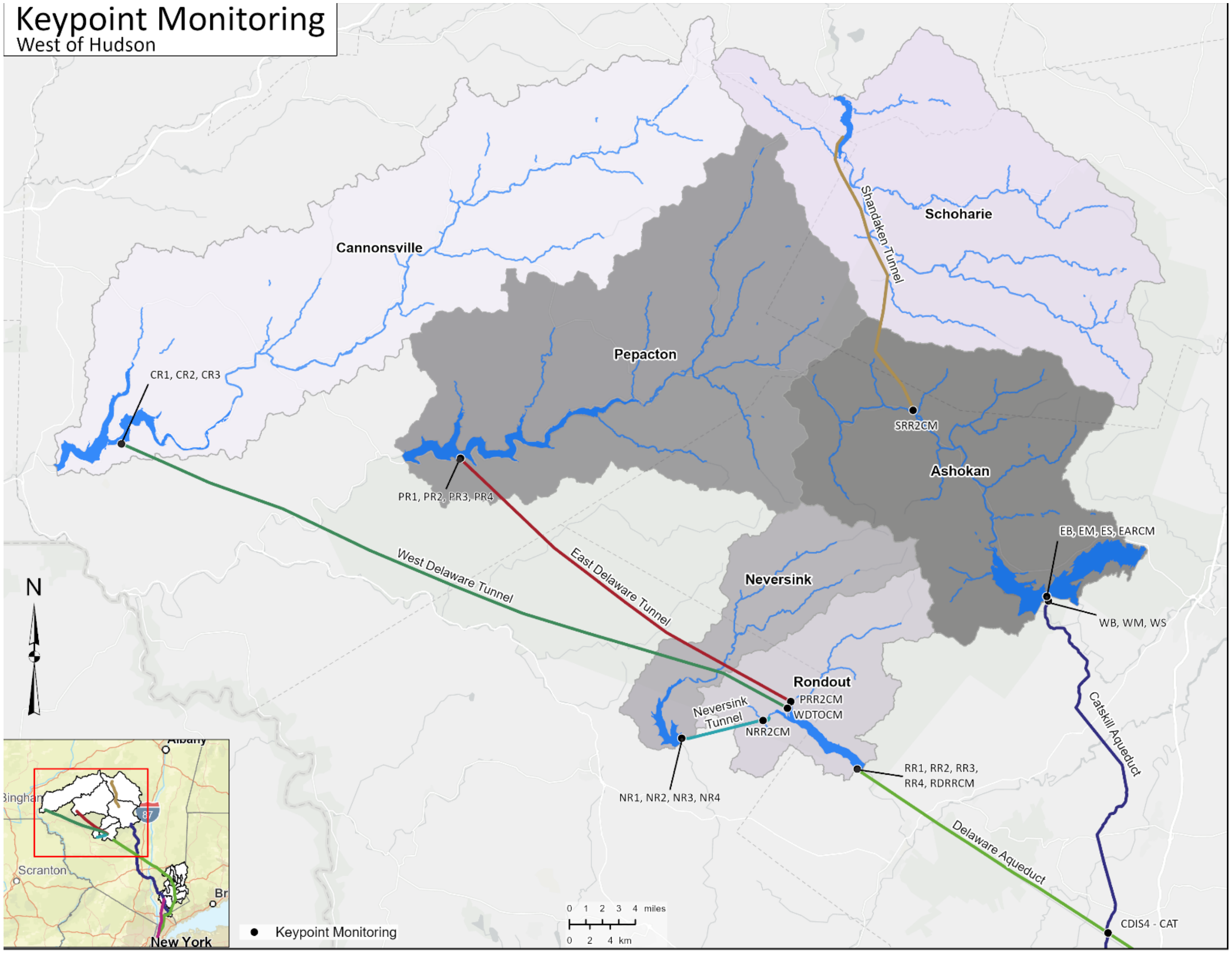


Appendix Figure 4 Catskill System stream monitoring sites.

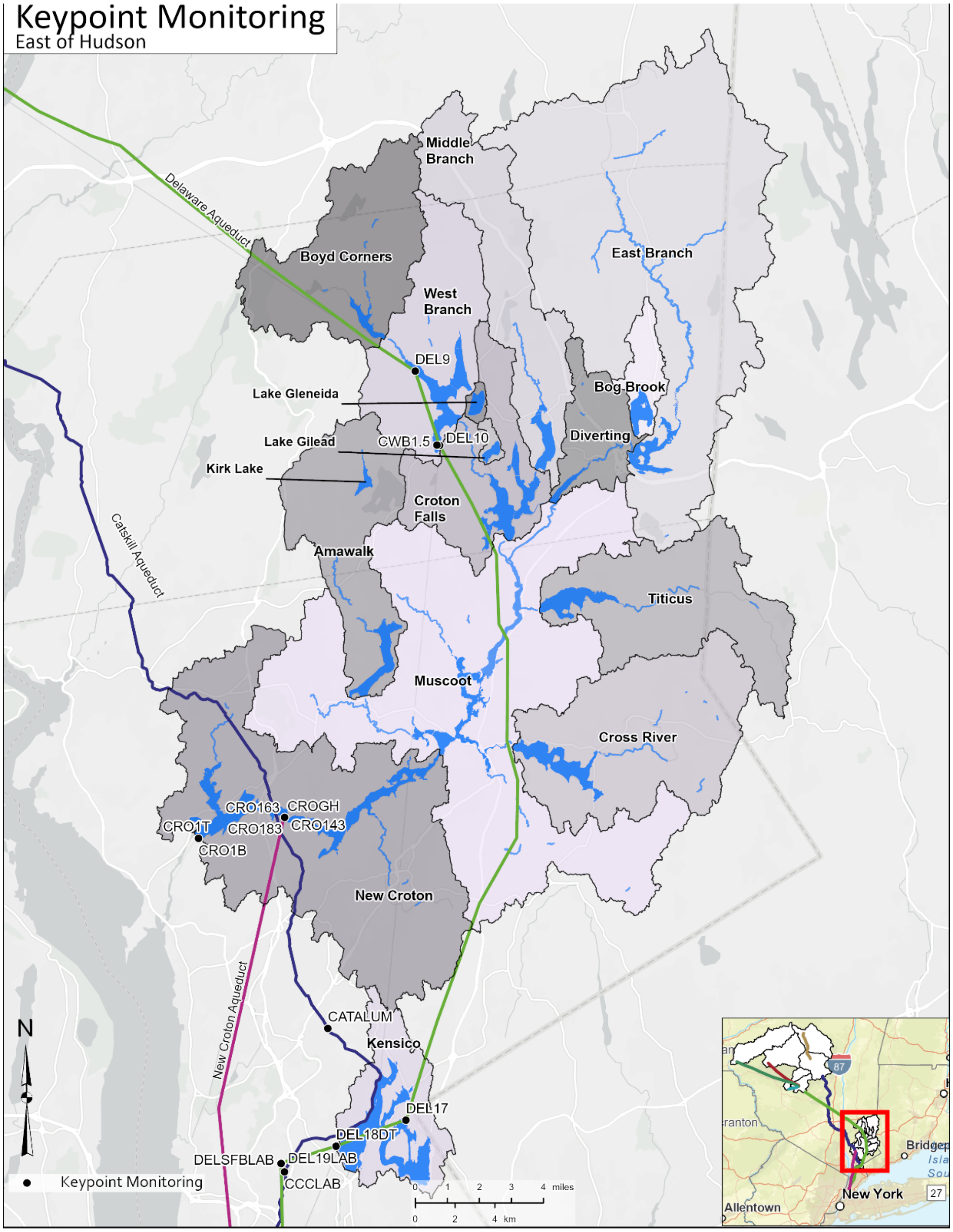


‘‘

Appendix Figure 5 EOH stream monitoring sites.



Appendix Figure 6 WOH aqueduct keypoint monitoring sites.



Appendix Figure 7 EOH aqueduct keypoint monitoring sites.

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

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
Amawalk	A (2400, 5000)	Apr-22	5	0	E32	0
		May-22	5	0	E30	0
		Jun-22	5	0	>=E5	0
		Jul-22	5	0	E10	0
		Aug-22	5	0	<10	0
		Sep-22	5	0	<10	0
		Oct-22	5	0	E10	0
		Nov-22	5	0	E20	0
Bog Brook	AA (50, 240).	Apr-22	5	0	>=E4	0
		May-22	5	0	E5	0
		Jun-22	5	0	E10	0
		Jul-22	5	0	E10	0
		Aug-22	5	0	<10	0
		Sep-22	5	0	E30	0
		Oct-22	5	0	E30	20
		Nov-22	5	0	E20	0
Boyd Corners	AA (50, 240)	Apr-22	7	0	E30	14
		May-22	7	0	E95	0
		Jun-22	7	0	>=E50	0
		Jul-22	7	0	E50	14
		Aug-22	7	0	E50	14
		Sep-22	7	0	E150	29
		Oct-22	6	0	E125	33
		Nov-22	0	0	No Samples	
Croton Falls	A/AA (50, 240).	Apr-22	8	0	E32	12
		May-22	8	0	82	38
		Jun-22	8	0	E20	0

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
		Jul-22	8	0	E60	12
		Aug-22	8	0	<50	0
		Sep-22	8	0	E200	25
		Oct-22	8	0	E100	50
		Nov-22	8	0	E40	12
Cross River	A/AA (50, 240)	Apr-22	6	0	>=E25	0
		May-22	6	0	E5	0
		Jun-22	6	0	E20	0
		Jul-22	6	0	E4	0
		Aug-22	6	0	E10	0
		Sep-22	6	0	<20	0
		Oct-22	6	0	E20	0
		Nov-22	6	0	E50	0
Diverting	AA (50, 240)	Apr-22	5	0	>=E76	0
		May-22	5	0	E40	0
		Jun-22	5	0	>=840	80
		Jul-22	5	0	8200	100
		Aug-22	5	0	E100	0
		Sep-22	5	0	E400	60
		Oct-22	5	0	E250	60
		Nov-22	5	0	E250	60
East Branch	AA (50, 240).	Apr-22	6	0	>=E22	0
		May-22	6	0	E15	0
		Jun-22	6	0	E22	17
		Jul-22	6	0	E10	0
		Aug-22	6	0	<10	0
		Sep-22	6	0	E90	17
		Oct-22	5	0	E10	0
		Nov-22	5	0	E40	0
Lake Gilead	A (2400, 5000)	Apr-22	5	0	<5	0
		May-22	5	0	E10	0
		Jun-22	5	0	<10	0

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
		Jul-22	5	0	<20	0
		Aug-22	5	0	E20	0
		Sep-22	5	0	E140	0
		Oct-22	5	0	<20	0
		Nov-22	5	0	E10	0
Lake Gleneida	AA (50, 240)	Apr-22	5	0	<5	0
		May-22	5	0	<5	0
		Jun-22	5	0	E20	0
		Jul-22	5	0	<20	0
		Aug-22	5	0	E20	0
		Sep-22	5	0	<100	0
		Oct-22	5	0	<20	0
		Nov-22	5	0	<10	0
Kirk Lake	B (2400, 5000)	Apr-22	5	0	E20	0
		May-22	5	0	E35	0
		Jun-22	5	0	E40	0
		Jul-22	5	0	>=<20	0
		Aug-22	5	0	>=E20	0
		Sep-22	5	0	E20	0
		Oct-22	5	0	E20	0
		Nov-22	5	0	<10	0
Muscoot	A (2400, 5000).	Apr-22	7	0	E120	0
		May-22	7	0	E40	0
		Jun-22	7	0	>=640	0
		Jul-22	7	0	E120	0
		Aug-22	7	0	E20	0
		Sep-22	7	0	E20	0
		Oct-22	7	0	E100	0
		Nov-22	7	0	E50	0
Middle Branch	A (2400, 5000)	Apr-22	5	0	E52	0
		May-22	5	0	E20	0

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF	Median Total Coliform (coliforms $100mL^{-1}$)	Percentage > Standard
		Jun-22	5	0	>=<20	0
		Jul-22	3	0	<50	0
		Aug-22	5	0	>=E50	0
		Sep-22	5	0	E50	0
		Oct-22	5	0	E100	0
		Nov-22	5	0	E100	0
Titicus	AA (50, 240)	Apr-22	5	0	E8	0
		May-22	5	0	E20	0
		Jun-22	5	0	E90	0
		Jul-22	5	0	<10	0
		Aug-22	5	0	E50	0
		Sep-22	5	0	E40	0
		Oct-22	5	0	E20	0
		Nov-22	5	0	E70	0
Cannonsville	A/AA (50, 240)	Apr-22	15	0	23	0
		May-22	15	0	E4	0
		Jun-22	15	0	E10	0
		Jul-22	14	0	<20	0
		Aug-22	13	0	<50	23
		Sep-22	12	0	<20	8
		Oct-22	12	0	E20	0
		Nov-22	12	0	<10	8
Pepacton	A/AA (50, 240).	Apr-22	16	0	E1	0
		May-22	16	0	3	0
		Jun-22	16	0	E4	0
		Jul-22	16	0	>=<20	12
		Aug-22	14	0	<10	21
		Sep-22	14	0	20	0
		Oct-22	14	0	18	0
		Nov-22	14	0	8	0
Neversink	AA (50, 240)	Apr-22	12	1	E4	0
		May-22	13	0	E12	0

Reservoir	Class & Standard (Median, Value not > 20% of sample)	Collection Date	N	CONF	Median Total Coliform (coliforms 100mL^{-1})	Percentage > Standard
		Jun-22	12	0	<4	0
		Jul-22	12	0	E5	0
		Aug-22	11	0	<20	9
		Sep-22	11	0	5	9
		Oct-22	11	0	E40	0
		Nov-22	11	0	E50	9
Schoharie	AA (50, 240).	Apr-22	12	0	115	25
		May-22	12	0	E20	0
		Jun-22	11	0	E25	0
		Jul-22	10	0	E40	0
		Aug-22	9	0	E75	0
		Sep-22	9	0	E80	11
		Oct-22	11	0	270	73
		Nov-22	11	0	E170	27

Analysis Note: The total of the N and CONF for each table row represents the total number samples analyzed. CONF indicates the number of samples with confluent growth where counts are indeterminate. Median calculations are based on “N” and exclude these CONF samples.

Notes: The reservoir class is defined by 6 NYCRR Chapter X, Subchapter B. For those reservoirs that have dual designations, the higher standard was applied. 6NYCRR Part 703 requires a minimum of five samples per month. Both the median value and >20% of the total coliform counts for a given month need to exceed the stated value for a reservoir to exceed the standard. Codes associated with data reporting include the following: E: Estimated count based on non-ideal plate; >=: plate count may be biased low based on heavy growth; >: observed count replaced with dilution-based value; <: below detection limit.

Appendix F. Phosphorus Restricted Basin Assessment Methodology

A phosphorus restricted basin is defined in the New York City Watershed Rules & Regulations (DEP 2019), 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 2019). 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 F Table 1 provides the annual geometric mean for the past six years.

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

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

Appendix F. 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	2017 (μg L^{-1})	2018 (μg L^{-1})	2019 (μg L^{-1})	2020 (μg L^{-1})	2021 (μg L^{-1})	2022 (μg L^{-1})
Non-Source Waters (Delaware System)						
Cannonsville Reservoir	15.4	14.3	15.6	14.3	15.3	17.3
Pepacton Reservoir	10.3	10.1	9.8	9.4	9.4	8.8
Neversink Reservoir	7.3	6.5	6.5	6.8	7.0	7.2
Non-Source Waters (Catskill System)						
Schoharie Reservoir	12.2	14.9	12.3	9.9	18.1	14.9
Non-Source Waters (Croton System)						
Amawalk Reservoir	26.3	25.4	17.3	NS	NS	26.5
Bog Brook Reservoir	27.8	19.4	14.1	NS	NS	20.7
Boyd Corners Reservoir	15.1	14.0	11.5	11.2	14.0	14.9
Diverting Reservoir	31.6	28.7	23.2	NS	43.3	35.2
East Branch Reservoir	25.1	27.5	21.6	NS	NS	25.3
Middle Branch Reservoir	28.4	29.4	18.3	NS	NS	29.3
Muscoot Reservoir	36.5	30.6	28.9	NS	40.2	34.6
Titicus Reservoir	25.2	25.0	23.1	NS	NS	28.4
Lake Gleneida	25.5	21.5	14.9	NS	NS	23.9
Lake Gilead	33.6	32.7	20.5	NS	NS	45.8
Kirk Lake	23.3	20.9	18.4	NS	NS	26.9
Source Waters (all systems)						
Ashokan West Basin Reservoir	8.2	8.3	7.8	7.8	9.9	11.4
Ashokan East Basin Reservoir	8.1	7.6	7.2	7.0	7.0	9.1
Rondout Reservoir	9.0	8.1	7.8	7.3	8.1	8.6
West Branch Reservoir	14.2	11.8	9.5	10.0	11.3	11.8
Cross River Reservoir	23.2	21.1	16.8	19.7	20.9	23.6
Croton Falls Reservoir	23.2	21.5	15.3	21.5	20.5	24.4
Kensico Reservoir	8.8	7.9	6.8	7.7	8.4	8.5
New Croton Reservoir	22.5	26.2	19.5	NS	NS	24.2

NS: "Insufficient Data" - Total phosphorus sampling was reduced or eliminated during 2020 and 2021 because of the COVID-19 pandemic resulting in no or a limited number of samples for the geometric mean calculation.

Appendix G. Comparison of Reservoir Water Quality Results to Benchmarks

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
Non-Source Waters (Delaware System)								
Cannonsville Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	108	65	60	NA	20	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	107	6	6	NA	8	
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	108	0	0	NA	3	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	108	23	21	0.3	0.32	KM
	Ammonia (as N) (mg L^{-1})	0.1	107	1	1	0.05	0.02	ROS
	Fecal Coliform (coliforms 100mL^{-1})	20	108	2	2	NA	3	ROS
	Turbidity (NTU)	5	108	29	27	NA	4.2	
	Total suspended solids (mg L^{-1})	8	48	0	0	5	2.5	KM
	Alkalinity (mg L^{-1})	NA	16	0	0	>=10	17.9	
	Dissolved Organic Carbon (mg L^{-1})	4	108	0	0	3	1.8	
	Sulfate (as SO4) (mg L^{-1})	15	16	0	0	10	3.9	
	pH (SU)	6.5-8.5	93	13	14	NA	7.28	
	Dissolved sodium (mg L^{-1})	16	16	0	0	3	8.3	
	Chloride (mg L^{-1})	12	16	10	62	8	13.0	
	Total dissolved solids (mg L^{-1})[3]		108	0	0		66	
	Chlorophyll *a* (µg L^{-1})	12	38	4	11	7	6.8	
	Total phytoplankton (ASU mL^{-1})	2000	55	0	0	NA	248	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	55	0	0	NA	113	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	55	0	0	NA	55	KM
Pepacton Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	120	17	14	NA	10	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	120	1	1	NA	5	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	120	1	1	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	120	0	0	0.3	0.18	KM
	Ammonia (as N) (mg L^{-1})	0.1	118	0	0	0.05	0.01	ROS
	Fecal Coliform (coliforms 100mL^{-1})	20	120	2	2	NA	2	ROS
	Turbidity (NTU)	5	120	7	6	NA	1.8	
	Total suspended solids (mg L^{-1})	8	60	0	0	5	1.3	KM
	Alkalinity (mg L^{-1})	NA	21	0	0	>=10	13.7	
	Dissolved Organic Carbon (mg L^{-1})	4	120	0	0	3	1.7	
	Sulfate (as SO4) (mg L^{-1})	15	21	0	0	10	2.8	
	pH (SU)	6.5-8.5	120	13	11	NA	7.15	
	Dissolved sodium (mg L^{-1})	16	21	0	0	3	5.1	
	Chloride (mg L^{-1})	12	21	0	0	8	8.2	
	Total dissolved solids (mg L^{-1})[3]		120	0	0		48	
	Chlorophyll *a* (µg L^{-1})	12	39	0	0	7	5.2	
	Total phytoplankton (ASU mL^{-1})	2000	59	0	0	NA	260	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	59	1	2	NA	121	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	59	0	0	NA	50	

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
Neversink Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	71	0	0	NA	8	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	71	0	0	NA	5	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	71	0	0	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	71	0	0	0.3	0.18	KM
	Ammonia (as N) (mg L^{-1})	0.1	71	0	0	0.05	0.01	ROS
	Fecal Coliform (coliforms 100mL^{-1})	20	70	4	6	NA	6	KM
	Turbidity (NTU)	5	102	1	1	NA	1.5	
	Total suspended solids (mg L^{-1})	8	24	0	0	5	1.3	KM
	Alkalinity (mg L^{-1})	NA	10	0	0	>=10	3.9	
	Dissolved Organic Carbon (mg L^{-1})	4	102	0	0	3	2.0	
	Sulfate (as SO4) (mg L^{-1})	15	10	0	0	10	2.1	
	pH (SU)	6.5-8.5	71	48	68	NA	6.32	
	Dissolved sodium (mg L^{-1})	16	10	0	0	3	2.1	
	Chloride (mg L^{-1})	12	10	0	0	8	3.6	
	Total dissolved solids (mg L^{-1})[3]		102	0	0		20	
	Chlorophyll *a* (µg L^{-1})	12	24	0	0	7	3.4	
	Total phytoplankton (ASU mL^{-1})	2000	40	0	0	NA	169	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	40	0	0	NA	93	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	40	0	0	NA	41	KM
Non-Source Waters (Catskill System)								
Schoharie Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	85	42	49	NA	19	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	66	0	0	NA	6	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	61	0	0	NA	3	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	61	0	0	0.3	0.15	KM
	Ammonia (as N) (mg L^{-1})	0.1	61	0	0	0.05	0.03	KM
	Fecal Coliform (coliforms 100mL^{-1})	20	85	16	19	NA	14	KM
	Turbidity (NTU)	5	85	68	80	NA	17.6	
	Total suspended solids (mg L^{-1})	8	85	28	33	5	10.5	KM
	Alkalinity (mg L^{-1})	NA	9	0	0	>=10	19.8	
	Dissolved Organic Carbon (mg L^{-1})	4	84	0	0	3	2.2	
	Sulfate (as SO4) (mg L^{-1})	15	9	0	0	10	3.2	
	pH (SU)	6.5-8.5	76	2	3	NA	7.15	
	Dissolved sodium (mg L^{-1})	16	9	0	0	3	6.2	
	Chloride (mg L^{-1})	12	9	1	11	8	9.7	
	Total dissolved solids (mg L^{-1})[3]		85	0	0		53	
	Chlorophyll *a* (µg L^{-1})	12	32	0	0	7	3.2	
	Total phytoplankton (ASU mL^{-1})	2000	45	0	0	NA	101	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	45	0	0	NA	51	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	45	0	0	NA	25	KM

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
Non-Source Waters (Croton System)								
Amawalk Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	40	36	90	NA	32	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		C19
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		C19
	Fecal Coliform (coliforms 100mL^{-1})	20	40	1	2	NA	6	ROS
	Turbidity (NTU)	5	0			NA		C19
	Total suspended solids (mg L^{-1})	8	0			5		C19
	Alkalinity (mg L^{-1})	NA	0			>=40		C19
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		C19
	Sulfate (as SO4) (mg L^{-1})	25	0			15		C19
	pH (SU)	6.5-8.5	40	5	12	NA	7.66	
	Dissolved sodium (mg L^{-1})	20	0			15		C19
	Chloride (mg L^{-1})	40	0			30		C19
	Total Dissolved Solids	175	0			150		C19
	Chlorophyll *a* (µg L^{-1})	15	0			10		C19
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		C19
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19
Bog Brook Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	16	14	88	NA	23	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		C19
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		C19
	Fecal Coliform (coliforms 100mL^{-1})	20	40	1	2	NA	4	ROS
	Turbidity (NTU)	5	0			NA		C19
	Total suspended solids (mg L^{-1})	8	0			5		C19
	Alkalinity (mg L^{-1})	NA	0			>=40		C19
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		C19
	Sulfate (as SO4) (mg L^{-1})	25	0			15		C19
	pH (SU)	6.5-8.5	24	4	17	NA	7.81	
	Dissolved sodium (mg L^{-1})	20	0			15		C19
	Chloride (mg L^{-1})	40	0			30		C19
	Total Dissolved Solids	175	0			150		C19
	Chlorophyll *a* (µg L^{-1})	15	0			10		C19
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		C19
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
Boyd Corners Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	20	9	45	NA	15	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	20	0	0	NA	4	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	20	0	0	NA	<2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	20	0	0	0.3	0.01	ROS
	Ammonia (as N) (mg L^{-1})	0.1	20	0	0	0.05	<0.02	ROS
	Fecal Coliform (coliforms $100mL^{-1}$)	20	48	1	2	NA	2	ROS
	Turbidity (NTU)	5	20	0	0	NA	1.4	
	Total suspended solids (mg L^{-1})	8	6	0	0	5	2.0	
	Alkalinity (mg L^{-1})	NA	6	0	0	>=40	37.2	
	Dissolved Organic Carbon (mg L^{-1})	7	20	0	0	6	3.8	
	Sulfate (as SO4) (mg L^{-1})	25	6	0	0	15	5.8	
	pH (SU)	6.5-8.5	20	2	10	NA	7.40	
	Dissolved sodium (mg L^{-1})	20	6	6	100	15	24.8	
	Chloride (mg L^{-1})	40	6	6	100	30	41.9	
	Total dissolved solids (mg L^{-1})[3]		20	0	0		149	
	Chlorophyll *a* (µg L^{-1})	15	7	0	0	10	6.7	
	Total phytoplankton (ASU mL^{-1})	2000	7	0	0	NA	794	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	7	1	14	NA	507	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	7	0	0	NA	140	KM
Diverting Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	40	40	100	NA	35	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		C19
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		C19
	Fecal Coliform (coliforms $100mL^{-1}$)	20	40	5	12	NA	16	KM
	Turbidity (NTU)	5	0			NA		C19
	Total suspended solids (mg L^{-1})	8	0			5		C19
	Alkalinity (mg L^{-1})	NA	0			>=40		C19
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		C19
	Sulfate (as SO4) (mg L^{-1})	25	0			15		C19
	pH (SU)	6.5-8.5	40	1	2	NA	7.73	
	Dissolved sodium (mg L^{-1})	20	0			15		C19
	Chloride (mg L^{-1})	40	0			30		C19
	Total Dissolved Solids	175	0			150		C19
	Chlorophyll *a* (µg L^{-1})	15	0			10		C19
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		C19
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
East Branch Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	24	22	92	NA	27	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		C19
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		C19
	Fecal Coliform (coliforms 100mL^{-1})	20	46	1	2	NA	3	KM
	Turbidity (NTU)	5	0			NA		C19
	Total suspended solids (mg L^{-1})	8	0			5		C19
	Alkalinity (mg L^{-1})	NA	0			>=40		C19
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		C19
	Sulfate (as SO4) (mg L^{-1})	25	0			15		C19
	pH (SU)	6.5-8.5	24	1	4	NA	7.44	
	Dissolved sodium (mg L^{-1})	20	0			15		C19
	Chloride (mg L^{-1})	40	0			30		C19
	Total Dissolved Solids	175	0			150		C19
	Chlorophyll *a* (µg L^{-1})	15	0			10		C19
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		C19
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19
Middle Branch Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	38	38	100	NA	34	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		C19
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		C19
	Fecal Coliform (coliforms 100mL^{-1})	20	38	0	0	NA	3	KM
	Turbidity (NTU)	5	0			NA		C19
	Total suspended solids (mg L^{-1})	8	0			5		C19
	Alkalinity (mg L^{-1})	NA	0			>=40		C19
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		C19
	Sulfate (as SO4) (mg L^{-1})	25	0			15		C19
	pH (SU)	6.5-8.5	38	5	13	NA	7.57	
	Dissolved sodium (mg L^{-1})	20	0			15		C19
	Chloride (mg L^{-1})	40	0			30		C19
	Total Dissolved Solids	175	0			150		C19
	Chlorophyll *a* (µg L^{-1})	15	0			10		C19
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		C19
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
Muscoot Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	56	56	100	NA	37	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		C19
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		C19
	Fecal Coliform (coliforms 100mL^{-1})	20	56	3	5	NA	7	KM
	Turbidity (NTU)	5	0			NA		C19
	Total suspended solids (mg L^{-1})	8	0			5		C19
	Alkalinity (mg L^{-1})	NA	0			>=40		C19
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		C19
	Sulfate (as SO4) (mg L^{-1})	25	0			15		C19
	pH (SU)	6.5-8.5	57	0	0	NA	7.50	
	Dissolved sodium (mg L^{-1})	20	0			15		C19
	Chloride (mg L^{-1})	40	0			30		C19
	Total dissolved solids (mg L^{-1})[3]	175	0			150		C19
	Chlorophyll *a* (µg L^{-1})	15	0			10		C19
	Total phytoplankton (ASU mL^{-1})	2000	5	4	80	NA	3828	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	5	4	80	NA	2972	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	5	0	0	NA	418	
Titicus Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	39	37	95	NA	37	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		C19
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		C19
	Fecal Coliform (coliforms 100mL^{-1})	20	40	6	15	NA	9	ROS
	Turbidity (NTU)	5	0			NA		C19
	Total suspended solids (mg L^{-1})	8	0			5		C19
	Alkalinity (mg L^{-1})	NA	0			>=40		C19
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		C19
	Sulfate (as SO4) (mg L^{-1})	25	0			15		C19
	pH (SU)	6.5-8.5	40	9	22	NA	7.70	
	Dissolved sodium (mg L^{-1})	20	0			15		C19
	Chloride (mg L^{-1})	40	0			30		C19
	Total Dissolved Solids	175	0			150		C19
	Chlorophyll *a* (µg L^{-1})	15	0			10		C19
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		C19
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
Lake Gleneida	Total Phosphorus (as P) (µg L^{-1})	15	9	4	44	NA	51	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		C19
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		C19
	Fecal Coliform (coliforms 100mL^{-1})	20	40	0	0	NA	2	ROS
	Turbidity (NTU)	5	0			NA		C19
	Total suspended solids (mg L^{-1})	8	0			5		C19
	Alkalinity (mg L^{-1})	NA	0			>=40		C19
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		C19
	Sulfate (as SO4) (mg L^{-1})	25	0			15		C19
	pH (SU)	6.5-8.5	15	4	27	NA	7.57	
	Dissolved sodium (mg L^{-1})	20	0			15		C19
	Chloride (mg L^{-1})	40	0			30		C19
	Total Dissolved Solids	175	0			150		C19
	Chlorophyll *a* (µg L^{-1})	15	0			10		C19
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		C19
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19
Lake Gilead	Total Phosphorus (as P) (µg L^{-1})	15	9	7	78	NA	101	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		C19
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		C19
	Fecal Coliform (coliforms 100mL^{-1})	20	40	0	0	NA	1	ROS
	Turbidity (NTU)	5	0			NA		C19
	Total suspended solids (mg L^{-1})	8	0			5		C19
	Alkalinity (mg L^{-1})	NA	0			>=40		C19
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		C19
	Sulfate (as SO4) (mg L^{-1})	25	0			15		C19
	pH (SU)	6.5-8.5	15	3	20	NA	7.34	
	Dissolved sodium (mg L^{-1})	20	0			15		C19
	Chloride (mg L^{-1})	40	0			30		C19
	Total Dissolved Solids	175	0			150		C19
	Chlorophyll *a* (µg L^{-1})	15	0			10		C19
	Total phytoplankton (ASU mL^{-1})	2000	0			NA		C19
	Dominant phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19
	Secondary phytoplankton genus (ASU mL^{-1})	1000	0			NA		C19

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
Kirk Lake	Total Phosphorus (as P) (µg L^{-1})	15	3	3	100	NA	28	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	0			NA		C19
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	0			0.3		C19
	Ammonia (as N) (mg L^{-1})	0.1	0			0.05		C19
	Fecal Coliform (coliforms 100mL^{-1})	20	35	2	6	NA	3	KM
	Turbidity (NTU)	5	2	1	50	NA	6.4	
	Total suspended solids (mg L^{-1})	8	0			5		C19
	Alkalinity (mg L^{-1})	NA	0			>=40		C19
	Dissolved Organic Carbon (mg L^{-1})	7	0			6		C19
	Sulfate (as SO4) (mg L^{-1})	25	0			15		C19
	pH (SU)	6.5-8.5	17	1	6	NA	7.75	
	Dissolved sodium (mg L^{-1})	20	0			15		C19
	Chloride (mg L^{-1})	40	0			30		C19
	Total Dissolved Solids	175	0			150		C19
	Chlorophyll *a* (µg L^{-1})	15	0			10		C19
	Total phytoplankton (ASU mL^{-1})	2000	2	1	50	NA	1950	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	2	1	50	NA	1230	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	2	0	0	NA	300	
Source Waters (all system)								
Ashokan West Basin Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	72	7	10	NA	12	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	72	0	0	NA	6	
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	72	0	0	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	72	0	0	0.3	0.16	KM
	Ammonia (as N) (mg L^{-1})	0.1	72	0	0	0.05	0.02	ROS
	Fecal Coliform (coliforms 100mL^{-1})	20	72	0	0	NA	1	ROS
	Turbidity (NTU)	5	72	32	44	NA	5.6	
	Total suspended solids (mg L^{-1})	8	72	9	12	5	4.6	KM
	Alkalinity (mg L^{-1})	NA	27	0	0	>=10	12.5	
	Dissolved Organic Carbon (mg L^{-1})	4	72	0	0	3	1.6	
	Sulfate (as SO4) (mg L^{-1})	15	12	0	0	10	2.5	
	pH (SU)	6.5-8.5	72	14	19	NA	6.93	
	Dissolved sodium (mg L^{-1})	16	12	0	0	3	4.6	
	Chloride (mg L^{-1})	12	12	0	0	8	7.4	
	Total dissolved solids (mg L^{-1})[3]		72	0	0		41	
	Chlorophyll *a* (µg L^{-1})	12	24	0	0	7	4.2	
	Total phytoplankton (ASU mL^{-1})	2000	40	0	0	NA	165	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	40	0	0	NA	77	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	40	0	0	NA	38	KM

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
Ashokan East Basin Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	64	3	5	NA	10	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	64	0	0	NA	5	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	64	0	0	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	64	0	0	0.3	0.06	ROS
	Ammonia (as N) (mg L^{-1})	0.1	64	0	0	0.05	0.03	ROS
	Fecal Coliform (coliforms $100mL^{-1}$)	20	63	0	0	NA	1	ROS
	Turbidity (NTU)	5	64	3	5	NA	1.8	
	Total suspended solids (mg L^{-1})	8	64	2	3	5	1.8	KM
	Alkalinity (mg L^{-1})	NA	15	0	0	>=10	12.5	
	Dissolved Organic Carbon (mg L^{-1})	4	64	0	0	3	1.7	
	Sulfate (as SO4) (mg L^{-1})	15	9	0	0	10	2.6	
	pH (SU)	6.5-8.5	64	11	17	NA	7.04	
	Dissolved sodium (mg L^{-1})	16	9	0	0	3	4.8	
	Chloride (mg L^{-1})	12	9	0	0	8	7.5	
	Total dissolved solids (mg L^{-1})[3]		64	0	0		38	
	Chlorophyll *a* (µg L^{-1})	12	24	0	0	7	2.3	
	Total phytoplankton (ASU mL^{-1})	2000	40	0	0	NA	268	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	40	0	0	NA	114	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	40	0	0	NA	62	
Rondout Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	80	1	1	NA	9	KM
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	56	0	0	NA	5	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	56	0	0	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	56	0	0	0.3	0.17	KM
	Ammonia (as N) (mg L^{-1})	0.1	56	0	0	0.05	<0.02	>80%
	Fecal Coliform (coliforms $100mL^{-1}$)	20	80	3	4	NA	2	ROS
	Turbidity (NTU)	5	80	0	0	NA	1.0	
	Total suspended solids (mg L^{-1})	8	32	0	0	5	1.0	ROS
	Alkalinity (mg L^{-1})	NA	12	0	0	>=10	10.9	
	Dissolved Organic Carbon (mg L^{-1})	4	56	0	0	3	1.8	
	Sulfate (as SO4) (mg L^{-1})	15	12	0	0	10	2.8	
	pH (SU)	6.5-8.5	80	11	14	NA	7.06	
	Dissolved sodium (mg L^{-1})	16	12	0	0	3	5.0	
	Chloride (mg L^{-1})	12	12	0	0	8	8.0	
	Total dissolved solids (mg L^{-1})[3]		80	0	0		44	
	Chlorophyll *a* (µg L^{-1})	12	24	0	0	7	4.4	
	Total phytoplankton (ASU mL^{-1})	2000	48	0	0	NA	313	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	48	0	0	NA	147	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	48	0	0	NA	72	KM

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
West Branch Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	72	14	19	NA	13	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	72	0	0	NA	4	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	72	0	0	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	72	0	0	0.3	0.15	KM
	Ammonia (as N) (mg L^{-1})	0.1	72	1	1	0.05	0.02	ROS
	Fecal Coliform (coliforms 100mL^{-1})	20	71	0	0	NA	2	KM
	Turbidity (NTU)	5	72	0	0	NA	1.1	
	Total suspended solids (mg L^{-1})	8	9	0	0	5	1.2	KM
	Alkalinity (mg L^{-1})	NA	15	0	0	>=10	18.9	
	Dissolved Organic Carbon (mg L^{-1})	4	72	0	0	3	2.3	
	Sulfate (as SO4) (mg L^{-1})	15	15	0	0	10	3.9	
	pH (SU)	6.5-8.5	72	14	19	NA	6.88	
	Dissolved sodium (mg L^{-1})	16	15	2	13	3	9.9	
	Chloride (mg L^{-1})	12	15	9	60	8	16.4	
	Total dissolved solids (mg L^{-1})[3]		72	0	0		60	
	Chlorophyll *a* (µg L^{-1})	12	32	1	3	7	3.5	
	Total phytoplankton (ASU mL^{-1})	2000	43	1	2	NA	526	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	43	2	5	NA	296	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	43	0	0	NA	111	KM
Cross River Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	48	45	94	NA	38	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	24	4	17	NA	35	
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	24	2	8	NA	12	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	24	0	0	0.3	0.10	ROS
	Ammonia (as N) (mg L^{-1})	0.1	24	7	29	0.05	0.24	KM
	Fecal Coliform (coliforms 100mL^{-1})	20	48	1	2	NA	3	KM
	Turbidity (NTU)	5	48	4	8	NA	2.5	
	Total suspended solids (mg L^{-1})	8	9	0	0	5	2.7	
	Alkalinity (mg L^{-1})	NA	9	0	0	>=40	55.5	
	Dissolved Organic Carbon (mg L^{-1})	7	24	0	0	6	4.0	
	Sulfate (as SO4) (mg L^{-1})	25	9	0	0	15	6.9	
	pH (SU)	6.5-8.5	47	6	13	NA	7.49	
	Dissolved sodium (mg L^{-1})	20	9	9	100	15	21.6	
	Chloride (mg L^{-1})	40	9	4	44	30	40.0	
	Total dissolved solids (mg L^{-1})[3]		48	0	0		168	
	Chlorophyll *a* (µg L^{-1})	15	16	0	0	10	6.0	
	Total phytoplankton (ASU mL^{-1})	2000	18	0	0	NA	576	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	18	0	0	NA	337	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	18	0	0	NA	123	KM

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
Croton Falls Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	64	55	86	NA	29	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	64	2	3	NA	9	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	64	1	2	NA	3	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	64	7	11	0.3	0.19	KM
	Ammonia (as N) (mg L^{-1})	0.1	64	15	23	0.05	0.09	KM
	Fecal Coliform (coliforms 100mL^{-1})	20	64	2	3	NA	4	KM
	Turbidity (NTU)	5	64	15	23	NA	4.1	
	Total suspended solids (mg L^{-1})	8	9	0	0	5	1.7	
	Alkalinity (mg L^{-1})	NA	18	0	0	>=40	70.3	
	Dissolved Organic Carbon (mg L^{-1})	7	64	0	0	6	3.7	
	Sulfate (as SO4) (mg L^{-1})	25	18	0	0	15	8.7	
	pH (SU)	6.5-8.5	64	14	22	NA	7.83	
	Dissolved sodium (mg L^{-1})	20	18	18	100	15	38.1	
	Chloride (mg L^{-1})	40	18	18	100	30	66.4	
	Total dissolved solids (mg L^{-1})[3]		64	0	0		282	
	Chlorophyll *a* (µg L^{-1})	15	24	7	29	10	19.0	
	Total phytoplankton (ASU mL^{-1})	2000	24	1	4	NA	966	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	24	5	21	NA	637	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	24	1	4	NA	165	KM
Kensico Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	176	3	2	NA	9	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	176	1	1	NA	4	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	176	1	1	NA	2	ROS
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	176	0	0	0.3	0.12	KM
	Ammonia (as N) (mg L^{-1})	0.1	176	1	1	0.05	0.02	ROS
	Fecal Coliform (coliforms 100mL^{-1})	20	174	1	1	NA	2	KM
	Turbidity (NTU)	5	176	0	0	NA	0.9	KM
	Total suspended solids (mg L^{-1})	8	56	0	0	5	1.1	KM
	Alkalinity (mg L^{-1})	NA	24	0	0	>=10	13.7	
	Dissolved Organic Carbon (mg L^{-1})	4	176	0	0	3	2.1	
	Sulfate (as SO4) (mg L^{-1})	15	24	0	0	10	3.8	
	pH (SU)	6.5-8.5	176	40	23	NA	6.85	
	Dissolved sodium (mg L^{-1})	16	24	0	0	3	6.5	
	Chloride (mg L^{-1})	12	24	0	0	8	10.6	
	Total dissolved solids (mg L^{-1})[3]		176	0	0		50	
	Chlorophyll *a* (µg L^{-1})	12	56	0	0	7	3.0	
	Total phytoplankton (ASU mL^{-1})	2000	72	0	0	NA	364	KM
	Dominant phytoplankton genus (ASU mL^{-1})	1000	72	0	0	NA	182	KM
	Secondary phytoplankton genus (ASU mL^{-1})	1000	72	0	0	NA	82	KM

Reservoir	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
New Croton Reservoir	Total Phosphorus (as P) (µg L^{-1})	15	168	146	87	NA	34	
	Total Dissolved Phosphorus (as P) (µg L^{-1})	15	168	24	14	NA	19	KM
	Soluble Reactive Phosphorus (as P) (µg L^{-1})	15	168	9	5	NA	6	KM
	Nitrate+Nitrite (as N) (mg L^{-1})	0.5	168	4	2	0.3	0.15	KM
	Ammonia (as N) (mg L^{-1})	0.1	168	36	21	0.05	0.12	KM
	Fecal Coliform (coliforms $100mL^{-1}$)	20	168	13	8	NA	8	KM
	Turbidity (NTU)	5	168	9	5	NA	2.2	
	Total suspended solids (mg L^{-1})	8	56	0	0	5	1.9	KM
	Alkalinity (mg L^{-1})	NA	30	0	0	>=40	71.6	
	Dissolved Organic Carbon (mg L^{-1})	7	168	0	0	6	3.7	
	Sulfate (as SO4) (mg L^{-1})	25	30	0	0	15	8.6	
	pH (SU)	6.5-8.5	167	23	14	NA	7.57	
	Dissolved sodium (mg L^{-1})	20	30	30	100	15	38.6	
	Chloride (mg L^{-1})	40	30	30	100	30	71.0	
	Total dissolved solids (mg L^{-1})[3]		168	0	0		255	
	Chlorophyll *a* (µg L^{-1})	15	56	6	11	10	10.0	
	Total phytoplankton (ASU mL^{-1})	2000	80	4	5	NA	893	
	Dominant phytoplankton genus (ASU mL^{-1})	1000	80	9	11	NA	560	
	Secondary phytoplankton genus (ASU mL^{-1})	1000	80	0	0	NA	152	

Reservoirs included in this analysis are required by WWQMP 2018, as per 3.2.2. Status of Reservoir Water Quality and 5.8. Croton System Reservoirs – Water Quality Status

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

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

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

Appendix H. Comparison of Stream Water Quality Results to Benchmarks

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
Catskill System - Ashokan Basin								
E10I (Bushkill at West Shokan)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.13	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	7	58	NA	8.7	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	0.9	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.0	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.6	
	Chloride (mg L^{-1})	50	12	0	0	10	3.9	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	26	
E16I (Esopus Creek at Coldbrook)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.16	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	2	17	NA	17.4	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.6	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.1	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	6.2	
	Chloride (mg L^{-1})	50	12	0	0	10	9.8	
	Total dissolved solids (mg L^{-1})[3]	50	12	5	42	40	50	
E5 (Esopus Creek at Allaben)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.16	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	5	42	NA	13.5	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.1	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.0	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	5.8	
	Chloride (mg L^{-1})	50	12	0	0	10	9.7	
	Total dissolved solids (mg L^{-1})[3]	50	12	3	25	40	44	
Catskill System - Schoharie Basin								
S5I (Schoharie Creek at Prattsville)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.16	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	22.5	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.7	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.3	
	Dissolved sodium (mg L^{-1})	10	4	1	25	5	7.0	
	Chloride (mg L^{-1})	50	12	0	0	10	11.8	
	Total dissolved solids (mg L^{-1})[3]	50	12	8	67	40	61	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
S6I (Bear Kill at Hardenburgh Falls)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.34	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	33.2	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	2.5	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	6.9	
	Dissolved sodium (mg L^{-1})	10	4	3	75	5	15.9	
	Chloride (mg L^{-1})	50	12	0	0	10	24.6	
	Total dissolved solids (mg L^{-1})[3]	50	12	12	100	40	106	
S7I (Manor Kill)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.12	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	28.4	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.6	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.9	
	Dissolved sodium (mg L^{-1})	10	4	1	25	5	7.1	
	Chloride (mg L^{-1})	50	12	0	0	10	10.2	
	Total dissolved solids (mg L^{-1})[3]	50	12	8	67	40	65	
SRR2CM (Schoharie Reservoir Diversion)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.11	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	0.01	ROS
	Alkalinity (mg L^{-1})	>=10.0	12	3	25	NA	17.3	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.9	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.1	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	5.3	
	Chloride (mg L^{-1})	50	7	0	0	10	5.0	
	Total dissolved solids (mg L^{-1})[3]	50	12	6	50	40	43	
Delaware System - Cannonsville Basin								
C-7 (Trout Creek above Cannonsville Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.35	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	17.7	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.5	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	4.7	
	Dissolved sodium (mg L^{-1})	10	4	3	75	5	11.5	
	Chloride (mg L^{-1})	50	12	0	0	10	17.8	
	Total dissolved solids (mg L^{-1})[3]	50	12	12	100	40	78	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
C-8 (Loomis Brook above Cannonsville Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.34	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	2	17	NA	16.6	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.4	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	4.8	
	Dissolved sodium (mg L^{-1})	10	3	3	100	5	12.2	
	Chloride (mg L^{-1})	50	12	0	0	10	15.0	
	Total dissolved solids (mg L^{-1})[3]	50	12	12	100	40	70	
CBS (formerly WDBN, West Branch Delaware River at Beerston Bridge)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.52	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	11	0	0	NA	22.8	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.8	
	Sulfate (as SO4) (mg L^{-1})	15	3	0	0	10	5.1	
	Dissolved sodium (mg L^{-1})	10	3	2	67	5	13.3	
	Chloride (mg L^{-1})	50	11	0	0	10	13.8	
	Total dissolved solids (mg L^{-1})[3]	50	12	11	92	40	78	
Delaware System - Neversink Basin								
NCG (Neversink River near Claryville)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.24	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	12	100	NA	3.9	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.3	
	Sulfate (as SO4) (mg L^{-1})	15	3	0	0	10	2.2	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.2	
	Chloride (mg L^{-1})	50	12	0	0	10	3.5	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	21	
NK4 (Aden Brook above Neversink Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.21	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	10	83	NA	7.2	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.2	
	Sulfate (as SO4) (mg L^{-1})	15	3	0	0	10	2.6	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.4	
	Chloride (mg L^{-1})	50	12	0	0	10	4.4	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	29	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
NK6 (Kramer Brook above Neversink Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.24	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	0.02	ROS
	Alkalinity (mg L^{-1})	>=10.0	12	5	42	NA	12.3	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	2.8	
	Sulfate (as SO4) (mg L^{-1})	15	3	0	0	10	3.0	
	Dissolved sodium (mg L^{-1})	10	4	4	100	5	20.0	
	Chloride (mg L^{-1})	50	12	0	0	10	32.9	
	Total dissolved solids (mg L^{-1})[3]	50	12	12	100	40	104	
Delaware System - Pepacton Basin								
P-13 (Tremper Kill above Pepacton Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.29	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	17.9	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.4	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.5	
	Dissolved sodium (mg L^{-1})	10	4	1	25	5	6.8	
	Chloride (mg L^{-1})	50	12	0	0	10	11.2	
	Total dissolved solids (mg L^{-1})[3]	50	12	9	75	40	60	
P-21 (Platte Kill at Dunraven)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.25	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	19.5	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.5	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.2	
	Dissolved sodium (mg L^{-1})	10	4	1	25	5	6.3	
	Chloride (mg L^{-1})	50	12	0	0	10	9.7	
	Total dissolved solids (mg L^{-1})[3]	50	12	8	67	40	59	
P-60 (Mill Brook near Dunraven)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.28	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	6	50	NA	11.2	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.1	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.0	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	1.4	
	Chloride (mg L^{-1})	50	12	0	0	10	1.8	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	28	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
P-7 (Terry Clove above Pepacton Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.36	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	2	17	NA	14.9	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.4	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.5	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	1.4	
	Chloride (mg L^{-1})	50	12	0	0	10	1.1	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	33	
P-8 (Fall Clove above Pepacton Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.42	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	3	25	NA	14.2	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.3	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.6	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.1	
	Chloride (mg L^{-1})	50	12	0	0	10	2.2	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	35	
PMSB (East Branch Delaware River near Margaretville)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.37	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	0	0	NA	20.1	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.4	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.4	
	Dissolved sodium (mg L^{-1})	10	4	1	25	5	9.4	
	Chloride (mg L^{-1})	50	12	0	0	10	13.3	
	Total dissolved solids (mg L^{-1})[3]	50	12	10	83	40	70	
Delaware System - Rondout Basin								
RD1 (Sugarloaf Brook near Lowes Corners)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.19	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	12	100	NA	5.2	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.2	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	3.1	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	3.6	
	Chloride (mg L^{-1})	50	12	0	0	10	6.2	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	30	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
RD4 (Sawkill Brook near Yagerville)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.11	KM
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	12	100	NA	5.7	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.8	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	4.2	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	3.5	
	Chloride (mg L^{-1})	50	12	0	0	10	5.4	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	30	
RDOA (Rondout Creek near Lowes Corners)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.25	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	12	100	NA	4.0	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	1.1	
	Sulfate (as SO4) (mg L^{-1})	15	4	0	0	10	2.8	
	Dissolved sodium (mg L^{-1})	10	4	0	0	5	2.3	
	Chloride (mg L^{-1})	50	12	0	0	10	3.8	
	Total dissolved solids (mg L^{-1})[3]	50	12	0	0	40	22	
RGB (Chestnut Creek below Grahamsville WRRF)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.4	0.31	
	Ammonia (as N) (mg L^{-1})	0.25	12	0	0	0.05	<0.02	>80%
	Alkalinity (mg L^{-1})	>=10.0	12	8	67	NA	8.7	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	2.3	
	Sulfate (as SO4) (mg L^{-1})	15	3	0	0	10	3.6	
	Dissolved sodium (mg L^{-1})	10	4	2	50	5	10.3	
	Chloride (mg L^{-1})	50	12	0	0	10	16.6	
	Total dissolved solids (mg L^{-1})[3]	50	12	8	67	40	62	
Croton System - Croton Basin								
AMAWALKR (Amawalk Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.35	0.16	KM
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	0.08	
	Alkalinity (mg L^{-1})	>=40.0	7	0	0	NA	87.7	
	Dissolved Organic Carbon (mg L^{-1})	25	7	0	0	9	4.4	
	Sulfate (as SO4) (mg L^{-1})	25	2	0	0	15	8.3	
	Dissolved sodium (mg L^{-1})	20	2	2	100	15	64.9	
	Chloride (mg L^{-1})	100	7	7	100	35	117.0	
	Total dissolved solids (mg L^{-1})[3]	175	7	7	100	150	376	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
BOGEASTBRR (Combined release for Bog Brook and East Branch Reservoirs)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.35	0.12	
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	0.08	
	Alkalinity (mg L^{-1})	>=40.0	7	0	0	NA	88.5	
	Dissolved Organic Carbon (mg L^{-1})	25	7	0	0	9	4.4	
	Sulfate (as SO4) (mg L^{-1})	25	2	0	0	15	11.5	
	Dissolved sodium (mg L^{-1})	20	2	2	100	15	34.5	
	Chloride (mg L^{-1})	100	7	0	0	35	62.1	
	Total dissolved solids (mg L^{-1})[3]	175	7	7	100	150	260	
BOYDR (Boyd Corners Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.35	0.03	KM
	Ammonia (as N) (mg L^{-1})	0.2	12	1	8	0.1	0.06	KM
	Alkalinity (mg L^{-1})	>=40.0	12	10	83	NA	39.3	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	3.9	
	Sulfate (as SO4) (mg L^{-1})	25	4	0	0	15	5.4	
	Dissolved sodium (mg L^{-1})	20	4	4	100	15	24.7	
	Chloride (mg L^{-1})	100	12	0	0	35	39.9	
	Total dissolved solids (mg L^{-1})[3]	175	12	0	0	150	147	
CROFALLSVC (Croton Falls Reservoir Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.35	0.23	
	Ammonia (as N) (mg L^{-1})	0.2	12	1	8	0.1	0.06	KM
	Alkalinity (mg L^{-1})	>=40.0	12	0	0	NA	60.9	
	Dissolved Organic Carbon (mg L^{-1})	25	11	0	0	9	3.3	
	Sulfate (as SO4) (mg L^{-1})	25	4	0	0	15	7.8	
	Dissolved sodium (mg L^{-1})	20	4	4	100	15	35.2	
	Chloride (mg L^{-1})	100	12	0	0	35	61.1	
	Total dissolved solids (mg L^{-1})[3]	175	11	10	91	150	226	
CROSS2 (Cross River above Cross River Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.35	0.12	KM
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	0.02	KM
	Alkalinity (mg L^{-1})	>=40.0	7	1	14	NA	57.9	
	Dissolved Organic Carbon (mg L^{-1})	25	7	0	0	9	5.0	
	Sulfate (as SO4) (mg L^{-1})	25	2	0	0	15	9.8	
	Dissolved sodium (mg L^{-1})	20	2	1	50	15	20.6	
	Chloride (mg L^{-1})	100	7	0	0	35	38.0	
	Total dissolved solids (mg L^{-1})[3]	175	7	4	57	150	179	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
CROSSRVVC (Cross River Reservoir Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	12	0	0	0.35	0.10	KM
	Ammonia (as N) (mg L^{-1})	0.2	12	2	17	0.1	0.08	KM
	Alkalinity (mg L^{-1})	>=40.0	12	0	0	NA	53.4	
	Dissolved Organic Carbon (mg L^{-1})	25	12	0	0	9	3.8	
	Sulfate (as SO4) (mg L^{-1})	25	4	0	0	15	7.2	
	Dissolved sodium (mg L^{-1})	20	4	4	100	15	21.6	
	Chloride (mg L^{-1})	100	12	0	0	35	39.5	
	Total dissolved solids (mg L^{-1})[3]	175	12	0	0	150	167	
DIVERTR (Diverting Reservoir Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.35	0.18	
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	0.06	KM
	Alkalinity (mg L^{-1})	>=40.0	7	0	0	NA	88.0	
	Dissolved Organic Carbon (mg L^{-1})	25	8	0	0	9	4.4	
	Sulfate (as SO4) (mg L^{-1})	25	2	0	0	15	10.7	
	Dissolved sodium (mg L^{-1})	20	2	2	100	15	37.1	
	Chloride (mg L^{-1})	100	7	0	0	35	67.1	
	Total dissolved solids (mg L^{-1})[3]	175	8	8	100	150	268	
EASTBR (East Branch Croton River above East Branch Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.35	0.04	KM
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	0.02	KM
	Alkalinity (mg L^{-1})	>=40.0	7	0	0	NA	96.5	
	Dissolved Organic Carbon (mg L^{-1})	25	7	0	0	9	5.7	
	Sulfate (as SO4) (mg L^{-1})	25	2	1	50	15	14.8	
	Dissolved sodium (mg L^{-1})	20	2	2	100	15	28.7	
	Chloride (mg L^{-1})	100	7	0	0	35	59.4	
	Total dissolved solids (mg L^{-1})[3]	175	7	7	100	150	274	
GYPSYTRL1 (Gypsy Trail Brook above West Branch Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	6	0	0	0.35	0.09	KM
	Ammonia (as N) (mg L^{-1})	0.2	6	0	0	0.1	<0.02	>80%
	Alkalinity (mg L^{-1})	>=40.0	6	5	83	NA	34.0	
	Dissolved Organic Carbon (mg L^{-1})	25	6	0	0	9	4.8	
	Sulfate (as SO4) (mg L^{-1})	25	1	0	0	15	17.0	
	Dissolved sodium (mg L^{-1})	20	1	1	100	15	24.8	
	Chloride (mg L^{-1})	100	6	0	0	35	47.1	
	Total dissolved solids (mg L^{-1})[3]	175	6	3	50	150	181	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
HORSEPD12 (Horse Pound Brook above West Branch Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.35	0.33	KM
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	<0.02	>80%
	Alkalinity (mg L^{-1})	>=40.0	7	0	0	NA	52.6	
	Dissolved Organic Carbon (mg L^{-1})	25	7	0	0	9	3.2	
	Sulfate (as SO4) (mg L^{-1})	25	2	0	0	15	13.2	
	Dissolved sodium (mg L^{-1})	20	2	1	50	15	22.8	
	Chloride (mg L^{-1})	100	7	0	0	35	48.5	
	Total dissolved solids (mg L^{-1})[3]	175	7	5	71	150	192	
KISCO3 Kisco River above New Croton Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.35	0.46	
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	0.02	ROS
	Alkalinity (mg L^{-1})	>=40.0	7	0	0	NA	89.7	
	Dissolved Organic Carbon (mg L^{-1})	25	7	0	0	9	4.6	
	Sulfate (as SO4) (mg L^{-1})	25	2	0	0	15	16.8	
	Dissolved sodium (mg L^{-1})	20	2	2	100	15	65.3	
	Chloride (mg L^{-1})	100	7	4	57	35	115.4	
	Total dissolved solids (mg L^{-1})[3]	175	7	7	100	150	393	
LONGPD1 (Long Pond outflow above West Branch Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.35	0.25	KM
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	<0.02	>80%
	Alkalinity (mg L^{-1})	>=40.0	7	0	0	NA	74.0	
	Dissolved Organic Carbon (mg L^{-1})	25	7	0	0	9	4.4	
	Sulfate (as SO4) (mg L^{-1})	25	2	0	0	15	10.1	
	Dissolved sodium (mg L^{-1})	20	2	2	100	15	54.5	
	Chloride (mg L^{-1})	100	7	3	43	35	96.8	
	Total dissolved solids (mg L^{-1})[3]	175	7	7	100	150	324	
MIKE2 (Michael Brook above Croton Falls Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	7	100	0.35	6.71	
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	0.01	ROS
	Alkalinity (mg L^{-1})	>=40.0	7	0	0	NA	85.6	
	Dissolved Organic Carbon (mg L^{-1})	25	7	0	0	9	4.3	
	Sulfate (as SO4) (mg L^{-1})	25	2	1	50	15	25.9	
	Dissolved sodium (mg L^{-1})	20	2	2	100	15	105.5	
	Chloride (mg L^{-1})	100	7	7	100	35	183.9	
	Total dissolved solids (mg L^{-1})[3]	175	7	7	100	150	576	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
MUSCOOT10 (Muscoot River above Amawalk Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.35	0.36	
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	0.03	KM
	Alkalinity (mg L^{-1})	>=40.0	7	0	0	NA	107.5	
	Dissolved Organic Carbon (mg L^{-1})	25	7	0	0	9	6.0	
	Sulfate (as SO4) (mg L^{-1})	25	2	0	0	15	17.5	
	Dissolved sodium (mg L^{-1})	20	2	2	100	15	69.9	
	Chloride (mg L^{-1})	100	7	7	100	35	151.4	
	Total dissolved solids (mg L^{-1})[3]	175	7	7	100	150	500	
TITICUSR (Titicus Reservoir Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.35	0.18	
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	0.10	
	Alkalinity (mg L^{-1})	>=40.0	7	0	0	NA	80.3	
	Dissolved Organic Carbon (mg L^{-1})	25	7	0	0	9	4.1	
	Sulfate (as SO4) (mg L^{-1})	25	2	0	0	15	8.8	
	Dissolved sodium (mg L^{-1})	20	2	2	100	15	23.0	
	Chloride (mg L^{-1})	100	7	0	0	35	42.5	
	Total dissolved solids (mg L^{-1})[3]	175	7	7	100	150	206	
WESTBR7 (West Branch Croton River above Boyd Corners Reservoir)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.35	0.08	KM
	Ammonia (as N) (mg L^{-1})	0.2	7	0	0	0.1	0.02	ROS
	Alkalinity (mg L^{-1})	>=40.0	7	4	57	NA	50.6	
	Dissolved Organic Carbon (mg L^{-1})	25	7	0	0	9	4.9	
	Sulfate (as SO4) (mg L^{-1})	25	2	0	0	15	8.0	
	Dissolved sodium (mg L^{-1})	20	2	2	100	15	29.6	
	Chloride (mg L^{-1})	100	7	0	0	35	44.3	
	Total dissolved solids (mg L^{-1})[3]	175	7	4	57	150	172	

Site	Analyte	Single Sample Maximum (SSM)	Number samples	Number that exceed SSM	Percent that exceed SSM	Annual Mean Standard	2022 Mean[1]	Note[2]
WESTBRR (West Branch Reservoir Release)	Nitrate+Nitrite (as N) (mg L^{-1})	1.5	7	0	0	0.4	0.17	
	Ammonia (as N) (mg L^{-1})	0.25	7	0	0	0.05	0.02	KM
	Alkalinity (mg L^{-1})	>=10.0	7	0	0	NA	13.3	
	Dissolved Organic Carbon (mg L^{-1})	25	8	0	0	9	2.1	
	Sulfate (as SO4) (mg L^{-1})	15	2	0	0	10	3.2	
	Dissolved sodium (mg L^{-1})	10	2	0	0	5	5.7	
	Chloride (mg L^{-1})	50	7	0	0	10	9.9	
	Total dissolved solids (mg L^{-1})[3]	50	8	0	0	40	46	

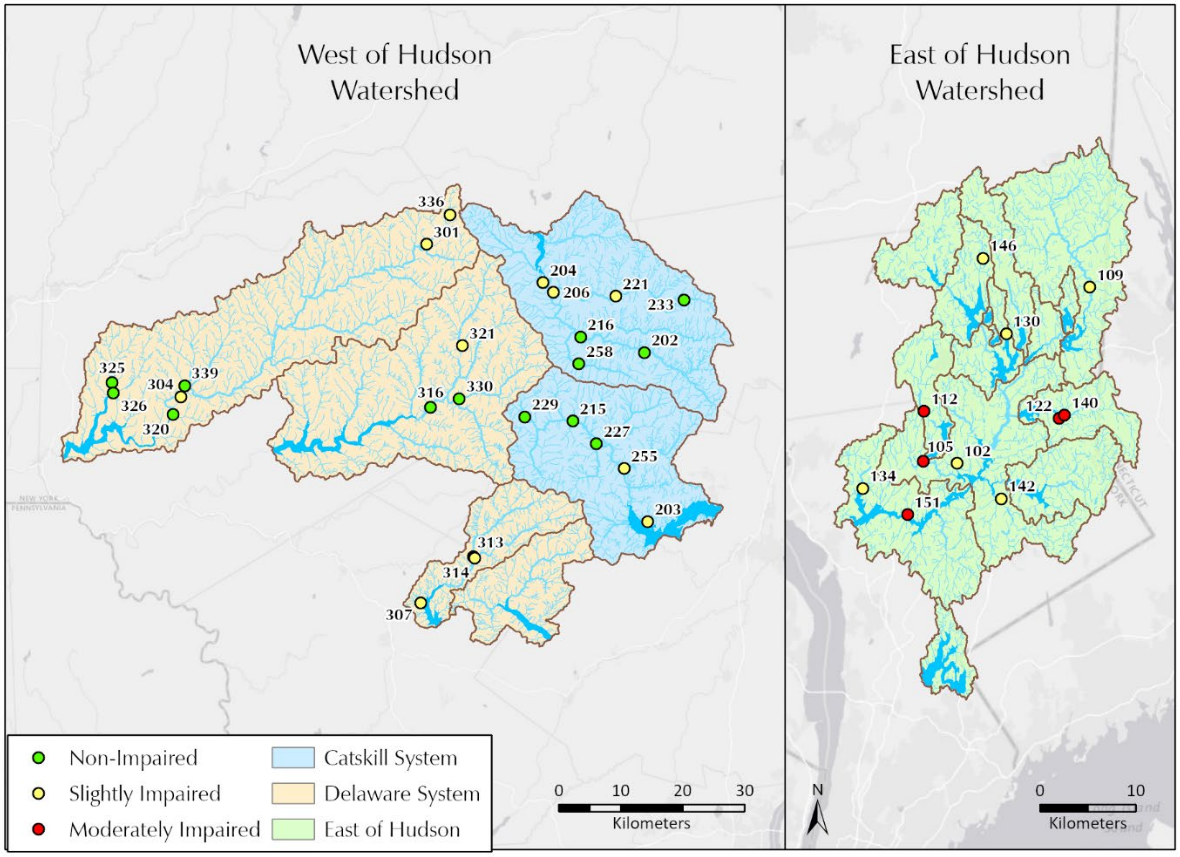
Streams included in this analysis are required by WWQMP (DEP 2018), as per 3.2.1. Status of Stream Water Quality and 5.7. Croton System Streams – Water Quality Status

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

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

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

Appendix I. Biomonitoring Sampling Site



2022 Biomonitoring Sites and their Water Quality (WQ) Status

SYSTEM	SITE	WQ STATUS	WQ SITE	STREAM
EOH	102	Slight	ANGLE3	Angle Fly Brook
EOH	109	Slight	EASTBR	East Br. Croton River
EOH	112	Moderate	MUSCOOT9	Muscoot River
EOH	134	Slight	HUNTER1	Hunter Brook
EOH	142	Slight	STONE5	Stone Hill River
EOH	146	Slight	HORSEPD12	Horse Pound Brook
EOH	130	Slight	MIKE2	Michael Brook
EOH	105	Moderate	HMILL4	Hallock Mills Brook
EOH	151	Moderate	SAWMILL1	Sawmill Brook
EOH	122	Moderate	NA	Crook Brook
EOH	140	Moderate	NA	Titicus River
Catskill	202	Non	S3	Schoharie Creek
Catskill	204	Slight	S5I	Schoharie Creek
Catskill	206	Slight	S10	Batavia Kill
Catskill	215	Non	E5	Esopus Creek
Catskill	216	Non	S4	Schoharie Creek
Catskill	227	Non	AEAWDL	Esopus Creek
Catskill	229	Non	BELLEGIG	Giggle Hollow
Catskill	221	Slight	NA	Batavia Kill
Catskill	233	Non	NA	Batavia Kill
Catskill	255	Slight	NA	Esopus Creek
Catskill	258	Non	NA	West Kill
Catskill	203	Slight	E12i	Butternut Creek
Delaware	301	Slight	WDHOA	W. Br. Delaware River
Delaware	304	Slight	WSPB	W. Br. Delaware River
Delaware	307	Slight	NK4	Aden Brook
Delaware	316	Non	PMSB	E. Br. Delaware River
Delaware	320	Non	WDBN	W. Br. Delaware River
Delaware	321	Slight	EDRB	E. Br. Delaware River
Delaware	330	Non	PBKG	Bush Kill
Delaware	336	Slight	WDSTA	W. Br. Delaware River
Delaware	339	Non	CTB	Third Brook
Delaware	313	Non	NWBR	W. Br. Neversink River
Delaware	314	Slight	NEBR	E. Br. Neversink River
Delaware	325	Non	NA	Trout Creek
Delaware	326	Non	NA	Loomis Brook

Appendix J. Semivolatile and Volatile Organic Compounds and Herbicides

EPA 525.2 – Semivolatiles

2-4-DDD, 2-4-DDE, 2-4-DDT, 4-4-DDD, 4-4-DDE, 4-4-DDT, 2-4-Dinitrotoluene, 2-6-Dinitrotoluene, 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 by method 525mod, Chlorobenzilate, Chloroneb, Chlorothalonil(Draconil-Bravo), Chlorpyrifos (Dursban), Chrysene, Delta-BHC Di-(2-Ethylhexyl)adipate, Di(2-Ethylhexyl)phthalate, Diazinon (Qualitative), 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 (ELAP), 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-Dichlorobenzene (1-3-DCB), Methyl Tert-butyl ether (MTBE), m-p-Xylenes, Naphthalene, n-Butylbenzene, n-Propylbenzene, o-Chlorotoluene, o-Dichlorobenzene (1-2-DCB), o-Xylene, p-Chlorotoluene, p-Dichlorobenzene (1-4-DCB), p-Isopropyltoluene, sec-Butylbenzene, Styrene, tert-amyl Methyl Ether, tert-Butyl Ethyl Ether, tert-Butylbenzene, Tetrachloroethylene (PCE), Toluene, Total 1-3-Dichloropropene, Total THM, Total xylenes, trans-1-2-Dichloroethylene, trans-1-3-Dichloropropene, Trichloroethylene (TCE), Trichlorofluoromethane, Trichlorotrifluoroethane (Freon 113), Vinyl chloride (VC)

Herbicides

Glyphosate