New York City Department of Environmental Protection
Bureau of Water Supply

Multi-Tiered Water Quality Modeling Program
Annual Status Report

March 2015

Prepared in accordance with Section 5.2 of the NYSDOH
Revised 2007 Filtration Avoidance Determination

Prepared by: DEP, Bureau of Water Supply

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Acknowledgements

The Watershed Water Quality Modeling Section (pictured from left to right, David Lounsbury (picture), Mark Zion, Elliot Schneiderman, Donald Kent, and Donald Pierson (picture)), received a Commissioners Award from Commissioner Emily Lloyd at the October 2014 Employees of the Month Recognition Ceremony.

The following statement accompanied the award:

The Watershed Water Quality Science and Research Modeling Section is based in Kingston, where they interact with many other groups throughout DEP.

Through their teamwork, this group of outstanding employees has contributed greatly to building DEP's integrated watershed modeling system over the past 20 years, providing timely operational guidance when severe storms create turbidity events, as well as evaluating the effectiveness of the Filtration Avoidance Determination watershed programs and their relative importance for wise investments. They also provide DEP with a look into the future of the water supply, with modeling potential impacts of climate change on hydrology and biology to allow for appropriate adaptation; this is a significant contribution to DEP's Climate Change Program Assessment and Action Plan. In addition, they have investigated such water quality issues as the sources of disinfection by-product precursors in order to meet increasingly stringent regulations.

The team has successfully built the watershed geographic information and modeling system over the past 20 years. They established a solid foundation based on the best science available by using a broad spectrum of highly technical data from sources such as the National Weather Service, National Aeronautics and Space Administration, United States Geological Survey, United States Department of Agriculture, Intergovernmental Panel on Climate Change, and networking with universities and prominent scientists worldwide. As a result, *DEP has a world class system to guide our watershed operation and protection for the future.*

This capability has allowed DEP to meet all its Filtration Avoidance Determination and regulatory requirements, to invest wisely in watershed protection and remediation, and to deliver safe, high quality water to New Yorkers without interruption both now and in the future.

David, Don, and Elliot have since retired from DEP, and Mark sadly and unexpectedly passed away in December 2014. They will all be greatly missed and long remembered by their colleagues at DEP for the good work they did, but more importantly for being great people.

1. Introduction

This status report describes work completed for DEP's Multi-Tiered Water Quality Modeling Program during January–December 2014. The report presents updates on the following modeling activities, as per Section 5.2 of the 2007 Revised Filtration Avoidance Determination (FAD) (NYSDOH 2014), are reported herein:

- Continuing model testing and development based on ongoing model simulations, data analyses, and research results.
- Updating land use, watershed programs, and time-series data (meteorological, stream flow and chemistry, reservoir chemistry) to support modeling.
- Continuing development of data analysis tools for modeling, and software for model connectivity.
- Providing modeling and technical support to the Catskill Turbidity Control Program including the development and use of the Operations Support Tool (OST).
- Using reservoir turbidity models to support operational decisions in response to unfavorable turbidity conditions.
- Developing and improving model applications to support watershed management and long-term planning.
- Developing model applications that simulate the impacts of future climate change on reservoir water quality and quantity.
- Updating future climate scenarios that can be used as inputs to the City's reservoir and watershed models.

2. Use of Models for Support of Operational Decisions

In 2014 seven separate turbidity modeling analyses were conducted for Kensico, Ashokan, and/or Schoharie Reservoirs. Table 2-1 summarizes the model runs performed during this period. The model runs where mostly in response to minor snowmelt and runoff events, although one analysis was performed to see if a planned recreational release from the Schoharie would adversely affect turbidity in Ashokan Reservoir, and another was done to determine if an internal seiche in Schoharie Reservoir would impact turbidity in Ashokan Reservoir.

In addition to the modeling analyses, an inventory of model runs conducted during previous reporting periods was developed. This inventory includes a total of 47 Kensico and 15 Ashokan/Schoharie model runs conducted over a total of 10 years. The purpose of the inventory is to allow staff to readily find examples of previous model runs done under conditions similar to those of current interest.

Table 2-1 List of modeling analyses performed during the reporting period (January 1–December 31, 2014) including descriptions of each analysis.

Date	Background	Modeling Description	Results
04/17/2014	Ashokan West Basin turbidity had risen to about 6-7 NTU due to spring snowmelt/rain events. Snowpack in the Esopus watershed was less than normal for mid-April. Delaware System turbidity was less than 1 NTU. Kensico Reservoir turbidity generally ranged from 0.65 – 1.6 NTU with somewhat higher turbidity >3 NTU near the Catskill influent.	Kensico reservoir sensitivity simulations were run to provide guidance for aqueduct flow rates into Kensico Reservoir for the given current and possible future Ashokan effluent turbidity. The tested Catskill inflow rates were 300, 400, 500 and 600 MGD with aqueduct turbidity of 5, 7.5, 10, and 12.5 NTU.	Results gave indicated that effluent turbidities would stay below about 2.5 NTU with input flow and turbidity combination s of 350 MGD at 8 NTU; 200 MGD at 10 NTU; and less than 200 MGD at 12 NTU.
05/22/2014	Ashokan West Basin turbidity had risen due to recent rainfall event with a plume of >20 NTU near the thermocline and turbidity generally <10 NTU at other depths. Similarly Ashokan East had been impacted with a plume of about 8-10 NTU at the thermocline depth and low turbidity (2-4 NTU) at other depths near the gate house. Delaware System turbidity was less than 1 NTU. Based on the limno survey from May 12, Kensico Reservoir turbidity generally ranged 0.65–1.6 NTU with somewhat higher turbidity (>3 NTU) near the Catskill influent.	These simulations were run to provide guidance for aqueduct flow rates into Kensico Reservoir for current and possible future Ashokan effluent turbidity. The tested Catskill inflow rates were 300, 400 and 500 MGD with aqueduct turbidity of 4, 6, 8, and 10 NTU.	The simulations indicated that Kensico effluent turbidity would remain below 2.5 NTU when turbidity load into Kensico Reservoir from the Catskill Aqueduct was less than 2400 MGD*NTU. Simulations show estimated Kensico effluent turbidity which averages turbidity from multiple layers of the model. In most cases a plume of higher turbidity was simulated to occur at or near the thermocline. Uncertainty in thermal structure, plume thickness and withdrawal dynamics can influence the simulated withdrawal turbidity.

Date	Background	Modeling Description	Results
4/8/2014	The snowpack was in the process of melting and during the previous week there was a moderate rain on snow event which elevated flow into the Ashokan Reservoir. Keypoint aqueduct and tap samples did not indicate any impact of this event on Ashokan West Basin turbidity with the most recent values ranging from 2.4-3.2 NTU. The dividing weir gate had been completely closed throughout most of the winter and elevation tap turbidity in the East Basin was quite low with a range of 0.8-1.6 NTU. The West Basin was being used for aqueduct diversions and conservation releases.	The current version of the OST was used to investigate the potential turbidity in the Ashokan Reservoir Catskill Aqueduct effluent during April and early May to further understand the potential for elevated turbidity during the remainder of the spring snowmelt period.	Ashokan Reservoir turbidity was not simulated to rise to extreme levels over the next 30 days. This was mainly due to relatively low streamflow predictions during the period with only moderate and short-lived storm events predicted. Ashokan West Basin turbidity was simulated to exceed 10 NTU in about 10% of the forecast traces. Ashokan East Basin turbidity was not simulated to exceed 5 NTU in any of the forecast traces and was simulated to exceed 4 NTU in about 4% of the traces. Note that water quality model results were uncertain. Initial conditions were estimated from aqueduct keypoint data, as opposed to in-lake measurement. There was also uncertainty associated with the forecast inflows and turbidity.
05/16/2014	A medium-sized runoff event was expected for the upcoming weekend. During the morning of May 14 Ashokan automated buoys indicated turbidity ranging from 2.5–5.5 NTU at site 4.2 near the gate house in the East Basin; 4.7–17.3 at site 1.4 in the West Basin; and 1.9–4.6 NTU at site 3.1 near the gate house in the West Basin. Schoharie turbidity as sampled on May 13 ranged from 9.1–18 NTU.	The current version of the OST was used to simulate the forecast turbidity in Schoharie and Ashokan Reservoirs during the next 33 days	Ashokan Reservoir turbidity was not simulated to rise to extreme levels over the next 30 days. This was mainly due to the forecast consisting of only moderate and short-lived storm events. Ashokan West Basin turbidity was simulated to exceed 10 NTU in only one out of the 48 forecast traces simulated. Ashokan East Basin turbidity was not simulated to exceed 4 NTU in any of the forecast traces.

Date	Background	Modeling Description	Results
05/27/2014	A medium-sized runoff event occurred on May 16 resulting in a plume of elevated turbidity near the depth of the thermocline in both the East and West Basins of Ashokan Reservoir. In the West Basin the plume had peak turbidity of about 31 NTU at 5 meter depth; about 18 NTU near the surface; and lower turbidity (4–7 NTU) at deeper levels as measured by site 3.1 automated buoy on May 22. In the East Basin the plume had a peak of about 7 NTU at 5 meter depth; about 5 NTU near the surface; and lower turbidity of 2–4 NTU at deeper levels as measured by the automated site 4.2 buoy on May 22.	The current version of the OST was used to simulate the forecasted turbidity in Ashokan Reservoir through the end of August to obtain an understanding of the potential transport and dispersion of the current plume over the summer.	On June 15 about 38% of traces exceeded 4 NTU and 10% of traces exceeded 5 NTU in Ashokan East Basin near the gate house. On July 15 about 6% of traces exceeded 4 NTU and 4% exceeded 5 NTU in Ashokan East Basin near the gate house. In most cases the turbidity plume in the Ashokan West Basin was simulated to slowly decrease in magnitude and sink to deeper zones of the reservoir. This was the typical response, other traces can have a variety of responses depending on forecasted inflows and temperatures. The turbidity plume in the Ashokan East Basin was generally simulated to persist and remain near thermocline depth. Over time the plume turbidity levels were reduced as the plume disperses more widely across the basin. This was the typical response, other traces can have a variety of responses depending on forecasted inflows and temperatures.

Date	Background	Modeling Description	Results
06/06/2014	There was a recreational release planned for Schoharie Tunnel for the upcoming weekend. The Operations Support Section asked if this would adversely affect turbidity in Ashokan Reservoir.	The current version of the OST was used to simulate the forecasted turbidity in Ashokan Reservoir through the end of August to obtain an understanding of the reservoir turbidity over the summer.	The effect of Shandaken Tunnel recreational releases was not apparent in the Ashokan turbidity simulations. Ashokan East turbidity near the gate house was predicted to generally stay between 1–2 NTU for the period except for a few scenarios with peaks generated by higher Esopus watershed events during August. In most cases the turbidity plume located in the Ashokan West Basin was simulated to slowly decrease in magnitude and sink to deeper zones of the reservoir. The low magnitude turbidity plume located in the Ashokan East Basin was generally simulated to remain near thermocline depth. Over time the plume turbidity levels were predicted to reduce as the plume disperses more widely across the basin and was transported out via reservoir aqueduct diversions.

Date	Background	Modeling Description	Results
08/01/2014	Turbidity in the Ashokan Reservoir was low with automated buoys indicating less than 10 NTU in the West Basin and less than 4 NTU in the East Basin. Schoharie Reservoir turbidity was elevated and there appeared to be an internal seiche which was causing Shandaken Tunnel turbidities to fluctuate from 20–100 NTU.	The current version of the OST was used to simulate the forecasted water quality in Ashokan Reservoir to understand the potential reservoir turbidity through the fall.	Simulated Esopus Creek inflow for the summer and early fall suggested mostly moderate and a few larger storms would impact the watershed. Generally streamflow, and turbidity load to the reservoir was expect increase slightly during October, as this is the normal seasonal pattern. Ashokan West Turbidity at the dividing weir gate was simulated to generally decrease slightly through the summer. There were two traces with larger events in August that increase turbidity to 20–50 NTU and a number of traces that indicate elevated turbidity of 10–200 NTU during October. During October, the turbidity forecast to rise above 10 NTU in about 17% of the traces. Ashokan East simulated turbidity near the gate house generally remained between 1–4 NTU through September. October events tended to increase simulated turbidity during that month. During October, the turbidity was forecast to rise above 3 NTU in about 8% of the traces. Although the scenarios showed generally low turbidity through the October, the forecast storm events in the fall were highly uncertain and there was a possibility that an extreme event not predicted in the forecast traces could occur.

3. Modeling Applications of Climate Change Impacts

3.1 Phase II of the Climate Change Integrated Modeling Project

The Climate Change Integrated Modeling Project (CCIMP) is led by the water quality modeling group and has the goal to evaluate the effects of future climate change on the quantity and quality of water in the NYC water supply. The project is an element of DEP's Climate Change Action Plan released in 2008. The CCIMP is designed to address three issues of concern to NYC: (1) overall quantity of water in the entire water supply; (2) turbidity in the Catskill System of reservoirs, including Kensico; and (3) eutrophication in Delaware System reservoirs. During the first phase of the project an initial estimate of climate change impacts was made using available GCM data sets and DEP's suite of watershed, reservoir and system operation models. Phase I focuses on water quantity in the West of Hudson (WOH) System, turbidity in the Schoharie Reservoir and eutrophication in the Cannonsville Reservoir. The first phase of the CCIMP was brought to a close in 2013 with the holding of a review workshop in September and the subsequent publication and distribution of a report detailing our Phase I activities and expert panel review (The report is available online at DEP website: http://www.nyc.gov/html/dep/html/about_dep/climate_resiliency.shtml.).

Phase II of the CCIMP was continued in 2014. The general goals were the same as Phase I, but in Phase II a more extensive set of GCM data will be used along with improved downscaling methods to develop a wider variety of future climate scenarios. DEP will also be making use of additional models and subject all models to increased testing and scrutiny in respect to their climate change predictions.

Work continued on the development of an initial application of the RHESSys hydro-ecological model that should be of value for estimating the effects of climate change on water supply forested lands. Work to improve the SWAT watershed model to better represent the hydrology in the West of Hudson watershed area, particularly Cannonsville watershed, also continued in 2014.

3.2 WRF Project 4262 - Vulnerability Assessment and Risk Management Tools for Climate Change: Assessing Potential Impacts and Identifying Adaptation Options

The Water Research Foundation (WRF) Project 4262 – Vulnerability Assessment and Risk Management Tools for Climate Change – was completed in 2013 and the final report entitled "Developing Robust Strategies for Climate Change and Other Risks: A Water Utility Framework" was published in 2014 by the Water Research Foundation (http://www.nyserda.ny.gov/-/media/Files/EERP/Commercial/Sector/Municipal-Water-Wastewater-Facilities/water-utility-framework.pdf). Project collaborators included researchers from Stockholm Environment Institute, Rand Corporation, Hydrologics, Hazen and Sawyer, NYC DEP, and National Center for Atmospheric Research (NCAR). The project focused on the use of a quantitative, iterative analytical framework called Robust Decision Making (RDM) to assess climate vulnerability for water supply systems. Guidelines for application of RDM were provided by means of examples in two pilot studies – Colorado Springs Utilities and the New York City Water Supply. RDM was demonstrated to be an efficient tool for testing the sensitivity of water supply systems to climate change, and may prove useful in future studies of the effects of climate change on the NYC Water Supply.

For the case study on the New York City Water supply (Chapter 4: Climate Vulnerability Assessment and Risk Management for the New York City Department of Environmental Protection), the report's executive summary lists the following:

> For the DEP application, 252 futures were evaluated and four adaptation alternatives were compared: (1) increasing capacity of the Catskill Aqueduct, (2) making operational changes, (3) augmenting supply, and (4) implementing all three of these options simultaneously. Key findings for the DEP system were:
>
> - DEP's system may not be able to meet specified water quality or water reliability targets under many plausible future conditions based on the preliminary analysis presented, even with the investments already planned for the Baseline system.
> - Higher-than-expected demand may be an important determinant of when DEP's system would no longer meet specified water quality targets.
> - Turbidity thresholds and changes in climate can lead to a wide range of outcomes, even with the same level of demand. The complex interaction between turbidity and climate suggests that it is worthwhile for DEP to continue research efforts in this area.
> - From a risk management perspective, the adaptation options considered in this analysis may not be sufficient for addressing specified water reliability goals in the long term future; DEP may wish to consider a wider range of options.
> - Inability to adequately characterize the uncertainty in future climate, specifically with respect to extreme event frequency and intensity, underscores the preliminary nature of the analysis and its conclusions. However, the methodological framework is robust and could be re-applied as climate science is able to provide better estimates of future conditions in order to obtain more precise conclusions.

3.3 WRF Project 4306 – Dynamic Reservoir Operations: Managing for Climate Variability and Change

The WRF Project 4306 – Dynamic Reservoir Operations: Managing for Climate Variability and Change – was completed in 2013 and the project produced two reports that were published in 2014: *Dynamic Reservoir Operations: Managing for Climate Variability and Change* (4306a) and *Reservoir Operations Development Guide: The Theory and Practice of Developing Reservoir Operating Rules for Managing Multiple Objectives* (4306b). The project focused on the use of Dynamic Reservoir Operations (DRO) in improving system reliability, resilience and performance under challenging climate conditions. DRO are operating rules that change based on the present state of the system, such as storage levels, current inflow, and/or forecasted conditions. The project included a literature review; creation of a DRO development guide with step-by-step guidelines for developing effective rules; and case studies that included the Washington D.C. Metropolitan Area, New York City, and the City of Calgary. The DRO guide and case studies provide valuable guidance for application of DRO in future studies of the effects of climate change on the NYC Water Supply.

To assess the potential of DRO as a climate change response, New York City (NYC) was one of three cities selected where the current reservoir operations were adjusted based on climate-adjusted hydrology. In the NYC case study, the focus was on forecasts, which are a central element of its DRO. The incremental effect of increasingly sophisticated forecasting techniques on performance measures was assessed under historical and climate-adjusted hydrology and two operational changes were also explored in response to identified vulnerabilities.

The NYC simulations indicated that days with poor water quality in its Catskill System could increase as much as 50% and drought periods could increase as much as 80%. However, modifying rule forms resulted in substantial improvement by decreasing drought days and water quality impacts. As such, the New York City case study provided evidence for the promise of forecast-based operating rules.

4. Model Development and Applications

4.1 Operations Support Tool (OST) Development

During 2014 more progress was made in the development and use of an Operations Support Tool (OST) as an integral component of the Catskill Turbidity Control Program and as a supporting tool for reservoir operations. OST is a suite of interconnected CE-QUAL W2 reservoir water quality models and OASIS (Operational Analysis and Simulation of Integrated Systems) reservoir system model, linked with data acquisition, database and data visualization tools.

As part of the goal to achieve OST water quality modeling functionality in 2014, we focused on: (i) testing new capabilities as they were integrated into the OST modeling framework; (ii) continued testing the newly-developed W2 model for Rondout reservoir in LinkRes modeling framework and (iii) accelerating the full integration of existing water quality W2 models in the new OST modeling framework. The preparation for full integration of the W2 models included:

- Extending the meteorology input time series data through 2012 and creating the capability within the OST framework to derive input data in near real-time, to support short-term operational simulations by using empirical relationships to local airport stations, including Binghamton (for the Delaware basin reservoirs), Albany (for Catskill basin reservoirs), and White Plains (for EOH basin reservoirs).
- Improving estimates of Ashokan effluent turbidity. An empirical correction for short circuiting at the Ashokan Dividing Weir/East Basin Gate House during high flow events was implemented in W2.
- Implementing a more refined turbidity loading relationship to improve accuracy of turbidity input to the reservoirs. An autoregressive moving average (ARMA) (Hirsch 1988) turbidity loading relationship that accounts for serial correlation present in turbidity observations was implemented at the Coldbrook, Allaben, and Prattsville gages. In OST ARMA is applied in conjunction with the available reservoir inflow forecast capability to support water quality operations (Hazen and Sawyer and Nova Consulting & Engineering 2012).
- Improved synchronization between Data Mart and Aquarius. Since Aquarius stores data in a compressed BLQB format that can only be accessed via Aquarius APIs, the synchronization is important because Aquarius can replicates data to the DataMart, a standard SQL database, where W2 models can access data with SQL statements. The implementation of this process led to improved W2 model efficiency by reducing model simulation run-time.
- A manual tool to set up initial conditions for Schoharie and Ashokan reservoirs W2 models was developed and is now available for OST modeling.
- Improved the OST Graphical User Interface (GUI) and Dashboard to include processing and visualization of OST water quality output.
- Added and tested a W2 model output animation tool using AGPM software.

The current functionality of OST support for water quality operations is not complete yet. In 2015 and beyond we will continue the process of improving, developing and adding new capabilities to the OST modeling framework at the same time we improve model robustness.

5. Data Analysis to Support Modeling

5.1 DOC/DBP Workshop

A "Dissolved Organic Carbon (DOC)/Disinfection By-Products (DBP) Workshop" was held at the Ashokan Center on April 14-15, 2014. The genesis of this workshop was an earlier review meeting for Phase I of the Climate Change Integrated Modeling Project (CCIMP) held in September 2013. As a consequence of that meeting, a report (DEP 2014) was prepared containing recommendations for future DEP work by several break-out groups: Climate Change Scenarios, Turbidity, DOC/DBP, and Water Supply/System Operations.

One recommendation from the DOC/DBP group was to: "convene another workshop to develop a strategy for DOC/DBP modeling". This was deemed important because New York City's water supply is largely untreated and subsequent chlorination of DOC contained in the water can produce 'disinfection by-products' which, as a result of recent regulatory changes, are now more stringently controlled in the water distribution system.

The goals of the DOC/DBP workshop were to:

1) consider the processes that need to be included in models of DOC and DBP formation potential in the water supply reservoirs; and
2) discuss how best to collect the data that can be used to both test and calibrate DOC/DBP models and at the same time be used to inform water supply operations in near real time.

These two tasks could ultimately support an expansion of the capability of DEP's Operations Support Tool (OST) and allow information on DBP formation potential, as measured by proxy indicators, to influence short-term operational forecasts. Additionally, the simulated effects of climate change on long-term trends in DBP formation potential might have implications on long-term future reservoir operation policy.

The workshop brought together experts with knowledge in three different areas: watershed hydrology and water quality; limnology; and DOC/DBP formation potential (FP) chemistry and monitoring. To begin the workshop, an overview of the DOC and DBP data that has already been collected by DEP was presented. Also presented was an overview of the watershed and reservoir models used by DEP that can simulate DOC, and which could potentially be further improved and linked to simulations of DBPs.

One goal of the workshop was to initiate a wide-ranging dialog on all aspects of DEP's long-term DOC/DBP modeling program. A second goal was to form a group of advisors who would remain engaged with the DEP Water Quality Modeling Section, and continue to provide support as the project matures (future workshops are planned). In both cases this workshop met these goals. The final goal was to develop a list of high priority tasks that could be undertaken to get this project off the ground once the next CUNY project was funded (August 2014) and as DEP can allocate resources to enhanced monitoring. A summary of the workshop and the resulting recommendations were compiled into a DEP report, *Recommendations and Presentations from the Dissolved Organic Carbon (DOC)/Disinfection By-Products (DBP) Workshop* (DEP 2014).

5.2 GLEON16 (Global Lake Ecological Observatory Network)

In October 2014, the acquisition of new modeling software and appraisal of data management tools was accomplished through participation in the GLEON16 (Global Lake Ecological Observatory Network) conference in Orford, Quebec. This five-day conference provided DEP with exposure to new ideas and possibilities for collaboration in an international arena. The conference provided an opportunity for DEP to enhance its abilities in data acquisition, management, and analysis for water supply management.

Working with GLEON provided access to the software tools and high-level expertise needed to analyze the data that will be collected by DEP's ROBOMON program (i.e., robotic monitoring of streams and reservoirs via buoys with sensors that record high-frequency data). This is one of DEP's new, expanding programs that support water supply operation. GLEON also provides water quality models that are may help provide insight and prediction for DEP's top priorities for regulatory compliance, i.e., turbidity, disinfection by-products (DBPs), and pathogens.

A summary of the data analysis tools to support modeling from GLEON16 is as follows:

Model developers from Pennsylvania State University presented models and data acquisition tools for creating coupled water and carbon budgets in a special workshop on "The Age of Water." The sources and fate of organic carbon are critical topics for water supply, given regulatory requirements for DBPs and anticipated changes in carbon export with current projections of climate change. The Penn State Integrated Hydrologic Model (PIHM) and the General Lake Model (GLM), fully-coupled catchment-lake-groundwater hydrodynamic models were demonstrated, followed by several interactive sessions throughout the conference. The aim of this modeling approach is to identify water age and associated flowpaths to infer the sources and fates (storage, conversion, or export) of organic carbon and gain insight into the associated uncertainties in these quantities. The net result is a dynamic model for lake (or reservoir) water, energy, and carbon cycling constrained by a fully coupled watershed mass balance that includes the effects of the groundwater basin. The model demonstration gave insights into some available options that are written in open-source code for DOC/DBP modeling that will be beneficial for DEP water quality management.

In addition to PIHM and GLM, other tools and models presented included the Framework for Aquatic Biogeochemical Models (FABM) for integrated simulations of lake and reservoir water quality and ecosystem health, a framework that allows multiple biogeochemical models to interact with each other and connect to a diverse array of hydrodynamic drivers (e.g., GLM). In combination with FABM, the Aquatic Ecodynamics (AED) library is a system of multiple models with a flexible series of hydrodynamic and water quality model components and options for static and dynamic linkages between models. Additionally, LakeAnalyzer, a set of software tools developed by GLEON members that allows users to calculate common metrics for lake and reservoir physical states such as stability, ice-cover, and thermocline depth and LakeMetabolizer, a set of software tools that estimates lake metabolism were demonstrated and distributed to participants.

To meet data needs for modeling, HydroTerre, a suite of data acquisition and integration tools to bring together geospatial datasets from multiple sources needed for multi-scale, multi-state model simulations was presented. This data service provided by Penn State University allows modelers to build and test models with rapid access to high resolution data at the US Geological Survey (USGS) National Hydrography Dataset Hydrological Unit Code (HUC) level-12 scale.

Avenues for formatting and cataloguing data using best practices for data management featured two alternatives. The first relied on tools developed by CUAHSI (The Consortium of Universities for the Advancement of Hydrologic Science). Main features included the HydroDesktop utility, a free, open-source application for acquiring and analyzing hydrologic data; WaterML, a form of XML developed specifically for sharing water resources data; and ODM, the Observations Data Model, a new format for the storage and retrieval of environmental observations in a relational database designed to facilitate integrated analysis of large data sets collected by multiple investigators. Observations are stored with sufficient metadata to provide traceable heritage from raw measurements to useable information. A second alternative for data sharing and management presented was DataONE (Data Observation Network for Earth). DataONE is a collaboration among many partner organizations, funded by the US National Science Foundation (NSF) under a Cooperative Agreement with a mission to create cyberinfrastructure and networks to ensure the preservation, access, use and reuse of multi-scale, multi-discipline, and multi-national science data.

DEP's attendance at GLEON16 established DEP's representation in GLEON and opened the door for additional DEP's participation in the future. DEP will benefit from its association with GLEON as it creates on-going access to top international expertise, sophisticated software for reservoir water quality analysis, and highly qualified personnel for recruitment into DEP's scientific research programs.

5.3 Statistical Training for Data Analysis

In 2014, training in the statistical software R was procured in order to evaluate the R-based GLEON model "General Lake Model" (GLM) and its associated analytical tools "Lake Analyzer" and "Lake Metabolizer". The Lake Analyzer tool determines many physical attributes of water bodies including indices of mixing and stratification. It was created specifically to work with high-frequency data collected from buoy systems similar to the DEP buoy system. The Lake Metabolizer tool is used to estimate primary production and ecosystem respiration. Together these tools provide insight into biogeochemical transformations at different time and spatial scales. In March 2014, statistical training was procured for building regression models for data measured frequently in time. These procedures are critical for model development in order to correctly interpret the high frequency water quality and meteorological data produced from the many continually monitored instruments located throughout the NYC water supply system.

In 2014 DEP held two courses were taught by Dr. Dennis Helsel, co-author of *Statistical Methods in Water Resources*, and has also written the book, *Statistics for Censored Environmental Data using Minitab and R*. The goal of the courses was to further develop our data analysis capabilities. The first course was an Introduction to the R Statistical Package and

Time Series Methods for Frequently Collected Data. The R Statistical Package is a free, but very robust statistical software package that is used world-wide by scientists in government and academia. For example, the model and tools discussed in the GLEON section above uses R, and some of the advanced statistical techniques can be implemented using R packages. The statistical portion of this examined methods which can be used for frequently collected data. Given the increase in usage of various robotic monitoring and sensors that collect data at a high frequency at DEP, it is important that the data are analyzed in an appropriate manner in order to maintain data integrity. Such high frequency, real time data helps DEP meet our FAD water quality monitoring objectives, e.g. trend analysis, modeling efforts, and reservoir operations, and enhances our "early warning" capability, but frequently collected data may violate the independence assumption of standard statistical procedures, so alternative methods should be used to ensure the validity of the statistical analysis.

The second course taught by Dr. Helsel for DEP in 2014 was a two-day course entitled, Untangling Multivariate Relationships. Environmental data, such as the water quality, meteorological and operations data collected at the DEP is often complex consisting of large datasets with several hundred variables many of which can range over several orders of magnitude. Standard statistical tests performed on individual variables cannot reveal critical interrelationships among the variables and this can potentially limit DEP's ability to model important watershed processes or to evaluate studies such as turbidity control on stream banks. Multivariate statistical techniques, on the other hand, reflect more accurately the multivariate nature of the natural ecological systems and provide the means to detect and quantify multivariate patterns in these systems. For example, water quality entering the aqueducts can be impacted by wind, temperature, rainfall, stream inputs, flow rates, algae, birds, etc., and the techniques taught in this course demonstrated methods to help untangle these relationships and prioritize which of these multiple variables or combination of variables is most important in determining the quality of drinking water delivered to consumers.

5.4 Turbidity and Suspended Sediment Monitoring in the Upper Esopus Creek Watershed

The USGS report, *Turbidity and Suspended Sediment Monitoring in the Upper Esopus Creek Watershed*, which was funded by DEP, was finalized in 2014 as a USGS Scientific Investigations Report, which is available on line at http://pubs.usgs.gov/sir/2014/5200/. The report was included as an exhibit with the November 2014 FAD Report, *Ashokan Stream Management Program Water Quality Studies Proposal*, to fulfill a FAD requirement to report on the status of this USGS study.

Abstract

Suspended-sediment concentrations (SSCs) and turbidity were measured for 2 to 3 years at 14 monitoring sites throughout the upper Esopus Creek watershed in the Catskill Mountains of New York State. The upper Esopus Creek watershed is part of the New York City water-supply system that supplies water to more than 9 million people every day. Turbidity, caused primarily by high concentrations of inorganic suspended particles, is a potential water-quality concern because it colors the water and can reduce the effectiveness of drinking-water disinfection. The purposes of this study were to quantify concentrations of suspended sediment and turbidity levels, to estimate suspended-sediment loads within the upper Esopus Creek watershed, and to

investigate the relations between SSC and turbidity. Samples were collected at four locations along the main channel of Esopus Creek and at all of the principal tributaries. Samples were collected monthly and during storms and were analyzed for SSC and turbidity in the laboratory. Turbidity was also measured every 15 minutes at six of the sampling stations with in situ turbidity probes.

The largest tributary, Stony Clove Creek, consistently produced higher SSCs and turbidity than any of the other Esopus Creek tributaries. The rest of the tributaries fell into two groups: those that produced moderate SSCs and turbidity and those that produced low SSCs and turbidity. Within those two groups the tributary that produced the highest SSCs and turbidity varied from year to year depending on the hydrologic conditions within each sub-watershed. During the 3-year study, Stony Clove Creek accounted for an average of 40 percent of the annual suspended-sediment load measured at the upper Esopus Creek watershed outlet at Coldbrook, more than all of the other measured tributaries combined. The other tributaries to the upper Esopus Creek, taken together, accounted for an average of about 20 percent of the load at Coldbrook during 2010 and 2011, when most of the tributaries were sampled. Woodland Creek, the third largest tributary in the watershed, also accounted for a substantial amount of the load at Coldbrook, an average of 10 percent during the 3 years. Stony Clove Creek appeared to be a persistent source of sediment to Esopus Creek; it had the highest sediment yield (load per unit area) of all monitoring sites, including the outlet at Coldbrook.

Discharge, SSC, and turbidity were strongly related at the Coldbrook site but not at every monitoring site. In general, relations between discharge and SSC and turbidity were strongest at sites with high SSCs, with the exception of Stony Clove Creek. Stony Clove Creek had high SSCs and turbidity regardless of discharge, and although concentrations and turbidity values generally increased with increasing discharge, the relation was not strong. Five of the six sites used to investigate the relations between SSC and laboratory turbidity had a coefficient of determination (r^2) greater than 0.7. Relations were not as strong between SSC and the turbidity measured by in situ probes because the period of record was shorter and therefore the sample sizes were smaller. Data from in situ turbidity probes were strongly related to turbidity data measured in the laboratory for all but one of the monitoring sites where the relation was strongly leveraged by one sample. Although the in situ turbidity probes appeared to provide a good surrogate for SSC and could allow more accurate calculations of suspended-sediment load than discrete suspended-sediment samples alone, more data would be required to define the regression models throughout the range in discharge, SSCs, and turbidity levels that occur at each monitoring site. Nonetheless, the in situ probes provided much greater detail about the relation between discharge and turbidity than did the grab samples and storm samples measured in the laboratory.

6. Model Data Acquisition and Organization

6.1 GIS Data Development for Modeling

6.1.1 Water Quality Monitoring and Meteorological Sites

In 2014 work continued on updating all water quality monitoring sites, biomonitoring sites, snow survey and snow pillow sites, and meteorological stations for the GIS data library. Also GPS support was provided to review water quality monitoring site locations.

6.1.2 Stream Power

Additional work was performed in 2014 on creating WOH hydrologic derivative rasters from the 1-meter Digital Elevation Model (DEM) to screen for stream reaches with greater stream power and potential erosion. This was done in order to expand work on using ArcGIS ModelBuilder to derive values of stream power as a function of stream gradient and stream discharge for tributaries throughout the watershed. This work may more accurately identify stream reaches of potentially increased erosion that merit field investigation.

6.1.3 Support Activities for Modeling

Additional data development efforts and mapping support were provided throughout the reporting period to various members of the DEP Water Quality Modeling Section, the Division of Watershed Water Quality Science and Research, and the Water Quality Directorate. A majority of this support was related to preparation of DEP reports, such as revised maps for an updated version of the Watershed Water Quality Monitoring Plan, peer-reviewed publications, conference posters, and conference presentations. Such events included the annual Watershed Science Technical Conference, the Catskill Environmental Research and Monitoring Conference, the Annual American Water Resources Association Conference, the North American Lake Management Society Symposium, the annual meeting of the American Geophysical Union, the Global Lake Ecological Observatory Network (GLEON) Meeting among others.

Tools were tested to import, run, and animate spatially-distributed, near-real-time meteorological data as input for water quality models.

Additional information on DEP's Geographic Information System can be found in section 5.4 of the Filtration Avoidance Annual Report for the period January 1 through December 31, 2014 (DEP 2015).

6.2 Ongoing Modeling/GIS Projects

6.2.1 Bathymetric Survey of NYC Water Supply Reservoirs

Bathymetric surveys of NYC reservoirs and controlled lakes are necessary to accurately derive relationships between water surface elevation and water surface area and/or water volume. Accurate assessment of the volume, or storage, of each of the City's reservoirs and controlled lakes is critical to water supply planning and delivery. Accurate bathymetric information is also critical to DEP efforts to mathematically model present-day water quality concerns (nutrient loads, turbidity, safe yield), as well as scenarios in the future that assess potential impacts of climate change.

An Intergovernmental Agreement with USGS to provide bathymetric surveys of the six West of Hudson reservoirs, last surveyed in the mid- to late-1990s, was approved in August 2013. Thus far survey work has been completed for Ashokan West Basin, Rondout, Neversink and Schoharie Reservoirs. Work on the remaining reservoirs (Ashokan East Basin, Cannonsville and Pepacton) will be undertaken in 2015. Final products are to include a triangulated irregular network (TIN) surface model of the reservoir bottoms, 2-foot elevation (depth) contours, and an updated elevation-area-capacity table for each reservoir. To date data products from Ashokan West Basin were received and reviewed.

6.2.2 Watershed Atlas

The *New York City Watershed Atlas* was completed in 2014. The atlas includes tables and maps with high-resolution Digital Elevation Models (DEM), catchment boundaries, and land use/land cover data. Figure 6-1 and Figure 6-2 are examples from the atlas depicting the Ashokan Basin land cover and the Ashokan Reservoir West Basin bathymetry.

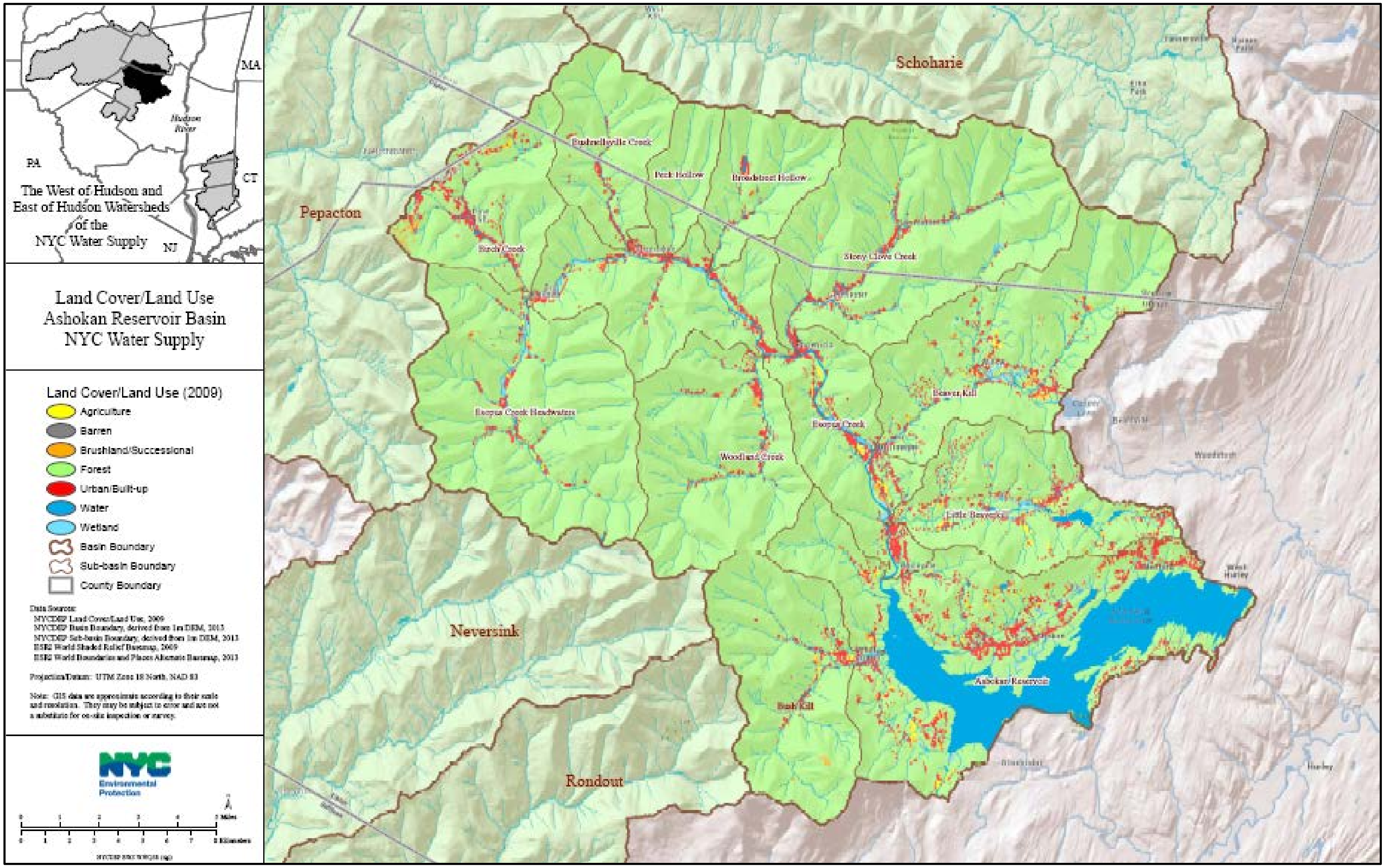

Figure 6-1 Ashokan Basin land cover.

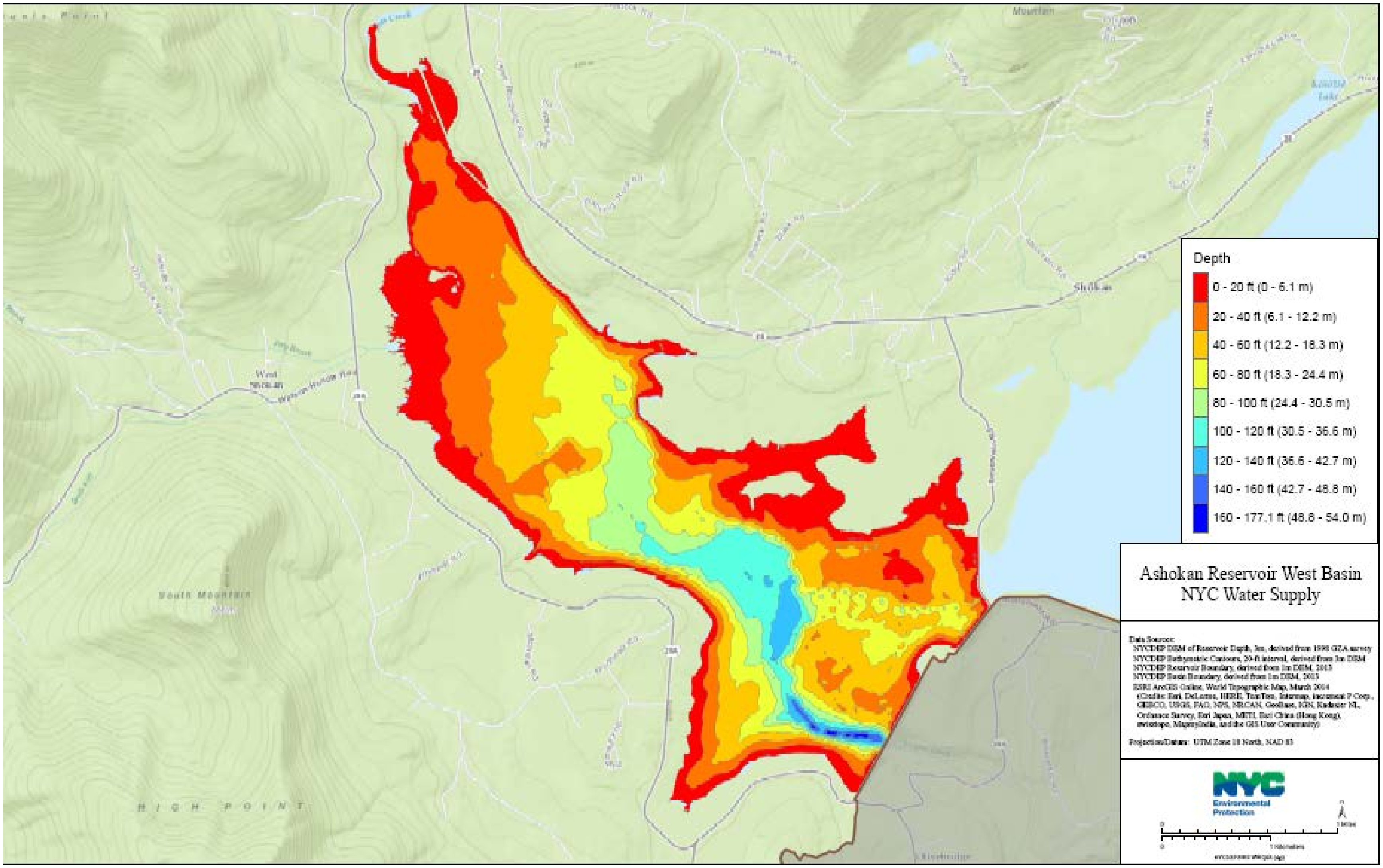

Figure 6-2 Ashokan Reservoir West Basin bathymetry.

6.3 Time Series Data Development

An inventory of the necessary raw time series data for watershed and reservoir model input and calibration is presented in Table 6-1 and Table 6-2, respectively. The time series data includes meteorology, streamflow, water quality, and point source loads for watershed models. For reservoir models the data includes meteorology, streamflow, stream, reservoir and key point water quality and reservoir operations. Data sets are updated as new data become available. Lag times between the current date and the dataset end dates are the result of QA/QC processes at the data source and/or procurement timelines driving the acquisition of any purchased data.

For this reporting period, the Northeast Regional Climate Center (NRCC) Meteorology, NYCDEP Meteorology, NYCDEP Stream and Limnology Water Quality, NYCDEP keypoint data have either become available via online sources and/or have been added to the inventory.

The NYSDEC Water Quality data has provided the Modeling Group with a robust dataset from baseline and storm event sampling of the West Branch of the Delaware River at Beerston from 1992 to the 2010. NYCDEP has taken over the collection and analysis of samples from this site and, as such, the data from this site are now included in the NYCDEP Laboratory Information Management System (LIMS) dataset.

The NRCC Meteorological Data is now also available via the NRCC's Applied Climate Information System (ACIS). ACIS is a data access system developed by the NRCC to assist in the dissemination of data. In addition to access to updated data from the NRCC cooperative stations the ACIS will provide access to gridded meteorological data sets.

Table 6-1 Inventory of data used for watershed modeling.

Data Type	Data Source	Data Description	Dates*	Modeling Needs
Meteorology	Northeast Regional Climate Center	Daily Precipitation and Max/Min Temperature	Pre 1960-2013	Model Input
Wastewater Treatment Plants	DEP	Monthly WWTP Nutrient Loads	1990-2009	Model Input
Streamflow	USGS	Daily and Instantaneous Streamflow	Period of record available online via USGS	Hydrology Module Calibration / Nutrient and Sediment Loads
Water Quality	DEP	Routine and Storm Stream Monitoring	Period of record avail. via LIMS	Nutrient and Sediment Loads for Water Quality Calibration
	NYSDEC**	Stream Monitoring at West Branch Delaware River	1992-2010 w/ recent years avail. via LIMS	Nutrient and Sediment Loads for Water Quality Calibration

*Dates represent total span for all data sets combined. Individual station records vary.
**Now part of the DEP Water Quality dataset.

Table 6-2 Inventory of data used for reservoir modeling.

Data Type	Data Source	Data Description	Dates*	Modeling Needs
Meteorology	DEP	Air Temperature, Relative Humidity, Solar Radiation, PAR, Wind Speed, Wind Direction, and Precipitation	1994-June, 2010 Period of record avail. Operations	Model Input
Keypoint and Reservoir Operations	DEP	Tunnel Water Quality, Flow and Temperature; Reservoir Storage, Spill, Withdrawal, and Elevation	Period of record avail. via LIMS	Model Input
Streamflow	USGS	Daily and Instantaneous Streamflow	Period of record available online via USGS	Model Input
Stream Hydrology	DEP	Stream Water Quality, Flow and Temperature	Period of record avail. via LIMS	Model Input
Limnology	DEP	Reservoir Water Quality, and Temperature Profiles	Period of record avail. via LIMS	Model Input

*Dates represent total span for all data sets combined. Individual station records vary.

7. Modeling Program Collaboration

7.1 Participation in Ongoing External Research Projects

In the last year, the Water Quality Modeling Section has participated in several projects related to the Section's ongoing work on testing and improving models simulating watershed hydrology and water quality, reservoir water quality and reservoir system operations. A number of projects also supported the Water Quality Modeling Section's evaluation of climate change as outlined in DEP's Climate Change Integrated Monitoring Project (CCIMP).

Water Research Foundation Project 4262 - Vulnerability Assessment and Risk Management Tools for Climate Change: Assessing Potential Impacts and Identifying Adaptation Options

Collaborators: Hazen and Sawyer, National Center for Atmospheric Research, Hydrologics, Stockholm Institute, Rand Corporation.

The main focus of the CCIMP is to identify potential climate change impacts on the water supply using the structured quantitative framework of water quality models. Project 4262 complements the CCIMP by going one step further. Once climate change impacts have been identified this project seeks to develop risk management approaches that will help managers prioritize risks and decide on a course of action. This project focused on climate change impacts related to turbidity and water availability, and made use of climate and streamflow scenarios developed as part of the CCIMP. Through an iterative modeling process, using the DEP OASIS and CE-Qual-W2 models, water supply vulnerability was examined in relationship to uncertainties, in future climate, stream turbidity relationships, and water supply demand. The project confirmed that under present conditions dynamic system operations remain an effective turbidity control measure. The project also showed that system vulnerability is sensitive to changes in future water supply demand and the erosional processes controlling the turbidity inputs to the reservoirs (as captured in present models by turbidity vs. flow relationships). This project ended in April 2013. A more detailed description of our contribution is given in Section 3.2 of this report.

Water Research Foundation Project 4306 – Analysis of Reservoir operations under Climate Change

Collaborators: Hazen and Sawyer, National Center for Atmospheric Research, Hydrologics.

WRF project 4306 evaluated the possibilities of adapting and modifying reservoir operation policy to mitigate the impacts of climate change on water supply quantity and quality. This project tested methodologies needed to systematically evaluate and update operational policies in response to a changing climate, by working with 6 water utilities as test cases. For NYC the project is closely related to WRF project 4262, and the same Water Quality Modeling Section future climate and stream flow scenarios used in project 4262 were also used here. The main difference between these projects is that 4306 focused more on the possibility of improving outcomes through better reservoir operation rules that make use of inflow forecasts (dynamic rules) whereas 4262 focused on identifying uncertainty in the modeling assumptions that would lead to unacceptable levels of system vulnerability. This project reached similar conclusions as 4262 regarding the resiliency of the NYC water supply to a range of hydrologic conditions and confirmed that uncertainty in water demand and stream turbidity response affected levels of resilience. Incorporation of inflow forecasts into dynamic reservoir operating rules (as is being done by the OST) was shown to improve water supply operation. This project ended in April 2013. A more detailed description of our contribution is given in Section 3.3 of this report.

Water Research Foundation Project 4422 – OnLine NOM Characterization: Advanced Techniques for Controlling DBPs and for Monitoring Changes in NOM under Future Climate Change Scenarios

Collaborators: Hazen and Sawyer, NYCDEP, and University of Massachusetts

The purpose of this research project is to evaluate the effectiveness of a dynamic on-line monitoring strategy and response system that can be used to detect subtle changes in the character and amount of natural organic matter (and its effect on disinfection byproduct formation potential) that can occur during "normal weather", extreme weather events, and under future climate change scenarios. Typical monitoring information such as total or dissolved organic carbon and UV_{254} absorbance measurements is useful, but often not sufficient. Thus, the monitoring protocols and techniques evaluated in this study are expected to provide monitoring tools that result in a more robust, sensitive analysis of DBPFP for influent waters. Specific research objectives include:

1. Evaluating the use of advanced on-line instrumentation technology (e.g., S::CAN units) based on UV spectral derivatives to detect changes in the concentration and characteristics of disinfection byproduct precursors.
2. Developing correlations between the output of the online units with NOM properties discerned from characterization methods including fractionation techniques based on NOM polarity, as well as examination of spectral properties, including generating 3-D fluorescence spectra and analyzing absorbance spectral slopes, for both whole NOM and separated fractions.
3. Evaluating specific excitation/emission pairings from the 3-D fluorescence monitoring for use in the future development of on-line monitoring tools
4. Developing correlations of NOM properties determined in the laboratory and using the online units with HAA and THM formation potential
5. Determining effectiveness of on-line instrumentation technology to predict changes in DBP formation potential of NOM in real-time as part of the development of an Operations Support Tool (OST) guiding reservoir operations in the NYC water system.

Anticipated completion for this project is 2015.

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

WUCA is a group of ten of the nation's largest water utilities, whose mission is to improve research on the effects of climate change on drinking water supplies, and to help water suppliers to develop strategies to cope with the potential impact of climate change (http://www.wucaonline.org). The purpose of the PUMA project is: 1) to identify climate modeling tools and techniques that are appropriate for analysis of climate change impacts on water supplies; 2) develop guidelines for the use of climate data and model simulation data including methodologies for describing uncertainty; 3) to suggest how these data can be used to support water planning and decision making; 4) to build and enhance collaboration between water utilities and NOAA Regional Integrated Sciences and Assessment (RISA) centers; and 5) to identify future research investments that would serve the water utility community. The Water Quality Modeling Section has participated in the WUCA/PUMA project by attending the project kickoff meeting in December 2010, and by participating in regular phone conferences and planning meetings since then. The NYC water supply and the work undertaken as part of the CCIMP will be highlighted as a case study in a white paper that will be a product of the PUMA project. The NYC water supply provides a unique case study since climate change impacts expected for the Northeastern United States are more water quality related as opposed to the water quantity concerns that are more prevalent in the Western United States. Furthermore, financial support for the CCIMP (as part of FAD funding) is unusually generous allowing DEP to have one of the most extensive climate change research programs of any of the WUCA utilities. DEP is the only utility using post-doctoral support scientists to carry out much of its climate change research in-house, whereas other utilities have instead to rely more extensively on contracts with outside consultants to evaluate climate change impacts. Information for the case study is being collected through a series of interviews and surveys developed by Status Consulting for WUCA. DEP was one of the first utilities to participate in the survey and during 2013 we were re-surveyed to follow our progress in the CCIMP.

In 2014 DEP continued to take part in monthly conference calls and also took part in the review of a draft white paper that describes how utilities are using climate data for adaptive planning. DEP is one of the four case studies presented in the paper, which is titled: *Bridging the Gap: Integrating Climate Model Output with Water Utility Modeling at Four Utilities through the Piloting Utility Modeling Applications Project*.

7.2 Modeling Program Contract Management

During 2014 the Water Quality Modeling Section continued to manage a contract with the Research Foundation of the City University of New York (RF-CUNY) that provides support for model and data development by post-doctoral scientists who work with the Water Quality Modeling section on a day to day basis as described below.

In 2014 the second contract with RF-CUNY ended, and a third contract commenced on August 15, 2014. The second contract provided CUNY with the funding needed to hire seven post-doctoral research associates (post-docs) who were jointly advised by CUNY faculty, external faculty advisors, and DEP scientists. The post docs were stationed in Kingston, NY working with the Water Quality Modeling Section on a day-to-day basis. The positions were for an initial two year period, with the possibility of an additional two year extension. This contract ended in August of 2014 with four of the post-docs completing their time at DEP while a fifth continued at DEP under the new contract. Three additional post-docs were selected in 2014 with one beginning to work at DEP in December 2014 and the other two beginning in early 2015.

The goal of the new third contract is for RF-CUNY to continue to supply support in order to produce modeling software and data sets that will help DEP achieve three goals that are part of the DEP water quality modeling program as defined in the most recent Filtration Avoidance Determination (FAD):

1) Evaluate the effect of climate change on the NYC water supply
2) Evaluate the effect of watershed management programs and land use changes on the NYC water supply

3) Develop models and datasets to evaluate the impacts of watershed and in-reservoir processes on reservoir dissolved organic carbon and disinfection by-product formation potential

The support is supplied in the form of the services of the four on-site support scientists, who will be advised and supervised by DEP staff as well as five part-time faculty advisors, one of whom will be a CUNY senior scientist and located at DEP's Kingston, NY location on a part-time basis. The support scientists were again hired by CUNY (with DEP approval) for an initial two year contract, with the possibility of a further two year extension if DEP approves such extension. Faculty advisors will assist DEP in managing the research activities and interpreting scientific data derived from the work of the support scientists.

Specific projects for the current contract include:

1. Evaluation of climate change

The purpose of this project is to continue the work already underway as part of the DEP Climate Change Integrated Modeling Project (CCIMP). A key task will be to update the future climate scenarios used to drive DEP watershed and reservoir models using information obtained from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) data archive. CMIP5 data will be downloaded and appropriate downscaling methods will be tested and applied to provide model-driving data. In addition to the change factor methods previously used by the water quality modeling group, other downscaling methods that better incorporate the effects of extreme events will be examined. For example, the use of weather generators will be tested. Updated climate scenarios will be used with DEP models to evaluate future impacts on watershed hydrology, forest processes and watershed biogeochemistry, reservoir nutrient loading and trophic status, reservoir turbidity and system operation. In concert with the future climate scenarios described above, model simulations will be undertaken using a bottom-up approach which will have the goal of identifying critical climate related stress levels, which could lead to significant water quality and supply concerns. These stress levels will be compared with results of top-down simulations to better understand the possibility of future stress on the water supply.

2. Evaluation of FAD programs and land use change

This project will directly support the DEP modeling group work in simulating the effects of FAD-mandated watershed management projects on reservoir water quality. An important component of this work will be to develop a SWAT modeling application for the Cannonsville and Pepacton watersheds that will provide more robust simulations of watershed nutrient loads and the effects of watershed management (particularly agricultural programs) on these loads. The impact of various agricultural land use and management practices on nutrient, carbon, and sediment loads to NYC reservoirs is very sensitive to the timing and location of agricultural activity in relation to watershed hydrology. The SWAT model can more completely account for the effects of specific agricultural land use and management practices on material transport and loadings. Concurrent with the development of SWAT model applications in the Cannonsville and Pepacton watershed will be the need to develop and update the databases of land use and agricultural practices that support the model simulations. The project will also run DEP reservoir eutrophication models and evaluate data from both the watershed and reservoir models in order to quantify the effects of FAD mandated programs on reservoir water quality.

3. Simulating DOC and DBP levels in NYC water supply reservoirs

This is a major new modeling initiative in response to increasingly stringent regulatory requirements on disinfection by products (DBP); possible future needs to predict DBP formation potential as a criterion for water source use in DEP's operation support tool (OST); the need to predict changes in DBP as a consequence of climate change: and the need to better understand the links between external watershed loading and internal reservoir production of dissolved organic carbon (DOC) on DBP formation. This effort will involve both watershed model development to simulate the external loading of DOC to water supply reservoirs, and reservoir modeling to help quantify the internal processing and production of DOC within the reservoirs. New reservoir model components will also be needed to simulate the DBP formation potential as a function of DOC concentration and the chemical composition of the DOC. The main product of this work will be the development and testing of new modeling tools and the work will focus on two test systems, Neversink and Cannonsville, where the relative roles of external vs. internal DOC sources are expected to vary. Given that this project contains a large component of research and development, it is anticipated that the first two project years will largely involve the evaluation of available models, and their ability to provide DOC/DBP simulation capability. Following initial model evaluation and testing recommendations will be made on the needs for future model and data set development that will be undertaken in the third and fourth project years.

8. Modeling Program Scientific Papers and Presentations

Papers published in peer-reviewed scientific journals and presentations given at professional meetings assist in meeting the goals of DEP's Modeling Program by having DEP scientists and external researchers working in collaboration with DEP develop and share tools and applications that advance the science of water quality modeling. The papers and presentations from 2014 are listed in the section below. They cover a wide range of modeling topics including model testing and development, data analysis tools, development and use of the Operations Support Tool, climate change studies, data collection efforts, process studies, and other relevant topics.

8.1 Published Scientific Papers for 2014

Huang, Y., 2014. **Comparison of general circulation model outputs and ensemble assessment of climate change using a Bayesian approach**. Global and Planetary Change 122:362-370. doi: 10.1016/j.gloplacha.2014.10.003.

Abstract: A number of general circulation models (GCMs) have been developed to project future global climate change. Unfortunately, projected results are different and it is not known which set of GCM outputs are more creditable than the others. The objective of this work is to present a Bayesian approach to compare GCM outputs and make an ensemble assessment of climate change. This method is applied to Cannonsville Reservoir watershed, New York, USA. The GCM outputs under the 20C3M scenario for a historical time period of 1981–2000 are used to calculate posterior probabilities, and the outputs under the scenarios (A1B, A2 and B1) for the future time period of 2084–2100 are then processed using the Bayesian modeling averaging (BMA) which is a statistical procedure that infers a consensus prediction by weighing individual predictions based on the posterior probabilities, with the better performing predictions receiving higher weights. The obtained results reveal that the posterior probabilities are slightly different for four variables including average, maximum and minimum temperatures, and shortwave radiation, implying that the GCM outputs are qualitatively different for these four variables, but the distributions of posterior probabilities are flat for precipitation and wind speed, suggesting that the GCM outputs are qualitatively similar for these two variables. The results also show that no one set of GCM data are the best for all six meteorological variables. Furthermore, the results indicate that the projected changes are for regional warming, but the changes in precipitation, wind speed, and shortwave radiation depend on the emission scenarios and seasons. The application of the method demonstrates that the Bayesian approach is useful for the comparison of GCM outputs and making ensemble assessments of climate change.

Huang, Y., 2014. **Multi-objective calibration of a reservoir water quality model in aggregation and non-dominated sorting approaches**. Journal of Hydrology 510:280-292. doi:10.1016/j.jhydrol.2013.12.036.

Abstract: Numerical water quality models are developed to predict contaminant fate and transport in receiving waters such as reservoirs and lakes. They can be helpful tools for water resource management. The objective of this study is to calibrate a water quality model which was set up to simulate the water quality conditions of Pepacton Reservoir, Downsville, New York, USA, using an aggregation hybrid genetic algorithm (AHGA) and a non-dominated sorting hybrid genetic algorithm (NSHGA). Both AHGA and NSHGA use a hybrid genetic algorithm (HGA) as optimization engines but are different in fitness assignment. In the AHGA, a weighted sum of scaled simulation errors is designed as an overall objective function to measure the fitness of solutions (i.e., parameter values). In the NSHGA, a method based on non-dominated sorting and Euclidean distances is proposed to calculate the dummy fitness of solutions. In addition, this study also compares the AHGA and the NSHGA. The purpose of this comparison is to determine whether the objective function values (i.e., simulation errors) and simulated results obtained by the AHGA and the NSHGA are significantly different from each other. The results show that the objective function values from the two HGAs are good compromises between all objective functions, and the calibrated model results match the observed data reasonably well and are comparable to other studies, supporting and justifying the use of multi-objective calibration.

Huang, Y., 2015. **Uncertainty Assessment in Reservoir Water Quality Modeling: Implication for Model Improvement**. Journal of Environmental Engineering 141:04014051. doi: 10.1061/(ASCE)EE.1943-7870.0000886.

Abstract: As reservoir simulation models become more widely used, there is greater need for uncertainty assessment in water quality modeling. In comparison with the modeling of quantity phenomena, such as hydrological modeling, water quality modeling involves additional uncertainties in the modeling of pollutant loadings and the transport and fate of contaminants in receiving waters. In this work, a general and flexible method based on generalized likelihood uncertainty estimation (GLUE) is used to estimate the uncertainty in reservoir water quality modeling that arises from parameter uncertainty and error in model inputs. A one-dimensional model which was set up to simulate the hydrothermal and water quality of Pepacton Reservoir, part of the New York City water supply system, was used to demonstrate the method. Obtained results show that most model parameters and inputs follow wide non-Gaussian distributions, indicating they are of high uncertainty. The results also show that uncertainty is low for the simulated water temperatures of the epilimnion and hypolimnion, and dissolved oxygen (DO) of the epilimnion. Unfortunately, the simulation uncertainty for total phosphorus and chlorophyll a of the epilimnion and hypolimnion, and DO of the hypolimnion is high, especially at peak concentrations. These results can be helpful in understanding and improving the model.

Mukundan, R. and R. Van Dreason, 2014. **Predicting Trihalomethanes in the New York City Water Supply**. J. Environ. Qual. 43:611-616. doi: 10.2134/jeq2013.07.0305.

Abstract: Chlorine, a commonly used disinfectant in most water supply systems, can combine with organic carbon to form disinfectant byproducts, including carcinogenic trihalomethanes. We used water quality data from 24 monitoring sites within the New York City water supply distribution system, measured between January 2009 and April 2012, to develop an empirical model for predicting total trihalomethane (TTHM) levels. Terms in the model included the following water quality parameters: total organic carbon, pH, water age (reaction time), and water temperature. Reasonable estimates of TTHM levels were achieved with overall R^2 of about 0.75, and predicted values on average were within 6 μg L^{-1} of measured values. A sensitivity analysis indicated that total organic carbon and water age are the most important factors for TTHM formation, followed by water temperature; pH was the least important factor within the boundary conditions of observed water quality. Although never out of compliance in 2011, the TTHM levels in the water supply increased after tropical storms Irene and Lee, with 45% of the samples exceeding the 80 μg L^{-1} maximum contaminant level in October and November. This increase was explained by changes in water quality parameters, particularly by the increase in total organic carbon concentration during this period. This study demonstrates the use of an empirical model to understand TTHM formative factors and their relative importance in a drinking water supply. This has implications for simulating management scenarios and real-time estimation of TTHMs in water supply systems under changing environmental conditions.

Pradhanang, S. M., R. Mukundan, M. S. Zion, E. M. Schneiderman, D. Pierson and T. S. Steenhuis, 2014. **Quantifying in-Stream Processes on Phosphorus Export Using an Empirical Approach**. Journal of Water Resource and Protection 6:120-131. doi: 10.4236/jwarp.2014.62017

Abstract: In-stream nutrient release and retention control the timing and quantity of export at the watershed outlet by mobilization and transport of phosphorus (P) sources from land to the channel, and remobilization of transient stores of P from stream beds. We investigated the significance of stream processes in regulating P loading to the Cannonsville watershed, NY, USA. A mass balance of estimated P inputs to the stream with observed P export at the watershed outlet was used to quantify P delivery and explore the behavior of P. Stream channel transport of both dissolved and particulate P is found to be non-conservative, with dissolved P being retained during low flows and particulate P released during high flows. The results suggest that differences in the magnitude and relative importance of in-stream biogeochemical processes under different flow regimes regulate P delivery in ways that may influence ecological impacts to downstream river reaches and reservoirs.

Rossi, N., 2014. **Potential Impacts of Changes in Climate on Water Quality in New York City's Ashokan**. Environmental & Water Resources Engineering Masters Project, University of Massachusetts - Amherst, Amherst, MA. http://scholarworks.umass.edu/cee_ewre/61.

Abstract: This thesis investigates an approach for determining water resources vulnerability caused by climate change and applies it to a case-study for the New York City Water Supply System (NYCWSS).The results provide potential responses of the system to changes in climate and guidance that can inform short and long-term planning decisions. This research models the hydrology and operations of the NYCWSS and includes a statistical model of turbidity concentration in the Ashokan Reservoir. Using a stochastic weather generator, incremental changes are made to precipitation and temperature and used to drive the coupled hydrology-simulation model. The results are aggregated and examined to show the sensitivity of the system, and in particular Ashokan Reservoir turbidity, to changes in climate. The results are briefly compared with the latest GCM data to provide insight into expected changes in turbidity over the next half-century.

Tang, G., T. Hwang and S. Pradhanang, 2014. **Does consideration of water routing affect simulated water and carbon dynamics in terrestrial ecosystems?** Hydrology and Earth System Sciences 18:1423-1437. doi:10.5194/hess-18-1423-2014.

Abstract: The cycling of carbon (C) in terrestrial ecosystems is closely coupled with the cycling of water. An important mechanism connecting ecological and hydrological processes in terrestrial ecosystems is lateral flow of water along landscapes. Few studies, however, have examined explicitly how consideration of water routing affects simulated water and C dynamics in terrestrial ecosystems. The objective of this study is to explore how consideration of water routing in a process-based hydro-ecological model affects simulated water and C dynamics. To achieve that end, we rasterized the regional hydro-ecological simulation system (RHESSys) and employed the rasterized RHESSys (R-RHESSys) in a forested watershed. We performed and compared two contrasting simulations, one with and another without water routing. We found that R-RHESSys was able to correctly simulate major hydrological and ecological variables regardless of whether water routing was considered. When water routing was considered, however, soil water table depth and saturation deficit were simulated to be greater and spatially more heterogeneous. As a result, water (evaporation, transpiration, and evapotranspiration) and C (forest productivity, soil autotrophic and heterotrophic respiration) fluxes also were simulated to be spatially more heterogeneous compared to the simulation without water routing. When averaged for the entire watershed, the three simulated water fluxes were greater while C fluxes were smaller under simulation considering water routing compared to that ignoring water routing. In addition, the effects of consideration of water routing on simulated C and water dynamics were more apparent in dry conditions. Overall, the study demonstrated that consideration of water routing enabled R-RHESSys to better capture our preconception of the spatial patterns of water table depth and saturation deficit across the watershed. Because soil moisture is fundamental to the exchange of water and C fluxes among soil, vegetation and the atmosphere, ecosystem and C cycle models therefore need to explicitly represent water routing in order to accurately quantify the magnitude and patterns of water and C fluxes in terrestrial ecosystems.

8.3 Conference Presentations for 2014

In 2014 DEP's Water Quality Modeling Program prepared presentations for several scientific conferences. These presentations help to illustrate DEP's continuing efforts to improve and expand their modeling capabilities.

NYC Watershed Science and Technical Conference
Sept. 10, 2014
West Point, NY

Potential Impacts of Climate Change on Turbidity in New York City Water Supply Catskill System.

Mark Zion, Donald C. Pierson, New York City Department of Environmental Protection (DEP) Nihar Samal, Rajith Mukundan, City University of New York, Institute for Sustainable Cities

Abstract: An integrated modeling system is used to investigate the potential effects of future climate change on turbidity in the Catskill System of the New York City water supply including Schoharie and Ashokan Reservoirs. The modeling is used to gain insight into how future climate changes affect the watershed inputs of water and turbidity into the reservoirs, and the transport of turbidity-causing particles within the reservoirs.

Developing a Long-Term Strategy to Simulate Dissolved Organic Carbon and Disinfection By-Products in NYC Water Supply Reservoirs.

Donald Pierson, New York City Department of Environmental Protection (DEP); David G. Smith, CUNY Hunter College Institute for Sustainable Cities

Abstract: The New York City Department of Environmental Protection is planning to undertake a long-term effort to develop, test and apply a series of models that can be used to simulate the quantity and composition of DOC exported to our drinking water reservoirs; DOC produced or transformed within the reservoirs; and the potential formation of disinfection by-products (DBPs) from DOC. The need to develop a DOC/DBP modeling effort has been given greater prominence by adoption of the stage II standard for distribution system DBP monitoring, evidence that extreme storm events can result in large rates of DOC loading to reservoirs, and the concern that DOC/DBP levels should be included in future scenarios produced as part of DEP's Climate Change Integrated Modeling Project. As a first step in this effort DEP convened a two day workshop involving invited experts in watershed hydrology and biogeochemistry, limnology, and water treatment and disinfection by-product formation. In this presentation we outline the challenges identified by the workshop, the longterm vision of a DBP modeling program and DEP's plan for the first year of program development.

The Occurrence of Dissolved Organic Carbon (DOC) in New York City's Catskill Mountain Watersheds.

Richard Van Dreason, New York City Department of Environmental Protection (DEP); Rajith Mukundan , City University of New York

Abstract: In this presentation we will describe the occurrence of DOC within the Catskill Mountain portion of New York City's water supply system. Regional and seasonal patterns will be compared using data collected from the Catskill reservoirs and from storm events collected on the major streams of the region. We also examine the patterns in DOC concentrations over time, since increases in the reservoirs could have important ramifications on future DBP formation in the distribution system.

Trophic Response of Catskill and Delaware Reservoirs Compared to OECD Regressions.

Lorraine Janus, James Mayfield, Karen Moore and Richard Van Dreason, New York City Department of Environmental Protection (DEP)

Abstract: New York City reservoirs vary in their trophic responses to nutrients according to different meteorological, physical and chemical factors. Twenty-five years of data from DEP's Catskill and Delaware reservoirs are used as an independent test case for the OECD standard regressions. Given the wide variety of responses possible at a given nutrient level, we explore patterns in variation to identify major environmental drivers of water quality.

Dissolved Organic Carbon and Streamflow Relationships in the New York City West of Hudson Watershed.

James Mayfield, Richard Van Dreason, New York City Department of Environmental Protection (DEP)

Abstract: The New York City Department of Environmental Protection (DEP) will develop relationships between dissolved organic carbon (DOC) and stream flow using data collected by the United States Geological Survey for DEP at multiple sites in the West of Hudson watershed. Ultimately these relationships will be used by DEP in its efforts to develop dissolved organic carbon (DOC)/disinfection by-product (DBP) models to simulate reservoir DOC and DBP production and help inform the operation of the water supply.

Effective Water Quality Monitoring of New York City's Reservoirs: An Overview of the RoboMon Project.

Michael Spada, Joseph Miller, New York City Department of Environmental Protection (DEP)

Abstract: Water quality monitoring information is critical to guide effective management and protection of water supplies. However, event-based water quality problems, such as the elevated turbidity levels that are experienced in certain New York City reservoirs in response to runoff events, represent special challenges for effective monitoring. The Robotic Water Quality Monitoring Network (Robomon) helps meet these challenges. The network currently consists of four Robo-buoys and two Robo-huts deployed east and west of the Hudson River.

Use of the Operations Support Tool (OST) with HEFS Forecasts: Winter 2013–14.
James Porter, New York City Department of Environmental Protection (DEP)

Abstract: The New York City Department of Environmental Protection (NYCDEP) operates the City's water supply system, providing more than one billion gallons of high quality water each day to more than nine million people. DEP has recently implemented the Operations Support Tool (OST), a decision-support system based on runoff forecasts from the National Weather Service's Hydrologic Ensemble Forecast Service (HEFS). HEFS forecasts include meteorological drivers and snowpack data. Several case studies of OST usage will be presented.

2014 Catskill Environmental Research & Monitoring Conference
October 23–24, 2014
Belleayre Mt. Ski Center, Highmount, NY

Adventures in Data: Revisiting Historical Water Quality and Streamflow Data in the Catskills
Karen Moore and Jim Mayfield, NYCDEP

Changing Frequencies of Extreme Hydrological Events in the Catskill Mountains
Allan Frei, CUNY- Hunter College

Potential Impacts of Climate Change on Water Temperature and Turbidity Transport in New York City Water Supply Catskill System Reservoirs
Mark Zion, NYCDEP

An Overview of DEP's Robotic Water Quality Monitoring Program
Andrew Bader, NYCDEP

The Occurrence of Dissolved Organic Carbon (DOC) in New York City's Catskill Mountain Watersheds
Rich Van Dreason, NYCDEP

Global Lake Ecological Observatory Network (GLEON) Meeting
October 27–31, 2014
Orford, Québec, Canada

Applying a Novel Approach to the Analysis of Long-Term Water Quality Data
Karen E.B. Moore and James D. Mayfield, NYCDEP

Abstract: Years of investment in watershed water quality monitoring have informed policy and planning efforts for New York City's water supply. We took advantage of the

wealth of accumulated streamflow and water quality data for the West Branch of the Delaware River and other long-term monitoring sites to apply the “Weighted Regressions on Time, Discharge, and Season” approach described by Hirsch et al. (2010) to gain insights into the long-term record and look for new revelations in the data. Software tools including EGRET (Exploration and Graphics for RivEr Trends) and dataRetrieval, R packages developed by Hirsch and others at the U.S. Geological Survey, are facilitating the process, and we believe there is great value in re-examining the long-term record as the record builds, particularly in the context of severe storms and climate change.

American Water Resources Association 2014 Annual Water Resources Conference
November 3–6, 2014
Tysons Corner, VA

Ensemble Streamflow Forecasts and Water Supply Reservoir Operations: New York City's Operations Support Tool (OST) - James Porter, NYC Department of Environmental Protection, Grahamsville, NY (coauthor: A. H. Matonse)

Abstract: The New York City Department of Environmental Protection (NYCDEP) operates the City's water supply system, providing more than one billion gallons of high quality water each day to more than nine million residents in the City and in several outside communities. The water is delivered via aqueducts from a 2,000 square mile watershed that extends more than 125 miles from the city. The system is comprised of 19 reservoirs and three controlled lakes with a total capacity of over 580 billion gallons. Managing such a complex system in an increasingly stringent regulatory environment and under a changing climate requires cutting-edge scientific tools. To meet this need, NYC worked with a team of consultants and expanded on its existing partnership with the National Weather Service (NWS) to build a decision support system known as the Operations Support Tool (OST). One of the keys to OST is streamflow forecasts derived from the NWS Hydrologic Ensemble Forecast Service (HEFS). HEFS is new system which ingests meteorological forecasts and current snowpack data to produce a set ("ensemble") of streamflow forecasts. These forecasts are input to OST to predict reservoir conditions in the future, allowing water supply managers to model potential operations a priori and assess the probability of resulting outcomes. OST has been in development for several years and has been used with statistical forecasts that did not include the meteorological drivers or snowpack data present in HEFS forecasts. OST including HEFS forecasts was implemented in late 2013. This talk will present some ways OST with HEFS has been used to help manage the water supply reservoir system, including during the winter of 2013-14 when a large snowpack presented challenging operational conditions.

Ensemble Forecasting in Support of Dynamic Reservoir Operations - Gerald Day, Riverside, Fort Collins, CO (co-authors: J. Schaake, M. Thiemann, S. Draijer, G. Miller)

Abstract: As water managers are faced with competing and increasing water demands, variable water supplies, and the potential impact of climate change, dynamic reservoir

operations present an attractive adaptation approach to stretch limited supplies. Dynamic reservoir operations leverage knowledge of the system state in variables such as flow, storage levels, snowpack, as well as forecasts of future flows and demands. Probabilistic forecasts of flows enable a water manager to take advantage of information about future water availability, while accounting for the uncertainty of the forecast. The uncertainty information provides the basis for risk-based decision making. Decision rules can be configured to minimize the frequency or severity of violating system operating objectives. Ensemble forecasts are becoming a common and popular way of providing probabilistic forecast information. When coupled with water supply system models, the ensemble forecasts can be used to generate an ensemble of system variables, e.g., reservoir inflows. The ensembles of future system states can be used to estimate the probability of reaching system targets, e.g., reservoir pool levels. The New York City Department of Environmental Protection (DEP) has developed an Operations Support Tool (OST) to support its water supply operations and planning activities. The OST includes a database of historical and real-time observations, a model of the water supply system that simulates reservoir operations, and lake water quality models developed to evaluate alternatives for managing turbidity in the Catskill and Delaware reservoirs. A key element of the OST is the use of ensemble streamflow forecasts to predict probability distributions of future system states. DEP managers review the results and make operations decisions using risk-based metrics such as the probability of refill or the likelihood of a turbidity event. The system includes the ability to select from four different methodologies for generating ensemble forecasts. The methods range in complexity from a conditional streamflow analysis technique developed by Hirsch in the late 1970's to the recently developed National Weather Service Hydrologic Ensemble Forecast System (HEFS). The four methods are described along with their advantages and disadvantages. It is important that ensemble forecasts be consistent with the historical data used to calibrate the system operating rules and that the ensemble spread provides a reliable estimate of the uncertainty of the forecast. A methodology is presented for ensemble post-processing to ensure unbiased and reliable forecasts. Hindcasts are generated to provide a means to verify the forecast methodology and to test system operating rules using historical data. Metrics for evaluating probabilistic forecasts are described and verification results are presented for several key nodes in the New York City water supply system.

Hydrologic Forecasts for Dynamic Reservoir Operations Under Climate Change - Ben Wright, Hazen and Sawyer, Baltimore, MD (co-authors: M. Rivera, G. Day, B. Stanford)

Abstract: Altered precipitation patterns caused by climate change are of primary concern to drinking water utilities due to the direct influence on supply and quality of drinking water, as well as influencing a utility's ability to meet other objectives (environmental releases, hydropower, recreation, etc.). Water utilities are struggling with how best to prepare for the broad range of possible climate change impacts and are searching for new approaches to respond to an uncertain future. Dynamic reservoir operations have great potential as an agile tool to help utilities respond to the uncertainty of climate change. In most cases, operating objectives, which generally include

reliability, cost, and regulatory compliance, are more successfully achieved using dynamic operating rules because they are more flexible and capitalize on more information than static rules. This diversity of information tends to result in a more robust operational framework, providing utilities more options for operating their system to meet objectives under varying conditions. Hydrologic forecasts are a key component of proactive dynamic reservoir management (e.g. release restrictions to prepare for a drought or preventative drawdown in advance of a large storm), which can reduce uncertainty of future conditions to allow water managers to make more informed operational decisions. However, there is some concern that probabilistic hydrologic forecasts developed based on historical hindcasts will lose forecast skill or become inconsistent under climate change scenarios. As part of a Water Research Foundation project to develop guidance for utilities implementing dynamic reservoir operations, the effectiveness of probabilistic hydrologic forecasting was evaluated under a variety of challenging climate change scenarios. This presentation will provide the results of the analysis and demonstrate the utility of hydrologic forecasts for improving water resource system performance.

Case Studies Using Water Quality Models and Forecasts to Inform Reservoir System Decisions for the New York City Water Supply - Mark Zion, NYC Dept. of Environmental Protection, Kingston, NY (coauthors: D. C. Pierson, A. H. Matonse)

Abstract: Turbidity is a factor that can limit the use of the Catskill System portion of the New York City water supply. During periods of elevated reservoir turbidity daily decisions are carefully made to optimize system operations to meet water quality standards while ensuring adequate water storage levels within the entire NYC water supply system. To support these decisions, a combination of watershed, reservoir water quality, and water supply system simulation models are used to evaluate alternative operational scenarios within a probabilistic framework. These simulation models form the basis for the Operations Support Tool (OST). OST model predictions, based on future forecasts of meteorology and streamflow, provide better understanding of the implications of various operating strategies on future water quality. Uncertainty in future forecasts is estimated using a range of possible future scenarios that are based on near-term streamflow forecasts and long term historical data. This presentation focuses on examples of OST usage to help inform water supply operating decisions relative to turbidity. OST is used to investigate alternative operating strategies that vary reservoir releases and diversions. These reservoir operations improve system performance by altering transport of turbidity causing particles in the water supply, thereby minimizing turbidity impacts at critical locations within the water supply system.

Evaluating the Performance of Multiple Alternative Operating Rules under Climate Change: A Case Study of New York City - Leslie DeCristofaro, University of Massachusetts, Amherst, Amherst, MA (coauthor: R. Palmer)

Abstract: An increase in climate variability due to increased greenhouse gases (GHGs) in the Earth's atmosphere poses challenges for water management. Of particular interest to New York City water managers is the occurrence of weather events that have negative

impacts on the quality of water. These events typically are associated with intense precipitation, increased erosion, high suspended sediment, and high turbidity in streams and water supply lakes. Current operating rules are designed to mitigate the effects of these events on the quality of water provided to the end user. Questions remain as to whether these rules will continue to be robust under future climates and to what climate extremes operational changes can be used without an investment in new infrastructure. A screening tool simulating the operations of the NYC water supply system is developed VENSIM to include manager-defined targets and turbidity functions. The screening tool couples with a hydrology model developed in part with the New York City Department of Environmental Protection (NYCDEP). To observe operating rules and alternatives under varying climate, this study used a stochastic weather generator combining a Markov chain and knearest- neighbor resampling to create a number of long time-series to test the system. Parameters used in the weather generator were incrementally varied. Through this framework, the questions of which rule changes are constructive and under which climate futures should they be implemented are answered. These preliminary screening results will allow NYCDEP to focus on the rule changes and climate futures of greatest interest to them.

New York City's Operations Support Tool: Motivation, Use Cases, and Components
- Grantley Pyke, Hazen and Sawyer, Baltimore, MD (co-author: J. H. Porter)

Abstract: The NYC water supply system serves nine million people with over 1 BGD of water drawn from 19 interconnected reservoirs. Operation of this system is complex due to the interplay between multiple, often competing objectives, including water supply reliability, drinking water quality, environmental and recreational releases, hydropower generation, and peak flow mitigation for downstream communities. To balance these competing objectives and provide a robust probabilistic foundation for reservoir operations decision-making, the New York City Department of Environmental Protection (DEP) developed the Operations Support Tool (OST), a state-of-the-art decision support system to provide computational and predictive support for water supply operations and planning. This presentation describes the key operational objectives the OST was designed to support, and provides an overview of major OST components and functionality. The OST was designed to meet the meet the needs of a diverse group of end users. Key use cases include: * Routine probabilistic simulations to support daily reservoir operations decisions. Simulations are driven by ensemble forecasts and are initialized with the current day's reservoir states. * Short-term simulations to investigate water quality model performance and develop initial reservoir states for routine operation simulations. Simulations are driven by recent observed inflows, reservoir operations, and meteorology. * Long-term simulations to evaluate system operating rules, infrastructure scenarios, and vulnerabilities/adaptation options. Simulations are driven by historical inflows, or by derived inflows representative of future climate states. The OST is unique in its ability to support these different needs with one system model and one database. Use of the same modeling system to meet operations and planning needs ensures that all simulations are based on consistent assumptions and baseline operating rules, and eliminates the need to maintain two separate code bases and model platforms. Key components of OST that support this functionality include: * Automated near-real time

(NRT) data acquisition from multiple sources (e.g. USGS streamflows, NWS forecasts, SCADA reservoir operations data, meteorological stations, in-reservoir and in-stream water quality monitoring sites). * Timeseries data management system (AQUARIUS) for semi-automated data review/quality control. * Ensemble forecasting system to generate daily reservoir inflow forecasts extending from the current day out for one year. Multiple types of inflow forecasts are available (NWS HEFS, NWS AHPS, monthly and daily statistical models, and historical/non-conditional). * Reservoir system operations model (OASIS) covering the NYC reservoir system and the entire Delaware River basin. OASIS simulates operation of the reservoir system at a daily timestep, within physical and regulatory constraints, based on system operating rules and objectives. * Reservoir water quality models for four key reservoirs (based on the CE-QUAL-W2 hydrodynamic model, customized to include turbidity as a state variable), dynamically linked to OASIS, to capture the feedback between water quality and reservoir operations. * Post-processing/visualization tools, including native OASIS plotting capabilities, a MS Excel-based Analytical Dashboard for data exploration and automated report/presentation creation, and reservoir water quality animation software. The structure and capabilities of OST are expected to be a useful template for water utilities and water system managers seeking to balance competing objectives in the context of both near-term operations and long-term planning.

2014 American Geophysical Union Fall Meeting
Dec 15-19, 2014
San Francisco, CA

Pattern Scaling for Developing Change Scenarios in Water Supply Studies. Aavudai Anandhi, Kansas State University, Donald Pierson, Water Quality Modeling Group, New York City Department of Environmental Protection, Allan Frei, CUNY Hunter College

Abstract: Change factor methodology (CFM), or delta change factor methodology, is a type of pattern scaling. Although a variety of methods are available to develop scenarios, CFMs are widely used for their ease and speed of application and their capability to directly scale local data according to changes suggested by the global climate model (GCM) scenarios. Change factors (CFs) can be calculated and used in a number of ways to estimate future climate scenarios, but no clear guidelines are available in the literature to decide which methodologies are most suitable for different applications. This study compares and contrasts several categories of CFM (additive versus multiplicative and single versus multiple) for a number of climate variables. The study employs several theoretical examples as well as an applied study from the New York City water supply. Results show that in cases where the frequency distribution of the GCM baseline climate is close to the frequency distribution of the observed climate, or when the frequency distribution of the GCM future climate is close to the frequency distribution of the GCM baseline climate, additive and multiplicative single CFMs provide comparable results. Two options to guide the choice of CFM are suggested: the first is a detailed methodological analysis for choosing the most appropriate CFM, and the second is a default method for circumstances in which a detailed methodological analysis is too cumbersome.

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