Research, Assessment and Monitoring Strategy

for the Ashokan Watershed

2018

A collaborative research agenda developed
to inform stream management efforts
in the Ashokan Watershed

AWSMP

The Ashokan Watershed Stream Management Program (AWSMP) works to educate and inform communities about stream stewardship and best management practices, and coordinates stream management activities in the Ashokan watershed. These activities include stream and watershed research, assessment and monitoring projects.

The AWSMP publishes an annual Action Plan that is guided by a Stakeholder Council and its working groups, including the Stream Ecosystem Working Group that produced this strategy. The AWSMP provides limited funding to advance priority science needs through its Stream Management Implementation Program (SMIP) fund.

The AWSMP is a joint effort between Cornell Cooperative Extension (CCE) of Ulster County, Ulster County Soil and Water Conservation District, and the New York City Department of Environmental Protection.

For more information about the AWSMP and the Stream Ecosystem Working Group, please visit www.ashokanstreams.org. Comments, suggestions, or other inquiries can be directed to the CCE Program Coordinator, phone: 845-688-3047.

How to cite this report

AWSMP Stream Ecosystem Working Group. 2018. *Research, Assessment and Monitoring Strategy for the Ashokan Watershed*. Shokan, NY: Ashokan Watershed Stream Management Program, Cornell Cooperative Extension of Ulster County, 2018.

Research, Assessment and Monitoring Strategy
for the Ashokan Watershed

Table of Contents

Preface

In 2004, Cornell Cooperative Extension (CCE) of Ulster County was contracted by the New York City Department of Environmental Protection (DEP) to facilitate development of a stream management plan for the upper Esopus Creek. CCE facilitated a Project Advisory Committee and several working groups, including an Aquatic Ecosystem Working Group to advise development of the stream management plan.

As part of this process, Walt Keller - retired New York State Department of Environmental Conservation (DEC) Region 4 Fisheries Manager - was contracted by CCE to compile and review all existing data and literature pertaining to the upper Esopus Creek. Using this analysis as basis, the Aquatic Ecosystem Working Group reviewed the current state of knowledge of aquatic habitat conditions, outstanding data gaps, and limitations in the existing data and proposed additional studies and actions in the *2007 Upper Esopus Creek Aquatic Ecosystem Research & Assessment Strategy*.

After 10 years of stream management plan implementation, CCE reconvened the working group to review a now expanded body of data and literature. The renamed Stream Ecosystem Working Group was asked to review three broad topics where science is needed to effectively manage streams in the Ashokan Reservoir watershed: 1) Fish and Aquatic Ecosystems; 2) Sediment and Water Quality; and 3) Stream Assessment. Newly expanded sediment monitoring efforts funded by the DEP were incorporated into the review.

The purpose of the working group and this updated Research, Assessment and Monitoring Strategy for the Ashokan Watershed have endured since 2007: (1) to share the most up-to-date knowledge of stream ecosystem management issues and relate that information to others; (2) to consolidate that knowledge into recommendations that will inform future stream management actions; (3) to provide a research mechanism for interested parties to scope studies that satisfy those recommendations; and (4) to provide a forum for parties to coordinate on mutually beneficial next-steps.

This strategy will be regularly revisited in order to assess results and update proposed actions. Actions will be incorporated into the annual *Ashokan Watershed Stream Management Program Action Plan* and will guide CCE in leveraging allocated funding to implement projects that meet multiple objectives.

Our goal is to develop science that informs adaptive stream management and that provides a mechanism to achieve better project outcomes.

Stream Ecosystem Working Group Participants

Barry Baldigo, U.S. Geological Survey (Co-Lead)

Michael Flaherty, NYS Dept. of Environmental Conservation (DEC) Region 3 Fisheries (Co-Lead)

Peter Malaty, New York State DEC Region 3 Fisheries

Scott George, U.S. Geological Survey

Walt Keller, New York State DEC Region 4 Fisheries (Retired)

Ed Ostapczuk, Trout Unlimited

Chester Karwatowski, Trout Unlimited

Jason Siemion, U.S. Geological Survey

Thomas Baudanza, New York City DEP Fisheries

Don Kent, New York City DEP Ecological Research and Assessment

Danyelle Davis, New York City DEP Stream Management Program

Chris Tran, New York City DEP Stream Management Program

Adam Doan, Ulster County Soil and Water Conservation District (SWCD)

Allison Lent, Ulster County SWCD

Leslie Zucker, CCE Ulster County

Setting and Background

The Ashokan Reservoir watershed covers a 255 mi^2 area in the south-central Catskill Mountain region of southeast New York State. The rugged watershed terrain includes 21 peaks greater than 3,000 feet above sea level that are drained by a network of at least 459 miles of stream. Forested lands exceed 95% of the total watershed land cover, and mean annual precipitation is among the highest in the northeast. Remnant glacial lake deposits make streams susceptible to erosion and are the main contributor to turbidity in Catskill streams. There is no large-scale agricultural land use in the watershed.

The upper Esopus Creek is the primary tributary to the Ashokan Reservoir and drains 75% of the Ashokan Watershed. The entire 26-mile main stem of the upper Esopus Creek flows "clockwise" from the headwaters at Winnisook Lake on Slide Mountain to the Ashokan Reservoir through the Ulster County Towns of Shandaken and Olive. Slopes range from 13% in the cascading headwater reaches to 3% – 0.5% in the Esopus valley. Residential and commercial development is largely restricted to stream valleys, with several areas of relatively concentrated residential and commercial development. The mainstem Esopus is fed by 304 miles of tributary streams.

The upper Esopus Creek below Allaben is regulated by an inter-basin transfer of water. The Shandaken Tunnel is a handmade aqueduct that connects the Schoharie Reservoir (18 miles north) to the upper Esopus Creek – which conveys the water to the Ashokan Reservoir. Approximately 40% of the City's average water supply demand is provided by this system. Shandaken Tunnel discharges are subject to state regulations that specify thresholds for stream flow, temperature, and turbidity in the discharged waters. State regulations also allow for up to four annual releases for white-water recreation, pending DEC approval and drinking water availability. Regulated creek flows support a recreational boating and tubing industry, and the cold water delivered via the Tunnel sustains a renowned trout fishery with one of the longest open seasons in the state (April 1st – November 30th).

In 2007, DEP consultants completed Phase II of the Catskill Turbidity Control Study. The study assessed data from several years of monitoring and modeling by Upstate Freshwater Institute to evaluate structural and/or operational modifications at the Shandaken Tunnel intake structure on Schoharie Reservoir. The study recommended development of an Operations Support Tool, and enhanced operability of the existing intake structure (rather than build a new multi-level intake structure), to reduce turbid water transfers and conserve cold water when conveying drinking water through the Tunnel. DEP now uses the Operation Support Tool to better predict weather and modify reservoir operations accordingly.

In 2015, DEP began construction of a Low Level Outlet to withdraw water from the Schoharie Reservoir for release to the lower Schoharie Creek. In response to stakeholder concerns, DEP modified plans to rehabilitate the Gilboa Dam to construct a High Level Outlet on the dam to provide conservation releases of warm water to the lower Schoharie Creek. The design is intended to prevent depletion of cold water available for transfer to the upper Esopus Creek during summer months. In addition, DEP plans to construct a High Level Intake during rehabilitation of the Shandaken Tunnel intake chamber scheduled for completion in 2021. The High Level Intake will have an adjustable intake elevation of approximately 1080 ft to 1125 ft. DEP is performing modeling to evaluate the performance of these alternatives.

Suspended sediment entering the creek from erosion sources and from the Shandaken Tunnel is the primary concern for drinking water and recreation in the Esopus Creek watershed, and is the primary focus of New York City's filtration avoidance efforts.

In 1997, DEP funded a stream restoration project on the Esopus Creek to demonstrate natural channel design principles and bioengineering stream bank stabilization practices. This restoration took place near the confluence with Woodland Valley Creek and was completed in 2003. A demonstration project on the Broadstreet Hollow Creek tributary to the Esopus was previously completed in 2001. DEP then funded the Ulster County SWCD to complete about two miles of stream restoration and 2.5 acres of hillslope stabilization between 2010-2016. Eight of the 11 stream and hillslope restoration projects completed were in the Stony Clove Creek watershed.

The Bush Kill is the second largest stream draining into the Ashokan Reservoir with a watershed of 19.6 mi^2. The Bush Kill flows north 7.6 miles and is joined by several tributaries. The main stem of the Bush Kill was assessed in 2012 and a major tributary, the Maltby Hollow Brook, was assessed in 2016. Erosion in the stream corridor is related to development and interaction with transportation infrastructure in the valley bottom.

The Stream Ecosystem Working Group has identified the Ashokan Watershed as having four distinct aquatic macro-habitats: (1) the west-basin of Ashokan Reservoir; (2) the regulated portion of Esopus Creek (downstream of Shandaken Tunnel); (3) the unregulated portion of Esopus Creek (upstream of the Tunnel); and (4) tributaries to Esopus Creek and Ashokan Reservoir. This habitat diversity presents a unique opportunity for resource managers, researchers, and watershed educators to further explore and refine the influence that human stream management actions have on this dynamic ecosystem.

At least 928 landowners own and manage property along streams in the Ashokan Watershed, about half of which are part-time residents. The SWCD has worked with landowners to restore native vegetation (stream buffers) on over 3 miles of stream banks through the Catskill Streams Buffer Initiative program. Many miles of roads and railroad are within 300 feet of stream channels. Through the Stream Management Implementation Program fund, CCE has supported the county and watershed municipalities to complete 12 projects to properly size and align crossings and treat chronic sources of channel instability threatening infrastructure.

Changes in climatic conditions already appear to have affected the frequency of extreme hydrological events in Catskill Mountain streams. The upper Esopus Creek flood of record occurred on August 28, 2011 during Tropical Storm Irene and measured 75,800 cfs at Coldbrook. The previous peak discharge at Coldbrook was 65,300 cfs in March 1980. In 2016, a late season drought prompted DEC to close the lower Esopus Creek fishery between the Tunnel and Reservoir to protect spawning trout. Tunnel discharges were maintained for as long as possible to provide cold water to the fishery despite high turbidity levels measured in discharges.

Several studies have documented an increasing frequency of warm season stream flows during the 2000s (Frei et al. 2015). In these datasets, the tendency for precipitation extremes was larger during the warm season. However, streamflow extremes were larger during the cold season. Increased fall and early winter flows were expected to lead to increased turbidity loading during these time periods with a possible reduction in turbidity loading during April.

A Local Flood Analysis (LFA) flood mitigation program initiated by DEP and NYC Watershed partners in 2014 has provided funding and technical support to municipalities for engineering and analysis to determine the causes of flooding in population centers. Completed flood mitigation plans include actions with measurable benefits that protect public and private infrastructure.

Watershed Assessments and Next Steps

Starting in 2001, DEP and Ulster and Greene County SWCDs began to address erosion problems by cataloging stream bank erosion, slope failures, exposed geology and other geomorphic data to create stream feature inventories for the watershed. The geomorphic assessments have been used to identify stream reaches for stream stability restoration and hill slope stabilization projects intended to reduce reach-sale production of turbidity.

Eleven tributary streams and the mainstem upper Esopus Creek have been assessed, and two re-assessed, from 2001-2017. Assessments characterize stream corridor condition and identify stream erosion hazards and/or water quality impairment that may require treatment. Stream management plans have been developed for Broadstreet Hollow Creek, Stony Clove Creek, Beaver Kill, Bush Kill, and Bushnellsville Creek (tributaries to the Esopus Creek) in addition to the upper Esopus Creek. The plans include detailed stream assessment findings at www.ashokanstreams.org/publications-resources/stream-management-plans/. Additional stream assessments are planned through 2022.

Sediment Studies and Next Steps

Stream assessments provide information on the distribution of erosional contact with suspended sediment sources. The percent erosion mapped in contact with non-alluvial fine sediment sources ranged from 9-54% across the assessed tributaries. The Stony Clove Creek at 54% had the highest percent contact with 11,980 ft of channel erosion, of which 6,535 ft is in contact with a fine sediment source. The dominant geologic source in Stony Clove Creek is lacustrine sediment, which further enhances the sediment loading potential.

From 2010 to 2012, suspended-sediment concentrations (SSC) and turbidity were measured at 14 monitoring sites throughout the upper Esopus Creek watershed to quantify SSC and turbidity levels, to estimate suspended-sediment loads within the upper Esopus Creek watershed, and to investigate the relations between SSC and turbidity. During the study, the Stony Clove Creek consistently produced higher suspended sediment concentrations and turbidity than other Esopus Creek tributaries (McHale and Siemion 2014).

Starting in 2010, turbidity and SSC monitoring sites were installed upstream and downstream of the completed Stony Clove Creek stream restoration projects with limited before/after sampling at some. Statistically significant reductions in turbidity levels and SSCs were measured by USGS during observed flows (Siemion et al. 2016). Recorded flows in the Stony Clove Creek exceeded bankfull streamflow only once during the study period.

Starting in fall 2016, DEP began a more intensive 10-year monitoring study to improve understanding of turbidity generation in the Ashokan Watershed and evaluate the effectiveness of stream management practices to reduce turbidity over a range of hydrologic conditions and at different spatial and temporal scales. The studies will characterize: 1) how suspended sediment yield/turbidity varies across upper Esopus Creek tributaries; 2) how suspended sediment yield/turbidity varies within reaches of the Stony Clove Creek and what reach-level conditions and processes lead to yields; and 3) the effectiveness of stream restoration projects to reduce turbidity using reach-level characterizations. In 2016, CCE funded monitoring of SSC and turbidity above and below a future stream restoration project site on Woodland Creek.

DEP initiated a sediment fingerprinting study in the Stony Clove Creek watershed in 2017. The project will establish a source sediment library, determine if the source library is sufficient to identify the spatial sources of sediment in the Stony Clove Creek, and assess the scalability of results to other watersheds by collecting and comparing samples in the Woodland Creek.

DEP and the Ashokan Watershed Stream Management Program have also begun a pilot bedload transport study at two locations in the upper Esopus Creek watershed. Bedload data is difficult to measure, but is needed to predict annual suspended and bedload sediment yields. A second study was funded to calibrate and validate the BANCS model (Rosgen 2001) to quantitatively predict streambank erosion rates in the Ashokan Watershed. The results will be used to convert lateral erosion rates into annual sediment supply in tons/year and estimate annual loading rates.

DEP is studying the potential impacts of climate change on turbidity in the New York Catskill Water Supply by examining both streamflow and reservoir thermal properties expected to influence turbidity. Modeled climate change scenarios indicate changes in the timing of inflows and turbidity input to the reservoir, and in the thermal structure of the reservoirs (Matonse et al. 2013).

Aquatic Ecosystem Assessments and Next Steps

Species of fish, macroinvertebrates, and periphyton in the upper Esopus Creek are short-lived, with most fish living no longer than five years. Those life forms are good indicators of current habitat conditions and also changes in habitat during their lives. Numerous studies of aquatic habitat and biota have been completed in the Ashokan Watershed. Reports for some of these studies are available at www.ashokanstreams.org/publications-resources/technical-data/.

The USGS, in cooperation with CCE, New York State Energy Research and Development Authority, the New York State DEC, and the New York City DEP, annually monitored fish communities and trout populations at 7 to 18 sites on the main stem and tributaries of the upper Esopus Creek from 2009 to 2015. Seven sites were surveyed annually since 2009. Three of these sites are on the main stem of the upper Esopus Creek, and four are on major tributaries near their confluences with the upper Esopus Creek. The surveys allowed the effects of extreme floods on trout populations and fish communities to be assessed (George et al. 2015), created a long-term reference database, and increased our understanding of year-to-year variability in the condition of fish assemblages in the upper Esopus Creek.

Surveys at nine sites on the main stem and tributaries of the upper Esopus Creek from 2009 to 2013 showed that the mean density of Rainbow Trout populations declined from 114 to 17 fish per 0.1 hectare during this period, supporting anecdotal observations of population decline. However, the density and biomass of Rainbow Trout populations were significantly higher at most sites in 2015 than in the preceding two years (George et al. 2016c).

The AWSMP provided funding to continue fish surveys at six of the original study sites from 2016 through 2018. A second study was funded in 2015 to examine the effects of introduction and establishment of two non-native fish species in the Ashokan Reservoir on Rainbow Trout populations.

A project began in 2017 to both model and map thermal variation of stream water temperature over time and across the watershed. The project should identify areas with connectivity of thermally suitable habitats that may be a high priority for management.

A review of existing literature, data sources, and observations on watershed aquatic ecosystem issues was performed by Walt Keller in 2006-2007 and again in 2016. A synopsis of the 2016 review findings is provided below:

- Studies related to identifying stream conditions optimal for aquatic biota in order to assist with operation of the Shandaken Tunnel have been largely completed in satisfaction of stream management needs. However, findings from various reports should be correlated to answer some questions.
- Shandaken Tunnel releases of Schoharie Reservoir water still require consideration in light of a proposal to make conservation releases to the lower Schoharie Creek, and as other changes in reservoir operations proceed.
- The connectivity of the Schoharie and Esopus Creek systems suggests management and monitoring in both portions of the system should be coordinated and use standard accepted protocols and common reporting formats.
- Regular fish and macroinvertebrate survey has supported analysis of community response to extreme flooding, drought events, and the introduction of invasive species. These surveys if continued, can help to determine habitat longevity and resilience, document suspected thermal refugia, and document the effects of extreme climatic events on communities and species.
- The location of groundwater up-welling in aquatic systems and thermal refuges is largely undocumented, as are landscape factors affecting groundwater flow paths and supply.
- The effects of forest decimation by invasive insects, climate change, and impacts of further human watershed development on stream ecology should be studied.
- There is a need to develop methods for engaging researchers and citizens in meeting science information needs. Citizen scientists may be particularly able to document short-term events.
- Information exchange, data-sharing, and mutually agreed upon data acquisition protocols could enhance overall knowledge and foster improved stewardship. More work is needed to make research data and information easily available to researchers and stream managers.

Recommendations and Proposed Actions

The following recommendations and proposed actions have been advised and/or proposed by participants in the Stream Ecosystem Working Group, and are thus open to further addition, revision, and evolution as additional knowledge is gained.

Recommendation #1:
Characterize contemporary physical (thermal, flow) and water-quality regimes and the condition of important species, their populations, and biological communities.

In order to understand and manage the relationship between influencing factors and resources of concern, such as water quality or the health and status of the biota, we need to first understand their condition or state. Research questions for this topic (see Appendix I) focus on the adequacy of current methods and sampling schemes and on developing approaches to cost-effectively gather additional information.

Studies/Actions Proposed (listed in no particular order):

1. *Characterize contemporary temperature, water-quality, and hydrology regimes in the main-stem Esopus and its tributaries.*

2. *Characterize the current status of important indicator species and biological communities in the main-stem Esopus and its tributaries.*

3. *Develop a robust sampling design for continued assessment of physical and biological variables in the main-stem Esopus and its tributaries. Determine the frequency of sampling needed for long-term monitoring programs that address Esopus-specific questions.*

The Ashokan Reservoir water supply is impaired by suspended sediment from stream erosion causing high levels of turbidity. The first step in managing streams for water quality improvement is to quantify which tributaries produce the most sediment, and how production varies over space and time. The recommendations below are for studies that monitor sediment amounts and movement and compare Ashokan Reservoir tributaries. Turbidity from tributary streams in the Schoharie Reservoir, delivered to the Esopus via the Shandaken Tunnel, is also significant.

4. *Characterize sediment yields and turbidity levels in the Esopus Creek watershed. Establish turbidity and suspended sediment monitoring sites in the main-stem Esopus Creek and tributaries throughout the Ashokan Watershed.*

5. *Carry out intensive monitoring within the Stony Clove Creek and other priority tributary watersheds to characterize the variability of suspended sediment yield and turbidity levels within different stream reaches.*

6. *Develop bedload sediment rating curves key to the successful application of the Watershed Assessment of River Stability and Sediment Supply (WARSSS, Rosgen 2007) methodology, to quantify sediment flux in treatment reaches over a range of flows, and to develop watershed sediment budgets for baseline and departure assessment. Pilot a bedload monitoring study in coordination with other basin programs in the NYC watershed.*

Recommendation #2:
Define key interactions or interrelations between local biota and physical regimes and identify the factors that affect Esopus Creek resources.

These recommendations develop our understanding of the interactions between ecological variables. Stream managers are particularly interested in understanding the effects of climate change on water quantity and quality, stream temperature, and habitat availability, and how these shifts affect local biota. In addition, we need to understand how the man-made diversion of water from the Schoharie Basin to the upper Esopus Creek through the Shandaken Tunnel interacts with climate-change influenced variables and outcomes.

Studies/Actions Proposed (listed in no particular order):

7. *Identify stream conditions in the main-stem Esopus and its tributaries that are optimal for aquatic biota and which could support informed operations of the Shandaken Tunnel.*

8. *Use ecological information (from Recommendation #1) to quantify the relations between the health and status of local biota (and their assemblages) and channel geometry, stability, habitat, water quality, flow and thermal regimes.*

Recommendation #3:
Characterize the response of important resources to current and past remediation or restoration efforts.

A significant effort began in the Ashokan Watershed in the mid-2000s to physically restore the natural form and function of streams to meet multiple objectives. Streams in the Ashokan Watershed are managed to improve water quality, protect infrastructure, mitigate flood hazards, and maintain or enhance habitat. This recommendation focuses on evaluating the outcomes of past stream management actions in order to adapt and improve management approaches. Specific study questions are listed in Appendix 1.

Studies/Actions Proposed (listed in no particular order):

9. *Evaluate how current and past channel restorations (and other factors) affect channel geometry, stability, geomorphic function, habitat, water quality, flow and thermal regimes, and the survival, health, and distributions of resident biota (e.g., trout and other coldwater species).*

10. *Evaluate the effectiveness of stream restoration projects in reducing reach- and watershed-scale suspended sediment yield and turbidity levels.*

Recommendation #4:
Predict the potential effects that changes in stream-management practices, or in current discharge, sediment, and thermal regimes, may have on important resources of the basin.

This recommendation looks to the future and asks for monitoring schemes and modeling that answers questions about the potential effects of climate change and management actions on key resources. Of particular interest is how climate change, management of stream channels, water diversions and releases, and habitat suitability for coldwater biota may intersect. See the full list of study questions in Appendix 1.

Studies/Actions Proposed (listed in no particular order):

11. *Establish objectives for long-term monitoring of stream temperature. Develop a temperature collection sampling design and protocols for consistent sampling. Determine the role of volunteers in collecting stream temperature data.*

12. *Evaluate the effects on the Esopus Creek coldwater fishery of scenarios for Schoharie Reservoir releases.*

Recommendation #5:
Assess streams to identify, estimate, and quantify the sources and causes of channel erosion, build a database of reference conditions, monitor channel stability and evaluate project performance.

Within tributary watersheds, stream assessment information is needed to identify stream erosion sites and characterize the sources of sediment at the site and reach levels. This includes understanding the amount and sources of sediment moving along the beds of stream channels, produced by banks, and suspended in the water column. Stream assessment information is used to target the largest sources for management. The information collected should support restoration of naturally stable channel forms and functions, and adjacent vegetative communities. Managers require a database of stable stream channels found in the upper Esopus Creek watershed in order to replicate these reference conditions in stream restoration designs. After projects are installed, monitoring of project performance at the site level is needed to guide improvements in management techniques.

Studies/Actions Proposed (listed in no particular order):

13. *Conduct Stream Feature Inventories (SFI) that map geomorphic and geologic variables to develop stream management recommendations. As part of SFI, map stream channel sediment sources to provide data needed for sediment and water quality studies.*

14. *Develop sediment-rating curves accurate to the Esopus Creek watershed. The curves will be used to validate the WARSSS model that predicts relative sediment loading from watersheds based on watershed conditions. Measure suspended sediment, and bedload when feasible, in the highest yield tributary watersheds (e.g., Stony Clove, Beaver Kill, Birch Creek, Woodland Creek) and at least one low-yield watershed to better calibrate future WARSSS models.*

15. *Validate or calibrate the Bank Assessment for Nonpoint Sources of Sediment (BANCS) model to better predict annual erosion rates and sediment supply. Develop streambank erosion rate curves, and the local relationship of BEHI and NBS to annual bank erosion rates, in order to effectively apply the BANCS model in the Ashokan Watershed. Monitor existing and new bank erosion sites and use the BANCS model to estimate erosion rates and sediment yields at individual sites.*

16. *Build a database of Esopus Creek watershed stream reference reaches. Study and monitor potential reference reaches that did not meet current criteria, but that seem to be maintaining stability despite recent destructive flooding.*

17. *Assess restoration project construction methods to improve cost-effectiveness.*

18. *Review past management intervention level designations within completed stream management plans and evaluate against current field conditions in order to improve the intervention level classification scheme.*

Recommendation #6: Enhance coordination and information sharing among regulators, scientists, educators and the public.

Every streamside landowner in the Ashokan Watershed is a stream manager. And every watershed resident should understand their streams and how they are being managed.

Outreach approaches are needed to extend scientific information to the public, stream managers, local decision-makers, and researchers who work within the Catskills and similar regions. A repository of information is called for to reach another important audience - future generations of stream managers and scientists.

Studies/Actions Proposed (listed in no particular order):

19. *Develop an electronic database and clearinghouse of previous studies that is accessible online by regulators, researchers, educators, and the public. Collaborate with existing Catskill regional database/clearinghouse efforts as necessary.*

20. *Identify mutually agreed upon protocols for consistent sampling and data sharing between entities. These protocols could and should be supplied to outside contractors and included in contractual agreements.*

21. *Encourage increased participation by affiliated and non-affiliated researchers and watershed residents in the Stream Ecosystem Working Group. Continue personalized information sharing via meetings, conferences, symposiums or other venues.*

22. *Create outreach programs that engage watershed residents in understanding and learning about Esopus Creek research, assessment, and monitoring strategies.*

23. *Develop youth education STEM curriculum for use in the Onteora Central School District that links to research, assessment, and monitoring projects and uses and even contributes to the data gathered. Engage students in science communication projects around the studies.*

24. *Develop communication tools (interactive website, apps for handheld devices, etc.) that allow watershed residents to contribute observations and interact with research results and data-gathering efforts.*

Appendix 1 – Questions for Additional Study

In Appendix 1, the Stream Ecosystem Working Group has provided specific questions for additional study that if answered, would provide information needed to inform management. The specific questions are listed below under broader questions.

RAMS Rec #1: Characterize contemporary physical (thermal, flow) and water-quality regimes and the condition of important species, their populations, and biological communities.

Questions for additional study, including but not limited to:

1. Characterize contemporary temperature, water quality, and hydrology regimes in the main stem Esopus and its tributaries.
2. Characterize the current status of important indicator species and biological communities in the main-stem Esopus and its tributaries.
    - Do existing macroinvertebrate surveys by the DEP and DEC provide sufficient information to detect long-term trends or extreme disturbances?
    - Are better methods available to characterize macroinvertebrate diversity/richness (for example, stoneflies) or seasonal changes in macroinvertebrate assemblages?
    - Are there long-term trends in macroinvertebrate assemblages related to changes in climate or tunnel operations?
    - Can the DEP macroinvertebrate database be used to address any the questions above?
    - Should macroinvertebrate assemblages be sampled annually, at how many sites, and why?
    - Can historical Brown Trout scale samples identify changes in growth rates that correlate with changes in invasive species in the Ashokan reservoir?
    - Have plankton communities (from DEP records 1994-2001 and new tows at 3 sites on the Ashokan) changed after the establishment of white perch populations in the reservoir?
    - Where do Brook Trout, Brown Trout and Rainbow Trout spawn in the Esopus? Can we survey ova and sac fry locations, or young of year trout to quantify recruitment success and/or survival of one or more trout species?

- Are annual fishery surveys needed to characterize long-term trends, and if so, at how many sites, and at what sites? Should the previously surveyed 18 sites be resampled at some longer interval, at what interval, and why? After major events?
- Can non-destructive lipid meters be used to assess fish health?
- How do trout Habitat Suitability Indices (HSIs) vary across the basin (mainly tributaries)? Can trout HSIs be related to trout population metrics and sustainability? What information is needed to characterize trout HSIs?
- Do HSI metrics of temperature, tributary flows, or other factors (e.g., connectivity, main stem and Shandaken Tunnel flows, and turbidity) explain why certain tributaries are favored by one trout species over another?

3. Develop a robust sampling design for continued assessment of physical and biological variables in the main-stem Esopus and its tributaries. Determine the frequency of sampling needed for long-term monitoring programs that address Esopus-specific questions.

    - What resolution of sampling will detect the changes we want to monitor?
    - How many years of data are needed to statistically detect reductions in trout populations?

4. Characterize sediment yields and turbidity levels in the Esopus Creek watershed. Establish turbidity and suspended sediment monitoring sites in the main-stem Esopus Creek and tributaries throughout the Ashokan Watershed.

    - How do suspended sediment yield and turbidity levels change under a range of flow conditions and through time?

5. Carry out intensive monitoring within the Stony Clove Creek and other priority tributary watersheds to characterize the variability of suspended sediment yield and turbidity levels among different stream reaches.

6. Develop bedload sediment rating curves key to the successful application of the WARSSS methodology, to quantify sediment flux in treatment reaches over a range of flows, and to develop watershed sediment budgets for baseline and departure assessment. Pilot a bedload monitoring study in coordination with other basin programs in the NYC watershed.

    - What sampling technology (direct, indirect, tracer, etc.) can effectively be used to measure bedload in the Esopus watershed?

- What sampling design should be used to measure bedload for development of bedload sediment rating curves? What sampling site number and location should be used? Over what range of flows should sampling occur?

RAMS Rec #2: Define key interactions or interrelations between local biota and physical regimes and identify the factors that affect Esopus Creek resources.

Studies/Actions Proposed (listed in no particular order):

7. Identify stream conditions in the main-stem Esopus and its tributaries that are optimal for aquatic biota and which could support informed operations of the Shandaken Tunnel.

8. Use ecological information (from Recommendation #1) to quantify the relations between the health and status of local biota (and their assemblages) and channel geometry, stability, habitat, water quality, flow and thermal regimes.

    - Does the DEC Biological Assessment Profile or other measures of biological integrity (e.g., IBI, HSI for individual species) vary with environmental conditions (flow, turbidity, temperature) across the basin?
    - Do current water temperatures and levels of turbidity affect survival of juvenile and adult trout in parts of the basin? Can the literature and/or caged-fish experiments address this question?
    - How do juvenile and adult coldwater species (e.g., trout) utilize thermal refuges/seepages that may exist in the Esopus and its tributaries?
    - Can cortisol levels that are indicative of stress in trout be used as a surrogate for environmental quality and conditions that trout prefer? What is the impact of high turbidity conditions?
    - What is the relationship between fish health and stream temperature regime?
    - How is stream temperature regime influencing biological interactions between fish species?
    - What factors are regulating year-class strength for key species?

RAMS Rec #3: Characterize the response of important resources to current and past remediation or restoration efforts.

Studies/Actions Proposed (listed in no particular order):

9. Evaluate how current and past channel restorations (and other factors) affect channel geometry, stability, geomorphic function, habitat, water quality, flow and thermal regimes, and the survival, health, and distributions of resident biota (e.g., trout and other coldwater species).

    - Based on historical investigations: 1) What impacts have historical stream management practices, stream corridor alteration, land management, and flooding had on geomorphic channel instability?; 2) Over what time period did the Stony Clove Creek alluvial fan at Phoenicia form, and at what rate over time?; and 3) Is elevation of the broad Esopus Creek Valley changing over time with deposition from large floods like Irene?

    - What impact do vertical/slope alterations that alter habitat connectivity, at stream project sites and/or tributary mouths have on fish movement, especially during spawning? Evaluate a range of stream projects, including culvert replacements.

    - How do large wood accumulations in restored reaches or in flood-remediated reaches affect fish and macroinvertebrate habitat and the condition of trout populations and entire fish assemblages?

    - How have fish assemblages and trout populations responded to stream restoration at sites that were restored 10-15 years ago (in the Esopus and in other systems)? How long have the benefits of stream restorations lasted and have they persisted?

    - Will future (new) stream restoration projects improve macroinvertebrate and fish habitat and communities? What restoration practices improve outcomes?

    - How do center bars (depositional gravel bars within the stream channel) contribute to fish spawning and recruitment in the Esopus Creek? Does the removal of center bars during restoration detrimentally affect fish recruitment within stream systems? If so, what management approaches, such as braided channels that are allowed to develop or remain within the watershed, can be used to meet multiple objectives?

    - How do large wood accumulations at the upstream ends of meander bends change the partitioning of flows between floodplains and channels? How could partitioning affect sediment transport in the channel and the accumulation of wood on the floodplain? What is the quantification of these effects?

    - What is the role of wood in the channel in creating alluvial floodplains in steep valley settings?

    - Is the wood recruited in the channel similar in composition to the floodplain forest community? Are some species easier to recruit and why? What are the implications for riparian management? Is there potential for recruitment that exceeds background rates and the potential to adversely affect natural channel stability?

- How much large wood is recruited into the channel? How long has it been there? How fast does it move? Under what conditions does wood remobilize with the potential to catch at bridges? Under what conditions is wood locked up long enough to age and rot? How much live wood is being recruited during storm events? What is the implication (pro/con) for removing large wood accumulations or leaving in in place?

10. Evaluate the effectiveness of stream restoration projects in reducing reach- and watershed-scale suspended sediment yield and turbidity levels.

    - How can characterization of the variability of suspended sediment yield and turbidity levels inform stream management strategies?
    - What are the reach-level geologic/geomorphic conditions and processes that lead to differing suspended sediment yields among stream reaches? What variables can be modified to suppress yields?
    - How does hydrology influence reach-scale to basin-scale sediment loading/turbidity? Can we develop spatially distinct sediment-discharge rating curves?
    - Can we improve our ability to select stream restoration projects sites to maximize potential turbidity reduction?
    - To what extent can suspended sediment yield and turbidity levels associated with geologic sources, channel conditions, and processes be managed within the stream system? Over what range of flows can turbidity and suspended sediment load be reduced?

RAMS Rec #4: Predict the potential effects that changes in stream-management practices, or in current discharge, sediment, and thermal regimes, may have on important resources of the basin.

Studies/Actions Proposed (listed in no particular order):

11. Establish objectives for long-term monitoring of stream temperature. Develop a temperature collection sampling design and protocols for consistent sampling. Determine the role of volunteers in collecting stream temperature data.

12. Evaluate the effects on the Esopus Creek coldwater fishery of scenarios for Schoharie Reservoir releases.

Temperature Regime, Flow Regime, and Habitat Suitability

- How will changes in Schoharie Reservoir and Shandaken Tunnel releases affect the coldwater trout fisheries in the Esopus? How might current and altered Tunnel flows (volumes) and water temperatures from Schoharie Reservoir affect thermal suitability for Brown and Rainbow Trout? How might current and projected thermal information affect the DEC's stocking policy in the Esopus?

- What will be the effect of proposed changes in coldwater release strategies from the Schoharie Reservoir into Schoharie Creek (via the Low and High Level Outlets) on temperature and coldwater biota of the Esopus Creek?

- How do supplemental flows via the Shandaken Tunnel affect the health of resident trout; their populations; or the condition of fish, macroinvertebrate, and periphyton communities?

- What are the current temperature regimes across the basin, how do they affect thermal suitability for Brook, Brown and Rainbow Trout, and how might they change with increasing air temperatures?

- Are there sufficient temperature data to characterize current and future thermal habitat suitability for Brook, Brown and Rainbow Trout across the basin? Are additional monitoring sites warranted?

- Could temperature data be integrated into the Stream Feature Inventory (SFI) data collection?

- How would changes in air and water temperatures affect the health of resident trout species and viability of their populations across the basin?

- What is the relationship between stream flow and temperature? Does it vary by site, season, and above/below the Shandaken Tunnel outlet? Can HEC-RAS or other models predict stream temperatures under various GCC scenarios?

Wetlands/Groundwater Seepages and Thermal Refugia

- Could stream temperature data (fixed temperature probes, thermal imaging, Topographic Wetness Index) and trout temperature selection be collected and assessed to quantify the locations of groundwater seepages and the availability of thermal refuges, define current thermal suitability, and project future thermal suitability in waters across the basin? Could volunteers help identify and monitor thermal refuges (plot coordinates in GIS for use) by permitting agencies and other authorities?

- Can we predict/project the potential impacts of increased frequency and severity of forest disturbance, changes in dominant tree species, and climate change on ground water inputs? Linking to studies on the outcomes of past stream management actions, how do these predictions inform stream corridor management in the Esopus watershed?

- Is there a predictive relationship between stream temperature, the number of seeps, and hillslope failures?
- Could the relative importance of groundwater at different sites be characterized using a fine stream-temperature logger network?
- How could stream restoration practices be used to protect groundwater sources? Can stream restoration practices be used to improve or maintain the availability of coldwater habitat?

RAMS Rec #5: Assess streams to identify, estimate, and quantify the sources and causes of channel erosion, build a database of reference conditions, monitor channel stability and evaluate project performance.

Studies/Actions Proposed (listed in no particular order):

13. Conduct Stream Feature Inventories (SFI) that map geomorphic and geologic variables to develop stream management recommendations. As part of SFI, map stream channel sediment sources to provide data needed for sediment and water quality studies.
    - What are the key geomorphic variables influencing suspended sediment yield at the reach scale? Can models that incorporate unit stream power, channel curvature, and confinement be used to evaluate SFI and BEMS results?
14. Develop sediment-rating curves accurate to the Esopus Creek watershed. The curves will be used to validate the WARSSS model that predicts relative sediment loading from watersheds based on watershed conditions. Measure suspended sediment, and bedload when feasible, in the highest yield tributary watersheds (e.g., Stony Clove, Beaver Kill, Birch Creek, Woodland Creek) and at least one low-yield watershed to better calibrate future WARSSS models.
15. Validate or calibrate the BANCS model to better predict annual erosion rates and sediment supply. Develop streambank erosion rate curves, and the local relationship of BEHI and NBS to annual bank erosion rates, in order to effectively apply the BANCS model in the Ashokan Watershed. Monitor existing and new bank erosion sites and use the BANCS model to estimate erosion rates and sediment yields at individual sites.

- What methods will improve our predictions of sediment supply at large hillslopes?
- How can we use BEHI in conjunction with characterization of larger hillslope failures to predict the sediment contributions of hillslopes (BEHI was not intended to characterize larger banks)?
- Can alternative survey methods at large failures be used to determine annual volumetric change more precisely and cost-effectively than cross-sections?
- Where erosion rates don't seem to be predicted well by BEHI and NBS, what other metrics might explain under- or over-prediction?

16. Build a database of Esopus Creek watershed stream reference reaches. Study and monitor potential reference reaches that did not meet current criteria, but that seem to be maintaining stability despite recent destructive flooding.
    - What is working in potential reference reaches to maintain stability where adjacent reaches have experienced severe damages? What is functioning in the reach, and can these features be incorporated into a design to treat impaired reaches with similar valley, sediment supply and stream corridor characteristics?
17. Assess restoration project construction methods to improve cost-effectiveness.
    - How do project designs that use rock structures to stabilize streams compare to designs that use plant material (possibly combined with rock) for long-term effectiveness in achieving a range of benefits?
    - How do the SWPPP practices employed at construction sites perform at various return-interval storms, base flows, etc. with regard to the volume of turbid discharge generated from construction activities? This could be analyzed using existing turbidity data collected by USGS.
    - What management techniques will improve the success of riparian buffer restoration projects? Interpret vegetation-monitoring data for the CSBI program to develop recommendations.
    - How well do individual flow structures (cross-vanes, j-hooks, deflectors, riffles, etc.) function in restoration projects? Particular functions of interest include channel stability, sediment transport, and fish habitat. Do structures function differently by setting, such as in differing valley types, geology, hydrology or other factors? What are the contributing factors to structure success? Recommendations are needed for improving design and constructability.
    - How well do current stream project installation techniques perform in tight stream corridors and confined valleys?

- What affect does restoring riparian vegetation through the CSBI program have on stream condition at different spatial and temporal scales?

18. Review past management intervention level designations within completed stream management plans and evaluate against current field conditions in order to improve the intervention level classification scheme.

    - Develop easily assessable indicators for when stream restoration intervention is necessary to restore stream stability. Better understand how erosion sites evolve over time and the potential for sites to recover without intervention, such as following vegetation regrowth. How can SFI assessment and data be used to answer this question?

19. Develop a framework for evaluating stream restoration project success relative to project goals and objectives. The evaluation framework would be applied to organizing post-project monitoring and evaluating design approaches. Evaluation results would be used to improve how we select new projects and improve methods.

RAMS Rec #6: Enhance coordination and information sharing among regulators, scientists, educators and the public.

Studies/Actions Proposed (listed in no particular order):

20. Develop an electronic database and clearinghouse of previous studies that is accessible online by regulators, researchers, educators, and the public. Collaborate with existing Catskill regional database/clearinghouse efforts as necessary.
21. Identify mutually agreed upon protocols for consistent sampling and data sharing between entities. These protocols could and should be supplied to outside contractors and included in contractual agreements.
22. Encourage increased participation by affiliated and non-affiliated researchers and watershed residents in the Stream Ecosystem Working Group. Continue personalized information sharing via meetings, conferences, symposiums or other venues.
23. Create outreach programs that engage watershed residents in understanding and learning about Esopus Creek research, assessment, and monitoring strategies.
24. Develop youth education STEM curriculum for use in the Onteora School District that links to research, assessment, and monitoring projects and uses and even contributes to the data gathered. Engage students in science communication projects around the studies.
25. Develop communication tools (interactive website, apps for handheld devices, etc.) that allow watershed residents to contribute observations and interact with research results and data-gathering efforts.

Appendix 2 - Annotated References

Baldigo, Barry P., Scott D. George, and Walter T. Keller. 2015. Fish assemblages in the Upper Esopus Creek, NY: Current status, variability, and controlling factors. *Northeast Naturalist* 22(2):345-371. https://doi.org/10.1656/045.022.0209

Water quality, hydrology, water temperature and fish assemblages for 18 sites in Upper Esopus Creek during 2009-2011 were studied and analyzed to characterize effects of Shandaken Tunnel outfall on resident fishes. Generally, fish communities were 2-3 species richer near Tunnel main stem sites. Tunnel waters appeared to adversely affect the density and biomass of young of the year Brown Trout, but Tunnel-augmented increased flows and lower water temperatures improved habitat for mature trout. Despite flow and watershed differences the median biomass of Brown Trout and all trout was similar between sites upstream and downstream of the Tunnel, but median densities of all trout downstream were significantly lower than upstream, reflecting the larger average size of downstream trout.

Burns, Douglas A., and Christopher L. Gazoorian. 2015. *Estimates of natural streamflow at two streamgages on the Esopus Creek, New York, water years 1932–2012*. U.S. Geological Survey Scientific Investigations Report 2015–5050, 20 pp. http://dx.doi.org/10.3133/sir20155050

Streamflow in the Esopus Creek watershed is altered by two major watershed management activities carried out by the New York City Department of Environmental Protection as part of its responsibility to maintain a water supply for New York City: (1) diversion of water from the Schoharie Creek watershed to the Esopus Creek through the Shandaken Tunnel, and (2) impoundment of the Esopus Creek by a dam that forms the Ashokan Reservoir and subsequent release through the Catskill Aqueduct. Stakeholders in the Catskill region are interested and concerned about the extent to which these watershed management activities have altered streamflow, especially low and high flows, in the Esopus Creek. To address these concerns, natural (in the absence of diversion and impoundment) daily discharge from October 1, 1931, to September 30, 2012, was estimated for the U.S. Geological Survey streamgages at Coldbrook (station number 01362500), downstream of the Shandaken Tunnel discharge, and at Mount Marion (01364500) downstream of the Ashokan Reservoir. The results indicate that Shandaken Tunnel discharge has a minor effect on flooding in the Esopus Creek Basin. Overall, estimates of natural discharge reflected the absence of effects of the Shandaken Tunnel and Ashokan Reservoir on flows in the Esopus Creek over broad time frames. However, caution is warranted if one is attempting to apply the natural estimates at short time scales because the regression prediction intervals indicate that uncertainty at a daily time step ranges from about 40 to 80 percent.

NYS Department of Environmental Conservation. 2010, 2011, 2012 and 2013. B*ureau of Fisheries Card Reports for fisheries surveys conducted by the DEC Region Three Fisheries.* New Paltz, NY: NYS Department of Environmental Conservation. 2010, 2011, 2012 and 2013.

Those reports include completed forms titled: Survey Background, Site Locations, Site Characteristics, Gear Performance, Water Chemistry, Species Present, Average Length at Age, and Individual Fish Length Frequency. The Individual Fish Length Reports reviewed for this status review included trout only. Trout year class strengths are indicated by sample sizes for different year classes.

Duffy, Brian T., Alexander J. Smith, Diana L. Heitzman, Lawrence E. Abele. 2011. *Upper Esopus Creek Biological Assessment, 2008 Survey*. Albany, NY: NYS Department of Environmental Conservation, 60 pp. http://www.dec.ny.gov/docs/water_pdf/sbuupesopscr08.pdf

Traveling kick samples of macroinvertebrates were taken at six historical sample sites and two new sites bracketing Phoenicia. Metrics on species richness, biotic indices, EPT [Ephemoroptera (mayfly), Plecoptera (stonefly) and Tricoptera (caddisfly)] richness and percent model affinity were used as indices of water quality. Headwater reach nutrient input is attributed to nitrification due to forest tent caterpillar forest defoliation. Tributary and Tunnel contributions downstream were thought to help diminish effects of upstream nutrient input. Causes of spikes in siltation downstream from the Tunnel, Stony Clove Creek and Phoenicia were not determinable from this study. Further study was recommended as necessary to fully define impacts from the Tunnel discharge, the Village of Phoenicia or the many upper Esopus Creek tributaries.

Frei, Allan, Kenneth E. Kunkel, and Adão Matonse. 2015. The seasonal nature of extreme hydrological events in the Northeastern United States. *Journal of Hydrometeorology* 16(5): 2065-2085. https://doi.org/10.1175/JHM-D-14-0237.1

Recent analyses of extreme hydrological events across the United States show that extremely large (extreme) precipitation and streamflow events are increasing over much of the country, with particularly steep trends over the northeastern United States. The authors demonstrate that the increase in extreme hydrological events over the northeastern United States is primarily a warm season phenomenon and is caused more by an increase in frequency than magnitude. The frequency of extreme warm season events peaked during the 2000s; a secondary peak occurred during the 1970s; and the calmest decade was the 1960s. Cold season trends during the last 30-50 yrs are weaker. Since extreme precipitation events in this region tend to be larger during the warm season than during the cold season, trend analyses based on annual precipitation values are influenced more by warm season than by cold season trends. In contrast, the magnitude of extreme streamflow events at stations used for climatological analyses tends to be larger during the cold season: therefore, extreme event analyses based on annual streamflow values are overwhelmingly influenced by cold season, and therefore weaker, trends. These results help to explain an apparent discrepancy in the literature, whereby increasing trends in extreme precipitation events appear to be significant and ubiquitous across the region, while trends in streamflow appear less dramatic and less spatially coherent.

George, Scott D., Barry P. Baldigo, Alexander J. Smith, and George R. Robinson. 2015. *Effects of an extreme flood on aquatic biota in a Catskill Mountain River*. Report 15-08. Albany, NY: NYS Energy Research and Development Authority, 16 pp. https://doi.org/10.13140/RG.2.1.1385.9362

Analysis of fish biomass and density from surveys at 18 Ashokan Watershed sites from 2009-2011 and nine of the 18 from 2012-2014 showed a steady annual decline in numbers for both metrics prior to tropical storm Irene and a resurgence in both metrics following Irene in 2012. The numbers for the post-2012 surveys diminished somewhat each year to about the same levels evident for 2010. Fish assemblages were dissimilar between sites but not from pre-flood (Irene) to post-flood. Trout populations did not differ relative to drainage area, site elevation or flood discharge. However, Brown Trout abundance exceeded Rainbow Trout abundance after Tropical storm Irene but not before. Macroinvertebrates were extremely depressed by the flood but recovered nearly completely in the year following. Periphyton impacts from the flood were not detected.

George, Scott D., Barry P. Baldigo, Alexander J. Smith and George R. Robinson. 2015b. Effects of extreme floods on trout populations and fish communities in a Catskill Mountain river. *Freshwater Biology* 60(12): 2511-2522. https://doi.org/10.1111/fwb.12577

Three years of fish community data from years before tropical storm Irene were compared to fish community data for the two subsequent years. Watershed wide fish assemblages were not impacted strongly. Total biomass and density of fish communities were greater at most sites about a year past Irene than one month before. Fish community composition was not significantly different pre- and post-flood periods or between years. Density of mature Brown Trout was low at most sites following the flood. However, yearly density of Brown Trout young of the year was greatest for the year immediately following the flood while Rainbow Trout densities diminished substantially during the entire study period. Findings suggested that late summer floods may less damage fish communities than winter or spring floods since there is little spawning then and smaller individuals of all fishes have grown. Post summer flood conditions may also benefit Brown Trout recruitment.

George, Scott D. and Barry P. Baldigo. 2015c. Didymosphenia geminata in the Upper Esopus Creek: Current status, variability, and controlling factors. *PLOS ONE* 10(7): e0130558. https://doi.org/10.1371/journal.pone.0130558

Periphyton was sampled five times at 6 to 20 study sites between two seasons and upstream and downstream from the Tunnel. Density of D. geminata was found to range from 0-12, 0-781 and

0-2,574 cells per square centimeter in tributaries, in the main stem upstream of the Tunnel and in the main stem downstream of the Tunnel, respectively. Algae sampling coincided with measurements of stream temperature, discharge and water quality and was analyzed accordingly. D. geminata was most abundant during November of 2009 and June of 2010 surveys and at sites immediately downstream of the Tunnel. There was no evidence of major ecological impacts nor did the bloom appear to reach nuisance levels during the study. Variable discharge, moderate levels of phosphorous and suspended sediment were noted as possible limiting conditions of D. geminata in the Ashokan Watershed.

George, Scott D., Anne G. Ernst, Barry P. Baldigo, and Dale C. Honeyfield. 2016a. *Response of periphyton fatty acid composition to supplemental flows in the Upper Esopus Creek, Catskill Mountains, New York*. Scientific Investigations Report 2015–5161. Reston, VA: U.S. Geological Survey, 22 pp. https://doi.org/10.3133/sir20155161

Fatty acids were analyzed from periphyton sampled upstream and downstream of the Tunnel for two seasons during 2009. Fatty acid data were compared to measures of standing crop, diatom community structure and integrity and basic water quality parameters. Measures of standing crop and diatom community structure and integrity downstream of the Tunnel showed little evidence of impairment. However, two physiologically important fatty acids were different between sites upstream and downstream of the Tunnel. Comparisons of samples did show differences in standing crop and diatom community structure although the fatty acid profiles did not show those seasonal differences.

George, Scott. D., Barry P. Baldigo, Martyn J. Smith, Donald M. McKeown and Jason Faulring. 2016b. Variations in water temperature and implications for trout populations in the Upper Schoharie Creek and West Kill, New York, USA. *Journal of Freshwater Ecology* 31(1): 93-108. https://doi.org/10.1080/02705060.2015.1033769

Surface water temperatures were assessed with continuous loggers from October 2010 to October 2012 and one day airborne thermal infrared (TIR) sensing on August 7, 2012. TIR showed Schoharie Creek thalweg temperatures varied from median surface water temperatures by one degree Celsius at 0.009% of the mapped surface area (690,170 square meters) and not at all by two degrees Celsius. The West Kill values for the same day were 0.085% and 0.018% for one and two degrees difference, respectively for the 79,098 square meters mapped. Logger data showed that water temperatures exceeded the 1-day and 7-day thermal tolerance limits for trout at five of the seven sites during both summers.

George, Scott D., and Barry P. Baldigo. 2016c. *Long-term trends in naturalized rainbow trout (Oncorhynchus mykiss) populations in the upper Esopus Creek, Ulster County, New York, 2009–15*. Data Series 992. Troy, NY: U.S. Geological Survey, 12 pp. http://dx.doi.org/10.3133/ds992

The U.S. Geological Survey, in cooperation with Cornell Cooperative Extension of Ulster County, New York State Energy Research and Development Authority, the New York State Department

of Environmental Conservation, and the New York City Department of Environmental Protection, surveyed fish communities annually on the main stem and tributaries of the upper Esopus Creek from 2009 to 2015. This report summarizes the density, biomass, and size structure of rainbow trout (Oncorhynchus mykiss) and brown trout (Salmo trutta) populations from the 2015 surveys along with data from the preceding 6 years. The mean density of rainbow trout populations in 2015 was 98 fish per 0.1 hectare, which was the highest value observed since 2010, and the mean biomass of rainbow trout populations in 2015 was 864 grams per 0.1 hectare, which was the highest value observed since 2012. These results tentatively suggest that rainbow trout populations may be in recovery after a number of poor years.

New York City Department of Environmental Protection. 2000. *Stream reclassification petitions for tributaries to the Ashokan watershed in 2000*. Thomas Baudanza. Kingston, NY: New York City Department of Environmental Protection Fisheries.

Seventeen (17) petitions for trout stream reclassification of sections of tributaries of Esopus Creek were submitted to the New York State Department of Environmental Conservation. Those petitions upgrade all for water classification standards from (T) designating trout to (TS) documented trout spawning. They included A (T) to A (TS) for three stream sections still classified A (T), 10 for B classified and 4 C stream sections. Fingerlings of one or two species of trout (Brook Trout, Brown Trout and/or Rainbow Trout) were found in seven or ten of those sites respectively.

Matonse, Adão H., Donald C. Pierson, Allan Frei, Mark S. Zion, Aavudai Anandhi, Elliot Schneiderman, and Ben Wright. 2013. Investigating the impact of climate change on New York City's primary water supply. *Climate Change* 116:437-456. http://dx.doi.org/10.1007/s10584-012-0515-4

Future climate scenarios were projected by three different General Circulation Models and a delta-change methodology used as input to the Generalized Watershed Loading Functions – Variable Source Area (GWLF-VSA) watershed model to simulate future inflows to reservoirs that are part of the New York City water supply system (NYCWSS). These inflows are in turn used as part of the NYC OASIS model designed to simulate operations for the NYCWSS. In this study future demands and operation rules are assumed stationary and future climate variability is based on historical data to which change factors were applied in order to develop the future scenarios. Results for the West of Hudson portion of the NYCWSS suggest that future climate change will impact regional hydrology on a seasonal basis. The combined effect of projected increases in winter air temperatures, increased winter rain, and earlier snowmelt results in more runoff occurring during winter and slightly less runoff in early spring, increased spring and summer evapotranspiration, and reduction in number of days the system is under drought conditions. At subsystem level reservoir storages, water releases and spills appear to be higher and less variable during the winter months and are slightly reduced during summer. Un-

der the projected future climate and assumptions in this study the NYC reservoir system continues to show high resilience, high annual reliability and relatively low vulnerability.

McHale, Michale R., and Jason Siemion. 2014. *Turbidity and suspended sediment in the upper Esopus Creek watershed, Ulster County, New York*. Scientific Investigations Report 2014–5200. Troy, NY: U.S. Geological Survey, 42 pp. http://dx.doi.org/10.3133/sir20145200

Turbidity and suspended sediment concentration (SSCs) levels were measured and analyzed from ten sites 2010-2012 in major tributaries and four main channel sites in Upper Esopus Creek. Stony Clove Creek provided 40% of the annual SSC and turbidity in the watershed. The other tributaries accounted for 20% of the load at Coldbrook during 2010 and 2011 when most of the tributaries were sampled with Woodland Creek contributing about 10% of that load during those 3 years. Discharge, SSC and turbidity were related at Coldbrook, but not at every monitoring site. Stony Clove Creek values were always high for SSCs and turbidity but increased with discharge. Greater use of in situ probes is suggested to provide greater detail of discharge and turbidity relationships.

Richardson, David C., Isabella A. Olesksy, Timothy J. Hoellein, David B. Arscott, Catherine A. Gibson, and Samantha Root. 2014. Habitat characteristics, temporal variability, and macro-invertebrate communities associated with a mat-forming nuisance diatom (Didymoshphenia geminata) in Catskill mountain streams, New York. *Aquatic Sciences* 76(4), 553-564. https://doi.org/10.1007/s00027-014-0354-7

Didymoshphenia geminata was documented in three New York City Catskill Mountain watersheds and studied during 2010-2012. Macroinvertebrate richness was negatively affected by diatom mats. Diatom cover was negatively related to 10-day maximum shear stress and also negatively related to water column nitrogen concentrations. Diatom cover was positively related to water column phosphorus concentrations and higher conductivities and was greater below reservoir discharges such as at the Tunnel on Esopus Creek. Diatom cover was therefore related to both physical and chemical conditions of the environment. Possible impacts on trout fry in redds was suggested.

Rosgen, Dave L. 2001. A practical method of computing streambank erosion rate. *Proceedings of the Seventh Federal Interagency Sedimentation Conference Vol. 1* (pp. II-9–II-15). Reno, NV: Subcommittee on Sedimentation. Available on the Wildland Hydrology website: https://wildlandhydrology.com/resources/docs/Streambank Erosion/Rosgen_2001_Streambank_Erosion.pdf

A model for developing quantitative prediction of streambank erosion rates uses a rational estimation, process-integration approach. A streambank erodibility index and calculated near-bank stresses are utilized in the prediction model. Streambank characteristics involve measurements of bank heights, angles, materials, presence of layers, rooting depth, rooting density and per cent of bank protection, and are used to develop the streambank erodibility index. Measured data are converted to a normalization index for application in a wide range of channel sizes and types. Near-bank stress requires calculation of vertical velocity profiles and shear stress for subsequent distribution of energy calculations in the near-bank region.

Rosgen, Dave L. 2007. WARSSS – Watershed Assessment of River Stability and Sediment Supply – An Overview. H*ydrological Science and Technology, Volume 23, No. 1-4 Proceedings of the 2007 American Institute of Hydrology Annual Meeting and International Conference "Integrated Watershed Management: Partnerships in Science, Technology and Planning,"* Reno, Nevada, April 22-25, 2007. Available on the Wildland Hydrology website: https://wildlandhydrology.com/resources/docs/Assessment/Rosgen_2007_WARSSS.pdf

WARSSS integrates the disciplines of hydrology, geomorphology, geology, engineering, soil and plant science into a watershed assessment methodology. WARSSS is a three-phase methodology that: identifies specific locations and processes adversely affected by various land uses; provides a consistent, quantitative analysis of sediment supply and channel stability; predicts hillslope, hydrologic and channel processes contributing to sediment yield and river impairment; establishes a basis for site- and process-specific mitigation; and documents a better understanding of the cumulative effects of various land uses on the water resources. The EPA has supported and peer reviewed WARSSS as an alternative to numeric standards for "clean sediment TMDLs." WARSSS is also used in river restoration by documenting the cause and consequence of impairment and establishing criteria for natural channel design.

Ross, Tyler J. 2012. *Effects of Anthropogenic Stream Alteration on Brown Trout Habitat, Movement and Physiology*. M.S. Thesis, Cornell University. http://hdl.handle.net/1813/31166

Alterations in water temperature, turbidity and flow regimes on Brown Trout in Esopus Creek were studied during the summers of 2009-2011. Aspects studied included biomarkers of trout health, trout movement, growth, condition, apparent survival and use of thermal refugia by radio tagged trout. Findings generally showed a positive influence to trout well-being for a distance downstream of the Tunnel. But trout downstream of the Tunnel were negatively impacted more so by turbidity than water temperature, despite the cooling influences of releases entering from the Tunnel. Trout upstream of the Tunnel were stressed by elevated water temperatures.

Siemion, Jason, Michael R. McHale and Wae D. Davis. 2016. *Suspended-Sediment and Turbidity Responses to Sediment and Turbidity Reduction Projects in the Beaver Kill, Stony Clove Creek, and Warner Creek Watersheds, New York, 2010–14*. Scientific Investigations Report 2016–5157. Troy, NY: U.S. Geological Survey, 28 pp. https://doi.org/10.3133/sir20165157

Suspended-sediment concentrations (SSCs) and turbidity were monitored within the Beaver Kill, Stony Clove Creek, and Warner Creek tributaries to the upper Esopus Creek in New York, the main source of water to the Ashokan Reservoir, from October 1, 2010, through September 30, 2014. The purpose of the monitoring was to determine the effects of suspended-sediment and turbidity reduction projects (STRPs) on SSC and turbidity in two of the three streams; no STRPs were constructed in the Beaver Kill watershed. During the study period, four STRPs were completed in the Stony Clove Creek and Warner Creek watersheds. Daily mean SSCs decreased significantly for a given streamflow after the STRPs were completed. The most substantial decreases in daily mean SSCs were measured at the highest streamflows. Background SSCs, as measured in water samples collected in upstream reference stream reaches, in all three streams in this study were less than 5 milligrams per liter during low and high streamflows. Longitudinal stream sampling identified stream reaches with failing hillslopes in contact with the stream channel as the primary sediment sources in the Beaver Kill and Stony Clove Creek watersheds.

Smith, Alexander J., Robert W. Bode, Margaret A. Novak, Lawrence E. Abele, Diana L. Heitzman and Brian T. Duffy. 2008. *Upper Esopus Creek Biological Assessment 2007 Survey*. Albany, NY: NYS Department of Environmental Conservation, 48 pp. http://www.dec.ny.gov/docs/water_pdf/sbuupesopscr07.pdf

Traveling kick samples of macroinvertebrates were taken at six sites from riffle areas in the main channel of Esopus Creek for a biological assessment of water quality based on species richness, biotic indices, EPT [Ephemoroptera (mayfly), Plecoptera (stone fly), Tricoptera (caddisfly)] richness and percent model affinity. Changes from the previous biological assessment included a slight decrease in water quality near Phoenicia. Birch Creek input of organics and nutrient was considered as a possible stronger invertebrate community detriment than the Tunnel outfall.

Smith, Alexander. J. 2013. *Upper Esopus Creek Biological Assessment 2009-2010 Survey*. Albany, NY: NYS Department of Environmental Conservation, 32 pp. http://www.dec.ny.gov/docs/water_pdf/barupperesopuscreek09.pdf

Kick samples of macroinvertebrates were taken from riffle habitats in Upper Esopus Creek for biological assessment of water quality. Sampling and analysis followed a long-standing DEC protocol. Assessment was based on species richness, biotic indices, EPT [Ephemoroptera (mayfly), Plecoptera (stonefly) and Tricoptera (caddisfly)] richness and percent model affinity. Most samples from sites downstream of the Tunnel, taken during the summer of 2010, indicated that those sites were slightly impacted. Significant shifts in the communities immediately downstream of the Tunnel were evident by the loss of sensitive taxa. Findings from the study suggest that differences in the biological condition downstream of the Tunnel were primarily driven by variation in yearly flow condition.

Appendix 3 – Acronym Glossary

A	Classification assigned to waters used as a source of drinking water
AWSMP	Ashokan Watershed Stream Management Program
B	Classification assigned to waters best used for swimming and other contact recreation, but not for drinking water
BANCS	Bank Assessment for Nonpoint Sources of Sediment
BEHI	Bank Erosion Hazard Index
BEMS	Bank Erosion Monitoring Site
C	Classification assigned to waters supporting fisheries and suitable for non-contact activities
CCE	Cornell Cooperative Extension of Ulster County
CFS	Cubic Feet Per Second
CSBI	Catskill Streams Buffer Initiative
DEC	New York State Department of Environmental Conservation
DEP	New York City Department of Environmental Protection
EPT	Ephemoroptera (mayfly), Plecoptera (stonefly) and Tricoptera (caddisfly)
FT	Feet
GCC	Global Climate Change
GIS	Geographic Information Systems
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HSI	Habitat Suitability Index
IBI	Index of Biotic Integrity
K	Kelvin
LFA	Local Flood Analysis
NBS	Near Bank Stress
NYC	New York City
SFI	Stream Feature Inventory
SSC	Suspended Sediment Concentration
STEM	Science, Technology, Engineering and Math
SWCD	Ulster County Soil and Water Conservation District
SWPPP	Stormwater Pollution Prevention Plan
T	Indicating that a classified water body may support a trout population
TIR	Thermal Imaging Radar
TS	Indicating that a classified water body may support trout spawning
TWI	Topographic Wetness Index
USGS	United States Geological Survey
WARSSS	Watershed Assessment of River Stability and Sediment Supply

Ashokan Watershed
Stream Management Program

Ashokan Watershed Stream Management Program
PO Box 667
Shokan, NY 12481
www.ashokanstreams.org
https://www.facebook.com/AWSMPUlster/