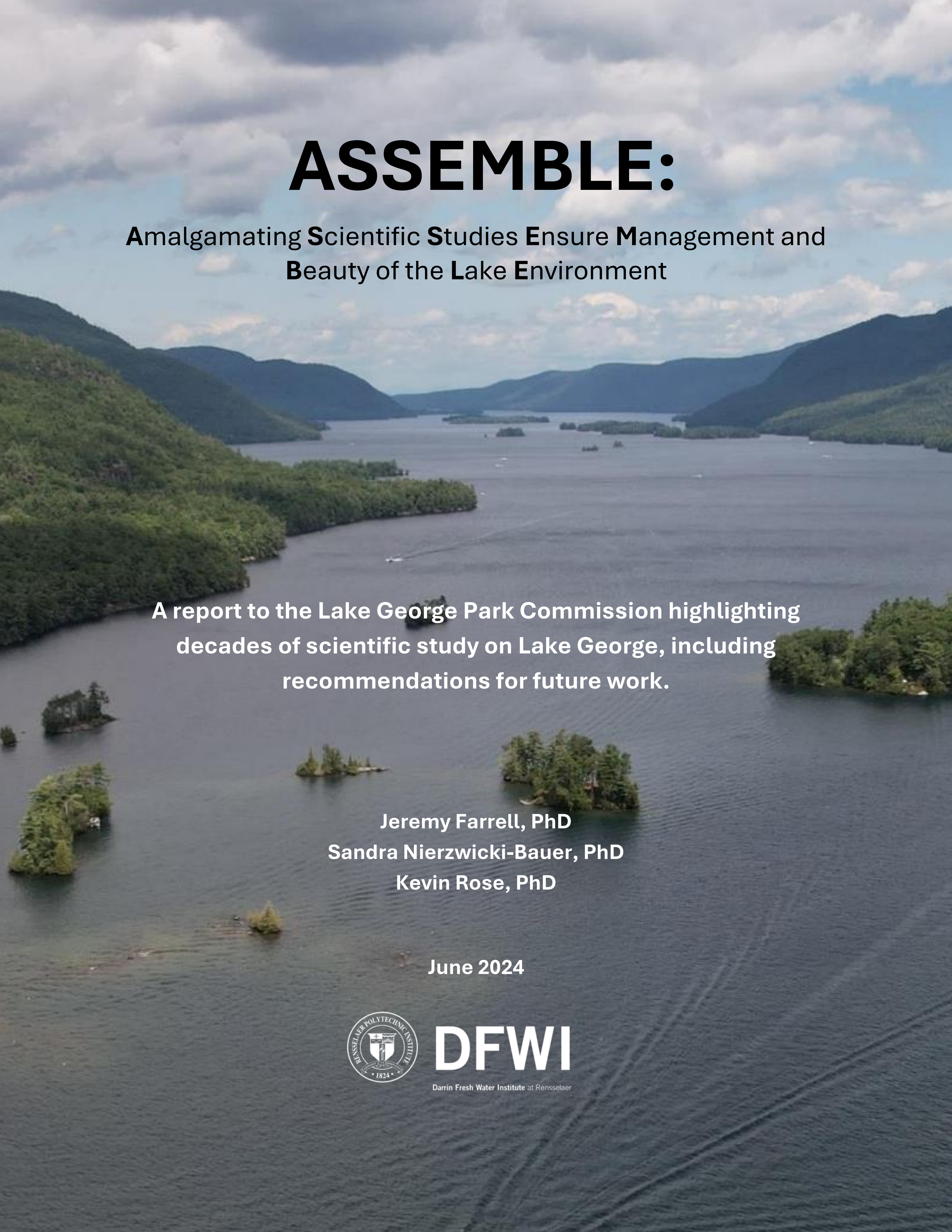

ASSEMBLE:

Amalgamating **S**cientific **S**tudies **E**nsure **M**anagement and **B**eauty of the **L**ake **E**nvironment

A report to the Lake George Park Commission highlighting decades of scientific study on Lake George, including recommendations for future work.

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June 2024

DFWI
Darrin Fresh Water Institute at Rensselaer

Acknowledgements

This report is based on publicly available data, scientific publications, and presentations. We are grateful to the leadership at Rensselaer and the numerous scientists and engineers at the Darrin Fresh Water Institute and collaborating organizations who conducted this research. These efforts were generously supported by many organizations and agencies, including the Jefferson Project, which is a partnership between the Lake George Association (previously, the FUND for Lake George), IBM Research, and Rensselaer Polytechnic Institute; the Froehlich Foundation; the US National Science Foundation; the US Environmental Protection Agency; the New York State Department of Environmental Conservation; the Lake George Park Commission; the Knapp Foundation; and The Nature Conservancy. We are also grateful for input for this report from DFWI researchers including Dr. Jonathan Borrelli, Dr. Mark Swinton, David Winker and for external reviews by Dr. Charles Boylen, Dr. James Sutherland, and Dr. Brendan Wiltse, whose input improved the report.

OVERVIEW

Lake George is widely recognized as a beautiful natural resource and cherished for its near-pristine waters. The Lake's natural beauty underpins the regional economy by drawing tourists to the area. Over the last 150 years, significant efforts and resources have been dedicated to safeguarding the Lake from human impacts. Alongside ongoing conservation endeavors, scientists and researchers have examined many of the Lake's physical, chemical, and biological characteristics. These scientific findings can provide the foundation for effective resource management efforts. Informed policy requires a deep understanding of the past, present, and potential future consequences of changes in the Lake and watershed. Now, more than ever, integrating science and management practices is needed to shape policies that ensure the enduring conservation of the Lake for generations to come.

The Darrin Fresh Water Institute (DFWI) was founded in 1967 with a goal of exploring and understanding the physical, chemical, and biological dynamics of Lake George using the most current technology available. Through the years the people and technology have changed but the fundamental mission has remained. The DFWI has studied nearly every aspect of the Lake's ecosystem and reported on it in numerous scientific journal articles, delivered presentations at local, regional, and international meetings, and testified at congressional hearings. The knowledge and insights gained through these efforts can be lost or misinterpreted if not condensed, summarized, and shared in a meaningful way to management and policy makers.

The primary goal of this document is to provide an engaging, succinct, and accessible summary of the many scientific studies of Lake George and its watershed. A secondary goal of this initiative is to help bridge the gaps between science, policy, and management. This should lead to well informed decision-making and efficient utilization of State and Local resources in the protection and improvement of Lake George for future generations.

WATER QUALITY & CLARITY

BACKGROUND

Lake George is an oligotrophic (low nutrient) lake with high water clarity and water quality. The Lake is designated as a Class AA-Special lake, a designation reserved for only the cleanest and clearest lakes in New York State. Despite this classification, there are many issues that threaten the Lake.

Eutrophication, the process in which a water body experiences increases in nutrients that promote excess algal and plant growth has arguably been the biggest threat to the Lake. The two key nutrients limiting algal and plant growth in Lake George (and most other lakes) are phosphorus and nitrogen. During the 1960s and 1970s, excessive inputs of nitrogen and phosphorus were assessed by RPI scientists including former DFWI directors Chuck Boylen and Nick Clesseri. The sources of these nutrients included wastewater treatment facilities, residential septic systems, and detergents high in phosphorus. These excess nutrients resulted in aesthetically displeasing odors, multiple reported large algal blooms. While there have been important regulatory actions to address phosphorus pollution, nutrient inputs from wastewater treatment facilities, septic systems, and storm water runoff remain concerns.

Additionally, while acid rain negatively impacted lakes throughout the Northeast and Europe, Lake George was not severely impacted. This is likely due to its location on the drier side of the Adirondack mountain range and its greater natural buffering capacity (i.e., ability to resist changes in pH) compared with many other lakes in the Adirondacks. This buffering capacity is afforded by a few limestone deposits in its small Watershed.

HISTORICAL WATER QUALITY MONITORING PROGRAM

Concerns about a changing Lake from excess nutrient loading spurred the creation of the Lake George Offshore Monitoring Program in 1980. This program measured a range of chemical, biological, and physical parameters to identify any detrimental impacts and changes occurring in the Lake. With ongoing support from the Lake George Association, this monitoring program continues today. Major findings from the first 30 years of this program included:

- Sodium chloride (NaCl), the dominant road deicer used in the Watershed, increased in the Lake by nearly 3-fold.

- Chlorophyll-*a* concentrations, a surrogate for phytoplankton biomass, increased by ~1/3 while water clarity, based on Secchi depth, decreased ~ 0.5 meters.
- Acidic compounds decreased with a ~1/3 reduction in sulfate over the 30 years and ~1/4 decrease in nitrate since 1997 when total nitrogen measurements began.
- The reduction of sulfate and nitrate from atmospheric deposition resulted in increases in the Lake's pH and buffering capacity.
- Surface water temperatures increased by 1.8 °C (3.2°F) which led to longer growing seasons and potentially extending the period of lake stratification.
- Oxygen depletion in deep waters (hypoxia) develops seasonally in the Caldwell Basin during late summer/early fall often resulting in phosphorus released from sediments, a process known as internal loading.
- Spatial analysis revealed a decreasing northward gradient within the Lake for salt, phosphorus, and chlorophyll-*a*, with an increasing gradient in water clarity.

JEFFERSON PROJECT

Findings from the Offshore Monitoring Program and concern for their potential negative impacts on the Lake were the impetus for the creation of the Jefferson Project. The Jefferson Project is a partnership between the Lake George Association (previously, the FUND for Lake George), IBM Research, and Rensselaer Polytechnic Institute. A goal of the Project was to establish an extensive and sophisticated environmental monitoring program that could help inform management efforts to ensure a healthy lake for generations to come. With considerable and sustained support from the partners, researchers at DFWI have deployed and maintained hundreds of sensors and developed and implemented models to advance the science and management of Lake George.

CURRENT MONITORING PROGRAMS AND TRENDS

Despite substantial increases in salt (NaCl) concentrations in past decades, during recent years they have appeared to level off, remaining between 17-18 mg Cl/l. This is possibly due to the Lake reaching a balance, where the salt that is entering (input) the Lake from streams, runoff, and culverts is similar to the amount of salt leaving (output) the Lake. However, apparent plateaus have been observed previously, which were later followed by

increases in salt concentrations. Therefore, while the current plateau is encouraging it is not definitive evidence of success in addressing the road salt issue. Additionally, streams in more developed areas still have salt concentrations that can negatively impact organisms.

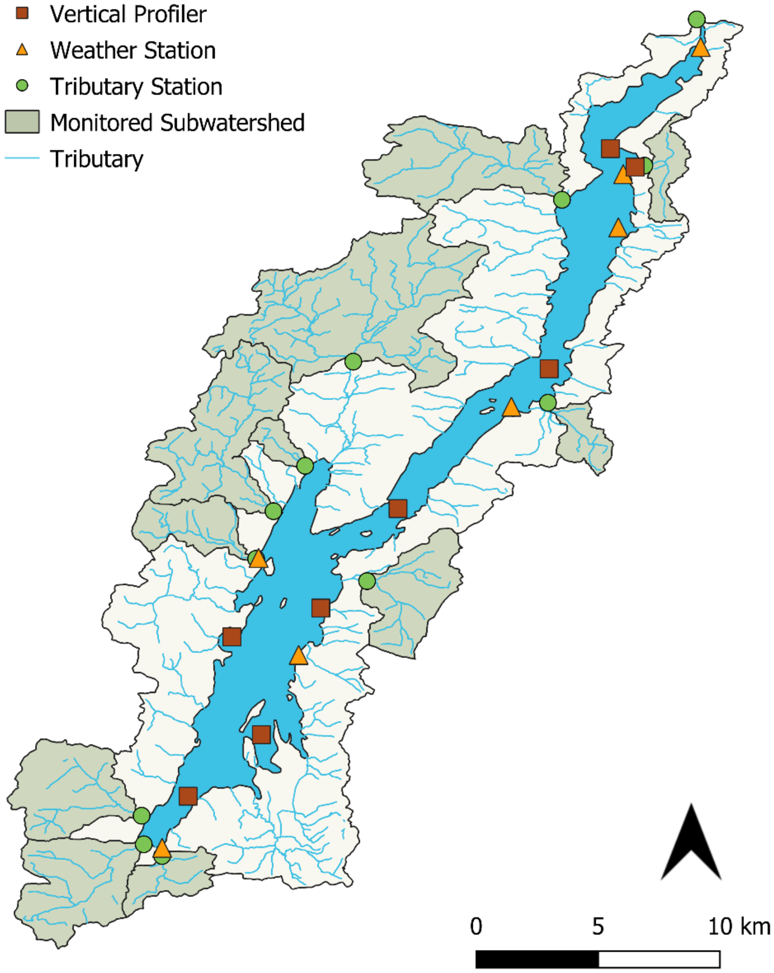
Nutrient concentrations in the Lake continue the same trajectory as observed in the 30-year report. While total phosphorus concentrations remain stable with average values in most years between 4-5 µg/l, the concentration of orthophosphate has increased over time. Monitoring data through 2016 showed that orthophosphate had increased by 0.5 µg/l, which represented a 70% increase since 1980. Total nitrogen has continued to decrease by ~1 µg/l each year, likely related to atmospheric reduction from the Clean Air Act Amendments. This has led to a significant and consistent lake-wide decrease in the ratio between Nitrogen to Phosphorus (N:P).

A lower N:P ratio has been shown to be favorable for the growth of some cyanobacteria and is a topic currently being investigated by researchers at DFWI. There has also been a significant increase in chlorophyll-*a* over time with the concentration increasing by 32% (0.41 µg/l) from 1980 to 2016. Despite this, no statistically significant trend in water clarity (Secchi depth) was detected over the same time period.

There was a 32% increase in chlorophyll-*a* but no statistically significant trend in water clarity (Secchi depth) over the 1980-2016 time period.

In general, the concentrations of dissolved oxygen in Lake George waters are sufficient to support a diverse and functioning food web. However, deep-water oxygen concentrations in the Caldwell Basin are depleted towards the end of the summer in most years. The depletion of oxygen in this area is likely related to the greater amount of biological activity in these isolated waters and is indicative of human impact. Low oxygen creates conditions that can result in the release of biologically-available phosphorus from the sediments back into the water, a process known as internal loading (see Physical Limnology section). During turnover in the fall, this biologically-available phosphorus can be used by algae and cyanobacteria and may contribute to late season algal blooms. The severity of oxygen depletion is a combination of the duration and depth of stratification, water temperature, and abundance of decaying algae and organic matter. Predicting the amount of oxygen loss and the potential for internal loading of phosphorus remains an ongoing research topic.

SENSOR NETWORK



Lake George has been referred to as "the smartest lake in the world" in large part because of the Jefferson Project's sophisticated and expansive sensor network. The network is comprised of dozens of interconnected platforms with hundreds of sensors collecting data throughout the Lake and its watershed at high frequency (up to four measurements per second). The sensors collect data on water quality, quantity, and meteorological conditions that provide researchers with insight into threats to the Lake including localized algal blooms, regional eutrophication, and global climate change. These data are published in a public online repository following a comprehensive quality checking and verification process (see reference section).

VERTICAL PROFILERS

The most visible portion of the sensor network are vertical profilers, which are small pontoon platforms that collect real-time information in and on the Lake. The vertical profilers have sensors that collect water quality measurements from each meter in the water column, usually once per hour. These vertically resolved measurements enable researchers to understand how water quality attributes vary with depth and through time. Measurements collected include conductivity (salt), temperature, dissolved oxygen, turbidity (cloudiness), dissolved organic matter, chlorophyll-*a* (algae) and phycocyanin (a pigment that only cyanobacteria produce that can be used to identify harmful algal

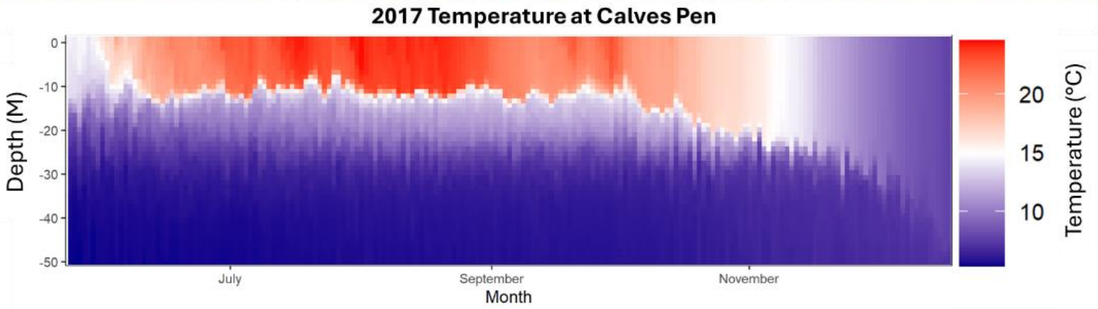
blooms). The profilers also are often outfitted with Acoustic Doppler Current Profilers (ADCPs) and weather stations, each described below.

ACOUSTIC DOPPLER CURRENT PROFILERS

Acoustic Doppler Current Profilers measure water movement at discrete depths from the near surface to near the lakebed. These instruments can be deployed in a variety of ways. Often, they are deployed on the vertical profilers, facing downward into the water. Other times they have been mounted on platforms that are placed on the bottom of the Lake looking upwards. Data that are collected enable researchers to measure and visualize hydrodynamic processes, as well as build and validate lake circulation models.

WEATHER STATIONS

Many in-lake chemical, physical, and biological processes are driven by weather conditions. Weather stations have been deployed to collect critical meteorological data such as wind speed, wind direction, air temperature, relative humidity, barometric pressure, precipitation, and solar radiation. These stations provide valuable context to better understand lake and watershed processes. Weather stations are positioned on land, on rock islands in the middle of the Lake, as well as on vertical profilers. Additionally, these weather measurements are essential for the development and validation of weather models that have been customized specifically for the Lake George Watershed.



TRIBUTARY STATIONS

Streams carry materials such as nutrients, organic matter, and chlorides (road salt) from the landscape to the Lake, especially during storm events. Tributary monitoring stations have been placed in and alongside 10 of the largest tributaries to the Lake, as well as the outlet in Ticonderoga. The stations are equipped with instruments to monitor the quality and quantity of water entering or exiting Lake George. While the stream stations monitor flow year-round, the bulk of the water and substances it carries enter the Lake during major storms. Up to 24 samples are collected by automatic water samplers for storm events, after which they are brought to the DFWI lab for nutrient and other chemical analyses. The relationship between flow and the inputs of various substances (e.g., nutrients, suspended sediments, salt) is an active area of research and one that varies with sub-watershed attributes such as slope and watershed land use. Monthly samples are also collected from tributary stations to monitor how baseline water chemistry is changing over time. Monitoring the volume of water coming in from tributaries and leaving at the outlet is also valuable for establishing a hydrologic and nutrient budgets.

SENSOR MONITORING NETWORK DATA

When deployed, the sensor network platforms are continuously transmitting measurements to an online database that allows researchers to view and analyze data in near real-time. Data from the sensor network are then carefully examined and undergo quality control to ensure that the highest quality information is retained in a final dataset. Laboratory measurements, as well as calibration metadata, are used to verify sensor readings. After the data have been verified and curated, they are then published in a freely accessible and public repository (Environmental Data Initiative), where it is available for download. Data are continually being quality checked and validated, and are released in annual batches when the quality control process is completed.

HISTORICAL STREAM MONITORING

Lake water quality can be substantially impacted by substances in the streams that enter into it. Recognizing this, the streams that enter Lake George have been the subject of numerous investigations since the 1970s. From 1970-1971, the New York State Department Of Health initiated a biweekly chemical monitoring program of 18 streams in the Watershed. This effort documented the baseline chemistry for these streams that still serve as a reference point against which comparisons can be made. The study also identified seasonal and spatial trends of chemical analytes.

In the early 1980s, the NYSDEC explored the impact of urbanization on nutrient chemistry in streams in the South Basin of the Lake. This study concluded that approximately 75% of the phosphorus loading was transported into the Lake from February to June. The study also revealed that the amount of phosphorus exported per area for each sub-watershed increased relative to the amount of urbanization. Jim Sutherland of the NYSDEC continued to monitor a subset of these streams, when possible, from the 1980s through the early 2000s.

The 1980s stream study concluded that the amount of phosphorus exported per area for each sub-watershed increased relative to the amount of urbanization.

In 2007-2010, researchers sampled eight sub-watersheds during storm events as well as collected monthly baseflow measurements. Exploration of these data revealed changing stream water chemistry related to salt use, urbanization, and the recovery from acid rain that were consistent with the in-lake trends.

BASIN WIDE TRIBUTARY SURVEY PROGRAM

In 2000, an effort was initiated by Sutherland et al. to quantify calcium concentrations entering the Lake from all streams in the Watershed. This was motivated by the then recent discovery of Zebra mussels in the Lake (Invasive Species section). There were 141 streams identified that had at least seasonal or intermittent flow that enter the Lake. This project served as inspiration for establishing a monitoring program to collect and analyze nutrients and physical parameters from all flowing streams 1-3x per year. Analyses of these data resulted in the identification of several 'groups' of streams that have similar chemical profiles. Each stream sampled was classified as baseline, moderately impacted, salt impacted or nutrient impacted. These data can be useful to identify potential areas for stormwater improvements and serve as a baseline for evaluating the efficacy of any future improvements.

TRIBUTARY MONITORING STATIONS

Over the last decade, the Jefferson Project has installed tributary monitoring stations in major streams around the Lake and the outlet. These monitoring stations have sondes that collect high-frequency sensor measurements on stream properties such as temperature, conductivity, dissolved oxygen and fluorescent dissolved organic matter. A scientific paper was published that predicted phosphorus and nitrogen concentrations (that otherwise can only be measured in the lab) from continuously measured tributary station data. The tributary station data is quality checked and regularly published in a public repository.

INTEGRATION OF ADVANCED TECHNOLOGIES

BENTHOTORCH

The DFWI has recently acquired a Benthotorch, an instrument capable of quantifying the abundance of several algal types growing on hard substrates in shallow waters. Researchers are using this instrument to characterize the benthic algal community in a Watershed wide stream survey. Preliminary examination of the data show that groupings based on these biological results follow a slightly different pattern than those based on nutrient and physical parameters. The groupings based on these data may be reflecting the type of nutrient pollution that results in the development of specific algal communities.

EXCITATION–EMISSION MATRIX (EEMS)

Another experimental approach employed by researchers at DFWI is Excitation-Emission Matrices (EEMs). A scanning spectrophotometer generates EEMs which can be analyzed to help elucidate the source(s) of dissolved organic carbon in the water. Samples were collected and analyzed by EEMs and then, through modeling, it is possible to identify contamination sources. For example, this approach revealed that water from West Brook has contamination consistent with wastewater sources.

FUTURE RESEARCH

A key challenge is predicting the amount of input of various substances, such as nutrients, salt, sediments, or organic matter, with increasing or variable streamflow. Creating these predictions would require developing instantaneous flow calculations and an evaluation of the relationship between stream flow and important constituent concentrations. As the severity of storms increase, additional research will be needed to accurately estimate loading during storms, especially severe storms that can be disproportionately important for loading. Models that can be used to estimate loading in unmonitored streams based on sub-watershed factors is also needed to approximate loading for nutrient and water budgets.

PRECIPITATION AND RUNOFF

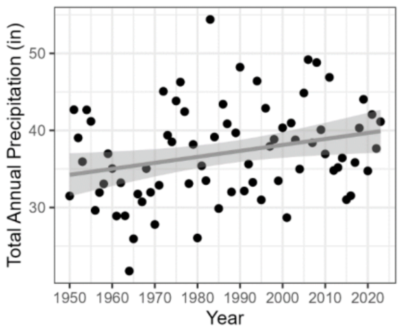
BACKGROUND

In addition to increasing air and water temperatures, climate change is affecting the timing, volume, and frequency of precipitation. Precipitation directly influences Lake George surface temperatures, mixing, and residence time (a measure of how long water stays in the Lake). Precipitation indirectly influences the Lake by transporting materials from the Watershed into the Lake. Changes in precipitation, including the number and severity of large storms, are important because inputs of sediment, nutrients, and other substances increase rapidly during severe storm events.

PRECIPITATION TRENDS

Over the last 120 years, the total annual precipitation increased by 10 to 20% across New York State. The variability in the amount of precipitation from year to year has also increased over time. An increasing proportion of precipitation is delivered during extreme storms. For example, across the Northeast, severe rainstorms of two inches or more have increased significantly over the past 70 years. In a 2023 report, the US National Climate Assessment determined that the Northeast region is most impacted by the increased severity of storms with more than a 70% increase in rainfall occurring during these storms.

The US National Climate Assessment (2023) determined that the Northeast region is most impacted by the increased severity of storms with more than a 70% increase in rainfall occurring during severe storms.



Regionally, precipitation data has been collected at Glens Falls, Ticonderoga, and Whitehall. Since 1950, an upward trend in precipitation has been recorded, increasing 5.5 inches at the Glens Falls station and 10.3 inches at the Whitehall station. As a percent relative to the mean in the first five years, this represents about a 15% - 30% increase in the volume of precipitation, respectively.

In addition to increases in the volume of precipitation, there have been more days with greater than 0.5 inches of precipitation observed. As of 2023, there's now about 5.5 extra days with these storms in Glens Falls and 8.7 more in Whitehall than there was in 1950. The mean number of storms of that magnitude had been 20.8, which is a 26% increase in the number of these storms in Glens Falls and 34% in Whitehall.

IMPACTS OF INCREASING PRECIPITATION AND HEAVY STORMS

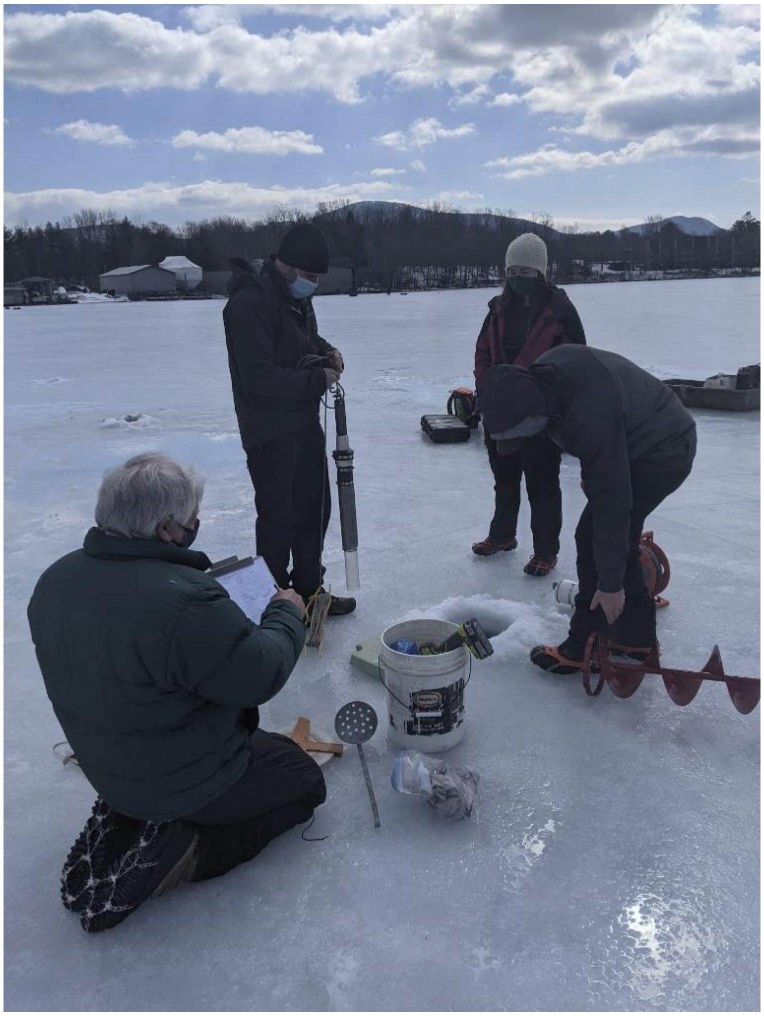
Increasing precipitation results in transport of greater quantities of substances from the Watershed into the Lake. Research in Lake George and elsewhere shows that severe storms disproportionately mobilize large volumes of sediments, nutrients, and other substances. This can detrimentally impact water quality and alter the bottom substrate (depth and texture), especially near tributary inflows. Storm events are responsible for as much as three-quarters of the annual loading of phosphorus to Lake George while accounting for less than one half of the total volume of stream discharge. The amount of phosphorus each stream transports to the Lake varies based on natural conditions (soil types, slopes, size) and land-use (roads, buildings, wastewater inputs) and is currently a primary area of research that aims to provide an updated hydrologic budget and annual loading of nutrients.

FUTURE RESEARCH

Research is ongoing at DFWI to understand the instantaneous loading of nutrients into the Lake. This work requires numerous measurements in streams before, during, and after storms, especially the most severe storms. Eventually, an accurate near real-time model of the nutrient budget could be built using data that includes these large storm events to understand nutrient loading throughout the Watershed and in response to variable and changing precipitation (both historic and forecasted).

PHYSICAL AND CHEMICAL CHANGES RELATED TO CLIMATE CHANGE

PHYSICAL LIMNOLOGY BACKGROUND



Climate change impacts the physical characteristics of a lake, which has consequences for the chemical and biological properties of the ecosystem. Lake George is dimictic, meaning that the entire water column mixes twice per year. In a typical year, as the Lake begins to warm in the spring, the water column mixes when it becomes isothermal (uniform temperature). During the spring, summer, and into fall, the Lake is stratified based on temperature separation (warm water in the upper 'epilimnion' and cold water in the deep 'hypolimnion'). These layers do not easily mix, allowing for different physical and chemical properties to exist in each layer. As the Lake loses heat in the fall, the epilimnion temperature will decrease and expand to deeper water. Eventually the water temperature through the entire water column will again mix and become isothermal.

ICE RECORDS

Long-term ice records have been collected for Lake George since 1908. Together with ice records from many other lakes throughout the northern half of the country, the Lake George ice record is used by the US EPA as an indicator of the effects of climate change. For Lake George, the seasonal ice cover period has been defined as the period during which one could travel on the ice from Lake George Village to Ticonderoga. Records show a shorter duration of ice cover and a modest shift toward earlier ice melt over time. Additionally, data reveals that the frequency of no complete ice cover has increased and become relatively common in recent years.

LAKE WARMING

As air temperatures increase, surface water temperatures also increase as reported in lakes around the world, including Lake George. Long-term data from Lake George monitoring show that surface waters have warmed at a rate of 0.5-0.6 °C/decade (0.9-1.1 °F/decade) since the 1980s. This warming rate is faster compared to many other lakes and the rate of atmospheric warming in the region, which has been about 0.34 °C/decade (0.6 °F/decade). However, in many lakes, deep-water (hypolimnetic) temperatures are not warming nearly as rapidly because deep waters remain isolated during periods of stratification and are not as sensitive to atmospheric changes. Faster warming of the surface water, compared with deep water, increases the density difference through the water column (i.e., increases the stratification strength).

DISSOLVED OXYGEN

In years when there is no ice or an early ice melt, Lake George warms up sooner and stratifies earlier than in years with historically normal ice cover. The amount of oxygen dissolved in deep waters is replenished each year during the spring turnover, the isothermal mixing event. During the stratified summer season, the density difference between layers acts as a barrier for oxygen-rich water mixing to the Lake bottom. In most lakes, including Lake George, the concentration of dissolved oxygen in deep waters declines over the course of the stratified season. While this is a natural phenomenon, it can be made worse through eutrophication and climate warming.

Studies on hundreds of lakes, including Lake George, have shown shifts towards an earlier onset of stratification along with lower dissolved oxygen concentrations in deep waters during the warm summer months. Monitoring data show that the deep water dissolved oxygen concentration is variable year to year in Lake George due to a variety of factors. While the concentration of dissolved oxygen in the deep waters of the Lake is sufficient to support a wide variety of organisms throughout the hypolimnion most of the year, there is still cause for concern. First, it is likely that reduced dissolved oxygen concentrations will become an important threat to water quality in the Lake if trends toward earlier ice off and

stratification onset continue. Second, if increases in algal biomass (as measured by chlorophyll-*a*) continue, this could increase the rate of oxygen consumption in deep waters, thereby exacerbating low oxygen conditions.

If dissolved oxygen concentrations in hypolimnetic waters in Lake George continue to decline, this could threaten cold-water fisheries habitat. Sensitive fish, such as some trout species, begin to experience detrimental impacts at low dissolved oxygen concentrations (<5 mg/l). Additionally, in low oxygen conditions, sediments release sequestered phosphorus into the water. Because phosphorus is an important nutrient that limits algal growth, release of this nutrient can stimulate algal growth and reduce water quality and clarity.

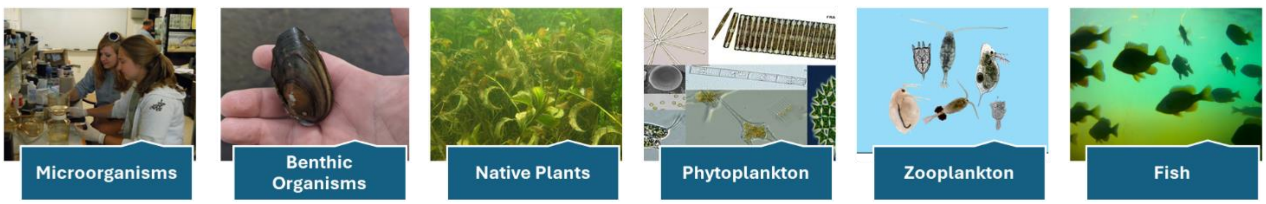
FUTURE RESEARCH

Continued monitoring of Lake George's ice cover and duration, temperature, and dissolved oxygen is needed to study long-term trends to better understand how the Lake is impacted by climate change. Among the many impacts of climate change is the potential influence on internal loading of nutrients. These nutrients would affect the composition and abundance of algal communities and could alter water quality and clarity.

NATIVE BIOTA

INTRODUCTION

The functioning of an ecosystem is based on interactions between the physical and chemical environment with the biota. A well-functioning ecosystem tends to be stable on the scale of decades. The DFWI has studied nearly all levels of the biota within the Lake George ecosystem, from microorganisms up to fish. Each of the organisms in the ecosystem plays a unique role and has multiple and often non-linear interactions with other levels of the ecosystem. Below is a short description of studies carried out at each level.



MICROORGANISMS

GENERAL BACTERIAL COMMUNITY ANALYSIS

Characterizing bacterial communities of lakes has been greatly advanced by the utilization of molecular techniques that do not require traditional methods of culturing microbes for their identification. In particular, the approach of characterizing microbial community composition and diversity based on sequencing and analysis of a particular gene (16S rRNA) is now widely used and accepted.

In Lake George, this characterization approach has been carried out several times by students and researchers since the late 1990s. In general, the overall microbial community assemblage in Lake George has been similar to that observed in other Adirondack lakes, excluding those lakes that have experienced substantial past acidification or other major human impacts.

To date, monitoring of bacterial communities has only occurred when resources were available. However, establishing a regular sampling program of the bacterial community in conjunction with a chemistry program could provide deeper insight on how the bacterial community and chemical constituents of the Lake interact. Additionally, exploring the bacterial community composition in different environmental niches within the Lake (e.g. in association with HAB's, biofilms on hard substrates, and anaerobic zones) will be valuable for understanding their role in ecosystem function and biogeochemical cycling.

E. COLI AS AN INDICATOR OF FECAL COLIFORM CONTAMINATION

E. coli is a bacterium that lives in the intestines of animals. When found outside of the body, it is generally considered problematic because some *E. coli* strains are capable of causing human sickness. These pathogenic *E. coli* can be transported and (in certain circumstances) thrive in waterbodies, thereby compromising drinking and recreational waters.

Researchers at DFWI have been engaged with several projects attempting to identify and quantify potentially pathogenic *E. coli* in the Lake. In 2009, at Shepards Park Beach, after a sewage pump failure led to direct discharge into the Lake, DFWI researchers collected samples on a daily basis to determine the extent of the problem and when the beach could be opened. During the summers of 2016-2018, when Million Dollar Beach was intermittently closed by the New York State Department of Health, DFWI researchers investigated potential contamination sources in the Watershed using the quick and effective Idexx Quantitray approach. Since COVID-19, DFWI no longer carries certification for pathogenic *E. coli* detection, therefore we can only use this approach for research purposes. However, re-certification is possible.

In the event of future *E. coli* contamination events, DFWI researchers have the capability to quantify pathogenic *E. coli* abundance in a rapid (24 hours) time period. If there are additional instances of *E. coli* contamination in the Lake it would be useful to determine the animal origin, which would require the development and use of molecular techniques.

PICOEUKARYOTES

The smallest aquatic eukaryotic organisms, called picoeukaryotes, are an understudied group that play a role in ecosystem dynamics including primary production, bacterial predation and in some instances they can be parasites. Therefore, it is important to understand the community composition of these organisms in the Lake.

In the early 2000s, researchers at DFWI explored the occurrence and classification of these organisms using molecular techniques. A significant portion of the picoeukaryotes identified by genetic sequence analyses belonged to species that had not been previously observed, and some couldn't be categorized into currently known groups. Interestingly, many freshwater organisms identified in this research were different from picoeukaryotes that are common in marine environments, indicating that microbial diversity of these eukaryotes are highly specific to their water environments. The exact role of picoeukaryotes in the food web remains a curiosity but is not currently a priority.

CYANOPHAGE

Cyanobacteria (bacteria capable of photosynthesis) that are associated with Harmful Algal Blooms (HABs) are generally thought to be nutrient limited which influences the size and duration of HAB events. However, another intriguing possible influence on the duration of blooms is infection of cyanobacteria by cyanophage (viruses that infect cyanobacteria).

To explore the presence and diversity of cyanophage in Lake George, DFWI researchers carried out preliminary work using molecular techniques. A total of 150 cyanophage sequences were analyzed and researchers determined that the sequences represented 13 distinct groups that varied both spatially (North vs South Basin) and temporally (June vs September). Through these studies we determined that in Lake George there are diverse groups of cyanophage that are capable of infecting many types of cyanobacteria.

Future work exploring the presence and abundance of different cyanophage during blooms, versus in locations without blooms, would help us understand if they are potentially playing a role in shaping the time, duration, and extent of HABs in the Lake.

BENTHIC ORGANISMS

Benthic (bottom-dwelling) organisms include larval stages of insects and small aquatic animals, including snails, clams, and mussels that live in and around the sediments of lakes. These organisms can have a major impact on nutrient cycling within the sediments which directly impacts water clarity and water quality of a lake. They are also often an important food resource for fish. The diversity and abundance of benthic organisms can also be used as indicators of overall water quality and human influence.

The earliest study that examined benthic organisms in the Lake, because of their importance as a food staple for fish, was conducted by Needham et al. (1920) at 5 deep water locations.

To get a better understanding of the longest-lived animals in Lake George, DFWI researchers initiated a long-term growth and health study of the native mussel community in the late 1990s. This study consisted of tagging and then recapturing mussels placed within enclosures at several locations in the Lake over time (every few years). These studies are ongoing but preliminary results indicate that some species of native mussels are capable of living over 80 years.

From 2015 through 2020 the Jefferson Project has conducted sampling at approximately 45 sites in the nearshore zone to document the benthic community and track changes in the community over time. As of 2024, long-term trends have yet to be assessed given the relatively short duration of this dataset.

Future work by DFWI researchers could focus on repeating the historic survey of benthic animals conducted by Needham (1920) in the deep waters of the Lake. This effort would enable an assessment of how the benthic community has changed (or not changed) in the last 100 years, potentially providing an indication of the overall century-scale trajectory of the Lake water quality. This work would make it possible to identify shifts in types and/or quantity of benthic organisms that could provide insight related to changes to the benthic habitat. Additionally, the impact of invasive species management on the benthic community could help inform management practices and minimize disturbance to other sensitive species in the Lake.

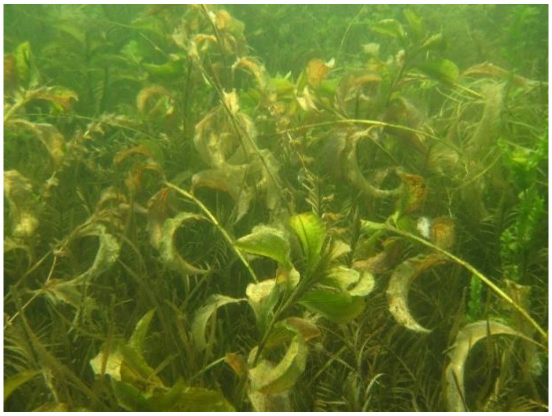
Historic surveys conducted by Needham in 1920 provides the opportunity to assess the current Native biota communities, providing an indication of the overall century-scale trajectory of the Lake water quality.

NATIVE PLANTS

Submerged aquatic vegetation (macrophytes and macroalgae) in a lake are an important component of the food web. These plants can use nutrients from the sediments and/or sometimes from the water column, slow down the movement of water stabilizing sediments, and provide habitat for many fish species.

Lake George has a large and diverse native plant community. In the 1970s, it was the subject of a study that resulted in a field guide to the plants of the Lake. This field guide identified 32 macrophyte species in the Lake, seven of which are considered rare, threatened, or endangered.

The plant community has typically been studied in conjunction with the removal of invasive species. Numerous studies have been completed noting the location, diversity, and abundance of native plants relative to the management efforts. Also, in the 1980s, studies were conducted to quantify the abundance of *Nitella* sp. (a macroalgae species) in deep water as it contributes to nutrient removal from the water column.



Future work could include a re-examination of the *Nitella* beds, as they are a major sink for nutrients but have been relatively understudied since the 1980s. Changes in the density and abundance of these macroalgae could provide insight regarding localized increases in nutrient enrichment.

PHYTOPLANKTON

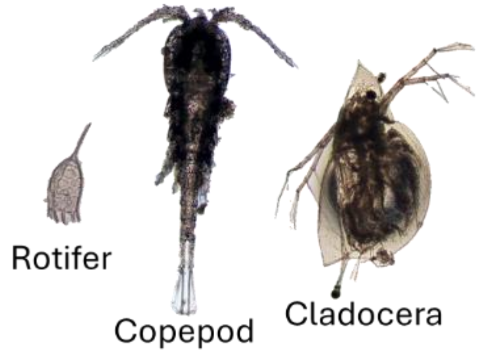
Phytoplankton are primary producers (photosynthetic organisms) in the Lake and are categorized by their general location, the open water, or attached to sediments and rocks. Phytoplankton tend to be very responsive to changes in water chemistry and, when large blooms occur, they can have a large impact on overall water quality. For additional information on cyanobacteria and Harmful Algal Blooms see the Emerging threats section.

A cursory examination of the open water plankton community was completed in the 1920s by Needham et al. In that study several locations were sampled to provide a general inventory of the species present. In the 1990s, a graduate student explored the diversity and abundance of phytoplankton species at different depths in the Lake and identified the importance of nutrients and light limitation to the community composition. More recently, the nearshore phytoplankton community was studied to identify the impact of nutrients on diatoms (a particular type of phytoplankton). The diatom community in the Southern Basin, which is more nutrient rich, was more impacted than the community in the more pristine Northern Basin.

Additionally, benthic algal growth is currently being examined using tile studies, wherein a ceramic tile is placed in the water, “incubated”, and then retrieved after a given amount of time. Plankton growing on the tiles are then broadly quantified using chlorophyll-*a* measurements, and more precisely identified using microscopy. These tile studies are ongoing to identify hotspots of benthic algal growth throughout the Lake, with the long-term goal of understanding what factors regulate the variability in growth and why some areas appear to have substantially more growth than others. Recently, researchers at DFWI purchased a Benthotorch, a probe that can provide general quantification of the main phytoplankton groups (Diatoms, Green Algae and Cyanobacteria).

Continued monitoring of the phytoplankton community is an important activity for assessing the overall health of Lake George and is also crucial for food web modeling. Researchers at DFWI have collected samples to analyze the phytoplankton community for many years as part of their Offshore Monitoring Program but many of these samples have not yet been analyzed. Analysis of these historic samples would provide insight into long-term changes in the phytoplankton community. Additionally, controlled mesocosm experiments are recommended to help determine why anecdotal observations of greater phytoplankton abundance in nearshore areas have been noted in recent years.

ZOOPLANKTON



Zooplankton are microscopic animals that generally cannot swim against a current. In freshwater systems, there are two main groups of zooplankton, the rotifers, a diverse group of herbivores that are typically a few microns long, and the larger crustaceans which can be further divided into two types, cladocera and copepods. Zooplankton are a key link in the food web. By eating phytoplankton, zooplankton can reduce algal abundance that can result in increased water clarity. Zooplankton are also an important source of food for fish. Therefore, understanding the dynamics of the zooplankton community is important for understanding the stability and health of the Lake George ecosystem.

The zooplankton community in Lake George has been categorized several times in the last 100 years. The first study was conducted in 1920 and identified the communities present in the Lake. Most recently, zooplankton communities were the subject of a dissertation that explored the impacts of climate change, eutrophication, and invasive species in Lake George. Specifically, results of this research indicated that rotifers can be used to identify subtle changes in nutrient concentrations in the Lake, and that the crustaceans are dramatically impacted by the timing of warming and presence of invasive species.

Future zooplankton community studies should explore how these organisms respond to other perturbations to the Lake. The role of zooplankton in regulating water clarity, translocating nutrients from deep layers to the surface via vertical migration, and the impacts of the Spiny waterflea invasion on these communities are also worth exploring.

FISH

The ‘top’ of the aquatic food web is occupied by fish. Different species have different dietary requirements or preferences and as a taxonomic group they eat everything from microscopic plankton to smaller fish. Lake George is considered a two-tier fishery with warm-water and cold-water fish. Warm-water fish (e.g. Sunfish and many Bass species) occupy the upper layers and nearshore zones in the Lake during the summer stratified season. Cold-water fish (e.g. Trout and Salmon) occupy the deeper, colder waters.

The most complete understanding of the fish of Lake George was carried out by Carl George (Union College) in 1980. In this work, he described the location and status of 36 fish species that inhabited the Lake, its tributaries and smaller waterbodies within the Watershed. Within the past 10 years, a history of the Lake George fishery was compiled from historical reports and newspaper accounts and presented at various forums. In 2014, a survey of the Yellow perch in the North and South Basins of the Lake was conducted and a significant difference in the growth rates and diets of this fish species was observed.

Future work could explore the movement of fish between basins using acoustic tags. This could determine if there is interaction between the fish populations in the Lake. An acoustic tagging study would also address whether there are areas in the Lake that are not being accessed by fish due to low oxygen concentrations. Other studies could examine the potential impact of invasive species on the stability of the food web.

FOOD WEB MODELING: PULLING IT TOGETHER

Food web modeling allows for predictions about how changes in some components of the ecosystem or surrounding environment could impact the stability of the food web and overall health of the Lake. Specifically, the consequence of key component changes like the introduction of invasive species or alterations in nutrient concentrations can be explored and predicted.

Modeling the food web has been one of the goals of the DFWI since its inception in 1967 with many notable advancements along the way.

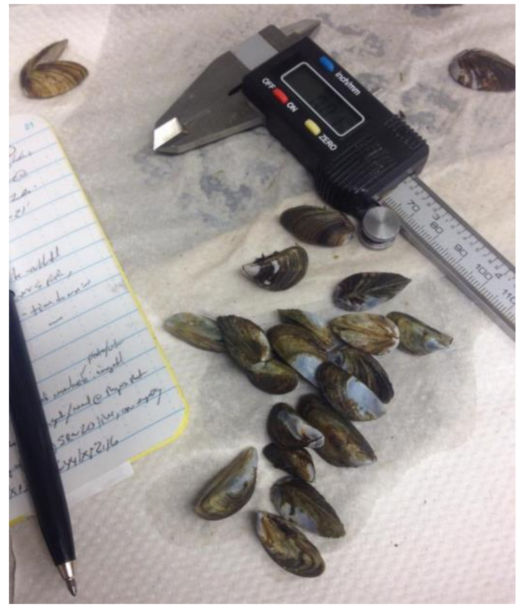
Modeling the aquatic food web in Lake George has been a goal of the DFWI since its inception in 1967. Efforts to study and model Northern Deciduous Biomes were initially made possible with funding from the National Science Foundation. Based on these early efforts, a model called "CLEANER" was developed by RPI scientists. This model was subsequently modified and contributed to the development of the EPA Aquatox model, which is used today to assess the impacts of contaminants and pollutants on aquatic food webs. For many years, due to limited resources, biota data sets, and modeling capabilities, little additional advancements were made on the development of a Lake George specific food web model. Recently, the development of a Lake George food web model has become a goal of the Jefferson Project. Therefore, researchers are now actively working to integrate a food web model with models that simulate weather, runoff, and lake circulation.

It is believed that accurate and predictive food web models can now be generated with the expansive biota database being established, along with weather, runoff, and hydrodynamic data. Preliminary results are promising, and work is ongoing to optimize this model for understanding the Lake George food web. This model should be valuable for making predictions as to how the food web could change given pressures from land use, climate change, invasive species introductions, or other changes.

INVASIVE SPECIES

ZEBRA MUSSELS (DREISSENA POLYMORPHA)

BACKGROUND



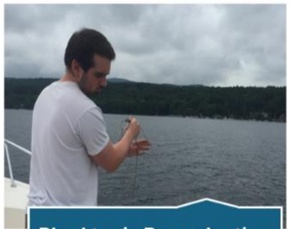
Zebra mussels were first found in the United States in the Great Lakes in 1986. Since their introduction the population has exploded, quickly colonizing lakes and rivers in at least 37 states. Zebra mussels generally require ~20 mg/l of calcium to thrive in a fresh waterbody. In Lake George, the ambient calcium concentration is typically between 12-14 mg/l, so it was originally hypothesized that the Lake's chemistry would not support this invasive species. However, Zebra mussels were identified in the southwest corner of the Lake in 1999, near the Shoreline Cruise Boat docks. A concrete walkway had recently been constructed in that area, potentially allowing for localized elevated calcium concentrations long enough for these organisms to establish a community. Subsequent to this initial observation, since 1999 we have found an additional 11 locations with adult Zebra mussels, usually in areas with elevated calcium concentrations.

POTENTIAL CONCERNS

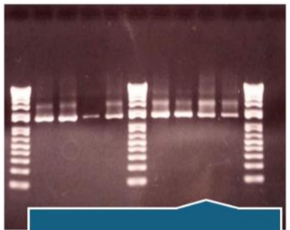
Zebra mussels have been shown to reshape and disrupt entire ecosystems. Typical economic concerns of Zebra mussels include clogging intake pipes, disruption of water facilities, and impacting tourism as their sharp shells can cause injury to swimmers. Ecological concerns vary based on the system they are in, but generally they have the capability to restructure entire food webs. Zebra mussels do this by filtering out nutrients and specific plankton species, which can result in regime shifts for the entire lake ecosystem. An additional concern in Lake George, is that Zebra mussels may adapt to the lower calcium concentrations. If this was to occur, it would lead to a scenario whereby Zebra mussels could dominate the benthic organisms which would have major impacts throughout the food web.

SCIENTIFIC STUDIES

Initial Management



Planktonic Reproduction Surveillance



Molecular Identification

Ongoing Search and Removal Efforts

INITIAL INTRODUCTION MANAGEMENT

Zebra mussels were first identified in Lake George by Joe Zarzynski of Bateaux Below in December 1999. Immediate efforts were launched to find and remove all Zebra mussels at the site to minimize the risk of reproduction that would lead to further colonization and spread in the Lake. To date, more than 22,000 mussels have been removed from the site, over 90% of them within the first six months of their discovery. Ongoing observations at this location for larvae, recruitment, and adult Zebra mussel growth indicate that they have not successfully reproduced at that site since the initiation of the project.

PLANKTONIC REPRODUCTION SURVEILLANCE

A concern of having Zebra mussel populations in the Lake is that they may reproduce, broadcasting their larvae and becoming more widely distributed throughout the Lake. To determine if Zebra mussels are successfully reproducing, we sample12 locations throughout the Lake at least five times over the summer months. Results of this effort are then used to inform our adult Zebra mussel survey and removal team to identify any new locations with Zebra mussels.

MOLECULAR IDENTIFICATION

In addition to microscopic detection of Zebra mussel larvae, we developed molecular techniques to identify these larvae in samples. Therefore, in instances where we are unsure of an identification based on microscopy, we employ a molecular technique to determine if the organism is, in fact, a Zebra mussel larvae.

ONGOING SEARCH AND REMOVAL EFFORTS

Twelve sites have been identified throughout the Lake where Zebra mussel populations are present. Each year DFWI researchers return to these sites and hand harvest all mussels that are observed. In all instances, fewer mussels have been observed and removed each year, and their median size is larger year after year. This indicates that the Zebra mussels are likely not successfully reproducing in the Lake. In addition to revisiting these sites, DFWI researchers search in areas adjacent to where larvae have been found, marinas, and respond to public reports of possible Zebra mussel sightings.

RECOMMENDATIONS FOR FUTURE WORK AND MANAGEMENT NEEDS

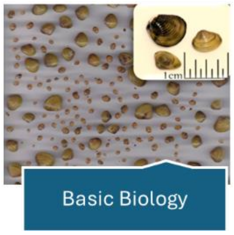
Currently, the DFWI has had success managing Zebra mussels in Lake George with an early detection and rapid removal approach. There are concerns that this may not always be possible if Zebra mussels develop a tolerance for the low calcium concentrations in the Lake. Additionally, long-term monitoring shows that calcium concentrations are increasing over time, which may aid in Zebra mussel spread. If that were to occur an alternative management method should be ready. Testing the efficacy and potential off-target effects of any management strategy to be used in Lake George would be valuable before it is implemented.

The DFWI has had success managing Zebra mussels in Lake George with an early detection and rapid removal approach, however an alternative method should be readied.

ASIAN CLAMS (CORBICULA FLUMINEA)

BACKGROUND

Asian clams were discovered in 2010 at Lake Avenue Beach in Lake George Village. After initial surveys, the population was determined to be limited to an area less than 10 acres in the immediate vicinity of this site. The Lake George Asian Clam Rapid Response Task Force was formed to develop an eradication plan using benthic barriers. Unfortunately, these efforts were not successful due largely to the high reproductive capacity of the species. Additionally, benthic barriers detrimentally impacted the majority of organisms in matted areas, creating open habitat for colonization by different organisms, potentially even other invasive species.



POTENTIAL CONCERNS

Asian clams are an invasive species, which means they can create large detrimental ecological and economic impacts when they proliferate. They grow abundantly and can displace and out compete native mussel species. Additionally, they can modify local water chemistry leading to elevated nutrients which can reshape the algal community and potentially create conditions that are favorable for algal blooms. After the clams die, shell decay can lead to areas with elevated calcium that can potentially create suitable conditions for Zebra mussels to thrive.

SCIENTIFIC STUDIES

BASIC BIOLOGY

Studies of the biology of Asian clams in Lake George revealed that ~5% begin to reproduce when they grow to 10 mm (~0.4 inches) in length. Reproductivity increases rapidly with size such that by the time they reach 15 mm (~0.6 inches) in length, about 50% are reproducing. July through October is the most active time of the year for reproduction, but individual clams have been found to reproduce from mid-May through mid-December.

Researchers at DFWI also tracked growth rates over a season. Asian clam growth was examined using a photographic analysis technique. Specifically, ~200 clams were collected from three locations and measured weekly over a season. Smaller clams tended to grow more quickly, up to 1.5 mm (~0.06 inches) per month, and larger clams grew more slowly until they reached a maximum size of ~30 mm (~1.2 inches).

MANAGEMENT

The use of benthic barriers as a control mechanism for Asian clams was studied by DFWI researchers in 2010 and subsequently used as a treatment method from 2011-2016. Results from the initial pilot study and subsequent treatment efforts showed that up to 99% mortality could be achieved after 45 days of treatment. Mortality was attributed to low oxygen and high ammonia concentrations measured under the benthic barriers. While these efforts were successful in the short term, within a few years the populations rebounded in the treated areas, and the barriers had detrimental impacts on other organisms.

MOVEMENT WITHIN THE LAKE

Researchers at DFWI have conducted studies to determine how clams spread and disperse in the Lake. These studies showed that movement throughout the Lake was possible due to both human transport and natural mechanisms. Human induced movement was shown to be possible by transport of clams in sediments from anchors in infested areas. As great as 80% of anchors pulled from infested areas contained sediments with Asian clams. Also, experiments demonstrated that clams could be moved more than 3 meters via boat propwash. Natural movement was observed with colonization of clams in habitat enclosures that were only accessible from the water column. Additionally, juvenile clams were found in sediments that were more than 20 meters from a source population.

MAPPING SPREAD: LAKE WIDE SURVEYS

Since 2011, yearly surveys have been conducted to determine the location of Asian clams in Lake George. The approach engages citizen scientist crews that are directed to survey areas in the Lake for Asian clams by sieving the sand with 2mm mesh screens. This effort has successfully tracked the proliferation of the species. As of 2023, Asian clams have been found in twenty-nine of the sixty-five sites examined.

PARASITE IMPACT

In 2015, researchers at DFWI discovered that *Chaetogaster limnaei*, a parasitic worm, was feeding on juvenile clams brooding in the gills of adult Asian clams. The impact of this parasite on Asian clams is not well studied. In Boon Bay, where the initial discovery was made, the abundance and reproductive success of adult Asian clams was lower than other locations where the parasite was not found in the clams. A series of experiments showed that *Chaetogaster* can readily infect clams after exposure. Ongoing work has shown that *Chaetogaster* has infected clams at other sites in the Lake, but to date, no formal study has been conducted on their impact at these locations.

RECOMMENDATIONS FOR FUTURE WORK AND MANAGEMENT NEEDS

As of 2024, there are no viable long-term strategies for the management of Asian clams in Lake George. Ongoing efforts to map the spread of Asian clams via the Lake Wide Survey provides an excellent way to engage citizen science and track the relative abundance of Asian clams. Future scientific studies of Asian clams should include tracking the impact of *Chaetogaster* at different sites in the Lake to understand if this parasitic worm may be an effective biocontrol of Asian clams. Finally, it would be valuable to periodically re-evaluate the growth and reproductive success of Asian clams. The Lake is changing in response to factors such as climate change and other human impacts, and how these changes may impact the growth and reproductive rates of Asian clams is poorly understood.

SPINY WATERFLEAS (BYTHOTREPHES LONGIMANUS)

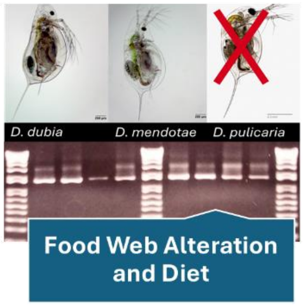
BACKGROUND

The Spiny waterflea was first reported in North America in 1984 and has spread across the Northeast USA since its introduction. The first documented evidence of this invasive species in Lake George was in 2012 by a fisherman. The Spiny waterflea is a planktonic organism that can be hard to detect, but are noticeable when they attach to fishing lines.

POTENTIAL CONCERNS

Spiny waterfleas can fundamentally alter the composition of the zooplankton community of a lake by consuming zooplankton while being resistant to fish predation. Following the introduction of Spiny waterfleas, populations of several zooplankton species including *Daphnia pulicaria*, an important grazer, typically crash. This often results in changes to zooplankton communities because some species like *Holopedium gibberum*, or *Daphnia menedotae* are more difficult for Spiny waterfleas to prey upon. Alterations of the zooplankton community can have far-reaching consequences on the health and function of the ecosystem, including loss of water clarity and increases in deep-water oxygen loss. The impacts of Spiny waterfleas can trigger regime shifts, as zooplankton play an important role in phytoplankton community composition and serve as a food source for larger organisms including fish.

SCIENTIFIC STUDIES



FOOD WEB ALTERATION

Based on the finding of Spiny waterfleas in 2012, a Ph.D. student project was initiated to follow the zooplankton community composition and structure from 2014-2017. Due to challenges with sampling protocols, a standardized sampling program did not begin until

2015 (Spiny waterfleas are fast and difficult to collect with traditional zooplankton sampling methods). At its peak abundance during this project, up to 1.6 individual Spiny waterfleas per cubic meter were observed in 2015. Concurrent with this population surge, the abundance of one of the dominant zooplankton species, *Daphnia pulicaria*, started to crash. The loss of *Daphnia pulicaria* can have a profound impact on the ecosystem and this species was not observed again for the duration of the study. It is noteworthy that this Spiny waterflea population crashed in 2016, but continued monitoring since then revealed a resurgence of this invasive species in 2023.

SPINY WATERFLEA DIET

Given the impact that Spiny waterfleas had on the zooplankton population in Lake George, DFWI researchers embarked on an effort to more precisely determine the diet of the Spiny waterflea. Direct microscopic observation of organisms in the gut of the Spiny waterflea is difficult given rapid digestion of the small and hard to identify prey. Therefore, a technique was developed to identify and quantify the organisms in the gut using molecular techniques. Specifically, Polymerase Chain Reaction (PCR) primers were developed to determine the exact makeup of the prey. Unfortunately for this project, the Spiny waterflea population was no longer detectable in Lake George by the time these techniques were developed. However, we were able to successfully use them to determine the gut contents of Spiny waterfleas present in two other Adirondack Lakes. These results showed that Spiny waterfleas did not eat *Holopedium*, a larger gelatinous coated organism that occasionally dominates lake zooplankton communities following Spiny waterflea invasions.

ONGOING SPINY WATERFLEA MONITORING

Following the completion of focused Spiny waterflea studies, researchers at DFWI have maintained a monitoring program for the Spiny waterflea to determine if it would rebound in the Lake, following its crash in 2016. This program consisted of sampling nine locations in the Lake 4-5 times over the fall months when Spiny waterfleas are known to emerge.

The Spiny waterflea population crashed in 2016 but continued monitoring revealed a resurgence in 2023.

Interestingly, Spiny waterfleas were not observed from 2016-2019. However, a small population was observed in the center of the Lake in 2020. Monitoring efforts continued for this population which remained small through 2022. In 2023, the population spiked throughout the Lake with over twice the number of organisms present than its previous peak in 2015.

RECOMMENDATIONS FOR FUTURE WORK AND MANAGEMENT NEEDS

The impact of this invasive species in Lake George is not fully understood, however they may be affecting fish health, altering algal growth, water clarity, and other important water quality attributes. Therefore, it is recommended that continued monitoring occur to assess the zooplankton population, before, during, and after the most recent emergence of Spiny waterfleas. This would be valuable for obtaining a better understanding of their direct impact on the zooplankton community. It would also be useful to directly quantify their diet in Lake George using the molecular tools and techniques we developed. Regarding management of Spiny waterfleas, unfortunately, at the present time, no viable options have been identified.

EURASIAN WATERMILFOIL (*MYRIOPHYLLUM SPICATUM*)

BACKGROUND

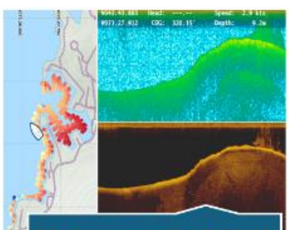
In August 1985, Eurasian watermilfoil was first found in Lake George Village, Huddle Bay, and Dunham's Bay. By 1993, the plant had already spread to over 100 locations in the Lake. To date, there are over 200 areas in the Lake that have been identified as having or had Eurasian watermilfoil present. A tremendous amount of time, resources, and effort has been spent attempting to control, manage or eliminate this invasive species from the Lake. Much less effort has been spent on research to study the biological impact or the efficacy and unintended consequences of various management approaches.

POTENTIAL CONCERNS

The introduction of Eurasian watermilfoil can cause a variety of issues for a lake ecosystem. Native macrophyte diversity and abundance declines because Eurasian watermilfoil beds grow into dense canopies that often reach the surface. This reduces light availability early in the season before many native macrophytes begin to grow. The downstream effect of outcompeting native plants species also generally results in fewer macroinvertebrates (including benthic invertebrates) and a reduced abundance of native fish species. In lakes with abundant Eurasian watermilfoil, economic concerns include difficulty of motorboating and swimming in infested areas, which can result in decreased tourism and potentially reduced shoreline property values. However, in general, the impact of Eurasian watermilfoil is lower in oligotrophic (low nutrient) lakes, like Lake George, when compared with eutrophic (nutrient rich) lakes.


Eurasian Water Milfoil Reproduction


Physical Management Strategies


Hydroacoustic Milfoil Detection

Long Term Evaluation of Milfoil Management

SCIENTIFIC STUDIES

In the late 1980s and 1990s, researchers at the DFWI conducted biological and management studies of the then, newly introduced invasive Eurasian watermilfoil. As this invasive species became more established in the Lake, the focus turned towards applying long-term management approaches.

REPRODUCTION

The spread of Eurasian watermilfoil has been investigated through field and laboratory experiments. Researchers found that there was local spread of Eurasian watermilfoil through root runners (stolon) by mid-summer, which was then followed by a decline in bed expansion late in the season associated with plant senescence. Spread of this invasive throughout the Lake could be attributed to colonization by plant fragments in littoral zone sediments and less frequently by seed propagation. Fragmentation can occur naturally, especially later in the season when plants tend to be relatively tall and near the surface. In laboratory aquarium experiments, watermilfoil fragments could grow while suspended in water for extended periods of time. Of note, watermilfoil is capable of flowering, but it is unclear how important seed dispersal from flowers is for reproduction and colonization of new habitats in Lake George, because it has been seldomly observed.

PHYSICAL MANAGEMENT STRATEGIES

Researchers at DFWI have been involved in assessing physical management strategies as a means of controlling Eurasian watermilfoil in the Lake. In a 1996 peer-reviewed publication, hand harvesting was recommended as a management approach in locations with scattered watermilfoil. It was observed that at 25% of the sites, this approach eliminated the plant for at least 2 years and limited regrowth at the remaining sites. In dense beds it was noted that hand harvesting was effective at reducing plant populations, but not eliminating them. Therefore, an alternative strategy, suction harvesting was employed and shown to be an effective control measure in dense beds. One-year post-treatment at sites utilizing suction harvesting showed a greater number of native species at all sites with a substantial reduction in watermilfoil biomass. A third strategy, benthic barrier treatment (covering with “mats”), was tested and deemed the least effective strategy for control. Post-treatment surveys of matted areas showed that watermilfoil recolonized 75% of the area within 90 days following removal of the mats. Additionally, benthic barrier placement has the unintended, but known, negative impact of killing most other organisms under them and can create conditions where phosphorus is released from the sediments.

HYDROACOUSTIC EURASIAN WATERMILFOIL DETECTION

Researchers at DFWI developed a method using hydroacoustics to rapidly survey shallow areas (the littoral zone) for the presence and abundance of Eurasian watermilfoil. The method can distinguish Eurasian watermilfoil from native species by analyzing physical growth parameters such as depth, lateral extent, and percentage of the water column occupied. This approach was successfully used in 2011 in five bays in the southern end of Lake George and resulted in the identification of six previously unknown Eurasian watermilfoil beds. Additionally, the use of this method confirmed the presence of ten locations known to contain watermilfoil.

LONG-TERM EVALUATION OF EURASIAN WATERMILFOIL MANAGEMENT

Eurasian watermilfoil has been in the Lake for at least 38 years. Over ten million dollars have been spent to control this invasive plant using benthic barrier, hand harvesting and suction harvesting. As of 2024, a detailed review of the results from these efforts is ongoing by Warren County (https://warren-county-gis-warrencountyny.hub.arcgis.com/).

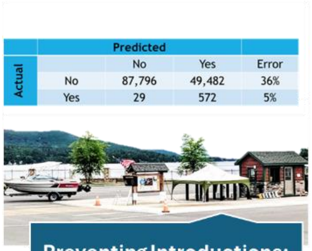
RECOMMENDATIONS FOR FUTURE WORK AND MANAGEMENT NEEDS

Eurasian watermilfoil is well established in Lake George. Active management practices have reduced Eurasian watermilfoil biomass in many locations throughout the Lake, but there are also many areas where the current approaches have not prevented the persistence and substantial abundance of watermilfoil. For instance, the watermilfoil bed at the mouth of West Brook has received management attention for over 30 years, but year after year the bed is still actively growing. Alternative approaches for dealing with Eurasian watermilfoil at this location (and others like it) should be considered, including the possibility of tracking but not actively managing beds where minimal detrimental impacts of the species occur.

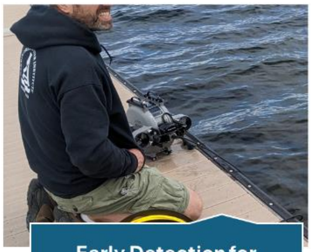
Rather than seeking to reduce or eliminate Eurasian watermilfoil throughout Lake George, managers may consider implementing different management approaches based on local and historical information. This could specifically address the impact (or lack thereof) presented by dense growth of Eurasian watermilfoil in different areas. Management decisions may also be guided by localized variation in the areas and habitat where watermilfoil is growing. For example, in areas where Eurasian watermilfoil has not grown densely (or at all), or where negative perception by lake users is limited, managers may consider reducing or eliminating active management programs (e.g. the beds at Eichlerville Bay, Indian Bay and the Waltonian Islands).

A comprehensive review of Eurasian watermilfoil management strategies on water clarity and water quality would result in increasing our understanding of the potential impacts of each strategy. For example, is there a nutrient reduction benefit of physically removing plants from the Lake, or is that benefit partially or fully offset by the agitation of the Lake bottom, potentially liberating nutrients from the sediments? Additionally, are there impacts of widespread watermilfoil death on nutrient availability, algal growth, and hypoxia formation? Quantifying these and other possible effects could help inform and guide future management efforts.

OTHER INVASIVE SPECIES ACTIVITIES



Preventing Introductions: Boat Wash Stations



Early Detection for Specific Invasive Species

Detection of Invasive Species using Molecular Techniques

PREVENTING INTRODUCTIONS: BOAT WASH STATIONS

DFWI researchers have developed machine learning models to determine the likelihood that an invasive species is on a boat.

In 2014, the Lake George Park Commission implemented the first mandatory boat wash stations in New York State. Partially due to the success of this program, in 2017 boat wash stations were installed throughout the State, with over 100 in operation during the boating season each year. In recent years, DFWI researchers have developed machine learning models to determine the likelihood that an invasive species is on a boat. Survey questions asked at the wash stations are used as data for the model to determine if an invasive species is present on an arriving boat. If a boat arrives at a station with an invasive species, the model will correctly identify it as having an invasive species 99% of the time. Boats arriving without an invasive species are correctly classified as not having one greater than 70% of the time. If adopted, the use of this model at boat wash stations could facilitate the rapid identification of boats that need extra attention by the boat wash station attendants. This approach holds promise for increasing the accuracy and efficacy of the program and minimizing the risk of new invasives entering Lake George.

EARLY DETECTION OF OTHER INVASIVE SPECIES

To establish a rapid response to combat invasive species, early detection is required. Researchers at DFWI have used a variety of approaches to determine if select invasive species are present in the Lake. Specifically, researchers have deployed minnow traps to look for Rusty crayfish (*Faxonius rusticus*) along with any invasive minnows. To detect the presence of Quagga mussels (*Dreissena bugensis*) throughout the Lake, we have carried out SCUBA and Remotely Operated Vehicle (ROV) surveys. We have explored nearshore areas of the Lake using plankton tows to look for the invasive Bloody red shrimp (*Hemimysis anomala*). In streams, we have used a Benthotorch to quantify algae and determine if Rock snot (*Didymosphenia geminate*) was present. While each of these efforts have been exploratory, rather than comprehensive, they could be helpful if they provide early detection of newly introduced invasive species. It is important that these efforts continue, and that additional efforts are initiated for the early detection of these and other invading species, when eradication may be possible.

DETECTION OF INVASIVE SPECIES USING MOLECULAR TECHNIQUES

In order to develop a rapid response program that responds to newly introduced invasive species it is imperative that an early detection program be developed that can detect invasives before they become established. One technique that the DFWI in collaboration with other groups have started to develop, test, and use is environmental DNA (eDNA) sampling. Essentially, most organisms shed trace amounts of DNA into the water they inhabit. These trace amounts of DNA can be amplified and sequenced in the lab. The sequenced DNA can then be used to detect the presence of most invasive species in the water. This could be a useful technique to use in areas potentially prone to invasion or to assess water from boat wash stations.

EMERGING CONCERNS

HARMFUL ALGAL BLOOMS

BACKGROUND AND CONCERN

Harmful algal blooms (HABs) are events where dense phytoplankton masses accumulate at the surface of the water resulting in a surface scum or streaky appearance. Blooms can be considered harmful due to the potential production of toxins, or their adverse aesthetic, economic, or ecological impacts. In lakes, HABs are usually the result of an overabundant growth of cyanobacteria, otherwise known as blue-green algae. Cyanobacteria are a common and diverse type of phytoplankton found throughout the globe in both marine and fresh waters. Cyanobacteria are a natural component of the phytoplankton community in Lake George, often becoming a major proportion of the total community in the late summer and fall. There is anecdotal evidence that blooms may have occurred several times throughout the 20th century. However, despite consistent monitoring since the 1980s, no blooms were observed in the Lake until the fall of 2020. Since then, blooms have been detected every year.

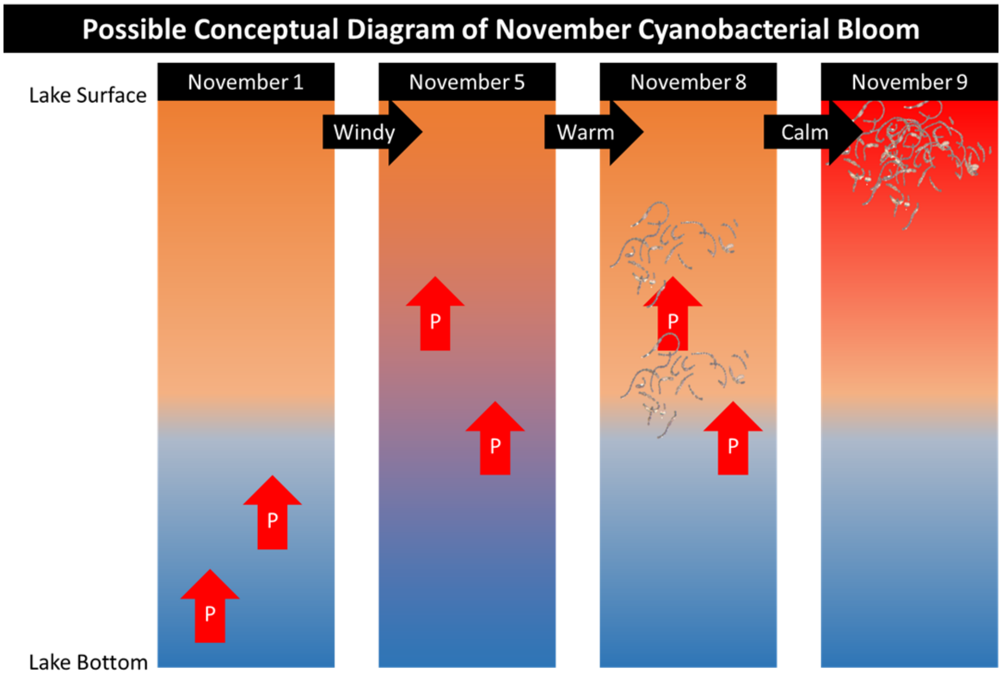
Part of the challenge in describing the history or extent of blooms is that there are many definitions and ways to characterize HABs. Additionally, not every cyanobacterial bloom produces toxins and therefore what constitutes “harmful” can be ambiguous. As of 2024, the NYS DEC defines a bloom as a water sample containing at least 25 µg/L chlorophyll-*a* from cyanobacteria and/or containing Microcystin, a toxin that cyanobacteria can produce. However, since 2020 the NYS DEC confirms HABs from pictures and therefore quantitative measurements of chlorophyll-*a* and/or toxins are not necessary for the DEC to confirm that a HAB has occurred. There are also toxins other than Microcystin that can be produced. These factors make it challenging to assess what, exactly, constitutes a bloom, or quantify the spatial and temporal dynamics of HABs in Lake George. A more definitive characterization of what constitutes a HAB would improve their detection and forecasting, thus allowing the assessment of trends through time to be more robust. Efforts are underway to establish a consistent definition specific to the Lake through coordination

among the several organizations that monitor and manage water quality in Lake George. For the purposes of this report we refer to all past events as “blooms”.

SCIENTIFIC STUDIES

RECENT OBSERVATIONS IN LAKE GEORGE

The causes of cyanobacterial blooms are poorly understood both in Lake George and in lakes around the world. In general, blooms are considered relatively rare in low nutrient lakes like Lake George, but some studies indicate they are increasing. Based on NYS DEC data, statewide HABs have been increasing in frequency since at least 2012.



The first reported and studied blooms in Lake George occurred in 2020. The preceding October experienced a series of large storms that researchers hypothesize delivered a substantial amount of sediment and nutrients into Lake George that may have stimulated cyanobacterial growth. In November of 2020, a period of deep water mixing is thought to have brought phosphorus up from the bottom of the Lake, and unusually warm weather immediately after, provided ideal conditions for cyanobacterial growth. Low wind during this period allowed cyanobacteria to float to the surface and aggregate, resulting in a bloom. There have been reports of blooms each year since, sparking concern that the large pulse of runoff from the 2019 severe storm, and others since, may be providing the necessary conditions for cyanobacterial blooms to form.

The blooms in Lake George have all been identified as being comprised primarily of *Dolichospermum*, a cyanobacterium that can process nitrogen gas from the atmosphere into ammonium (i.e., nitrogen fixation). The ability to fix nitrogen gives *Dolichospermum* an advantage in conditions where nitrogen availability is relatively low. Blooms of *Dolichospermum* can occur on warm, sunny days with calm wind conditions and *Dolichospermum* is known to be capable of producing multiple toxins including microcystins, cylindrospermopsins, anatoxins, and saxitoxins.

While *Dolichospermum* is capable of producing toxins, researchers at DFWI have not measured any toxins in samples from the Lake. In addition to testing for the presence of toxins, researchers at DFWI have sampled water from multiple blooms on Lake George to test whether the dominant strain of *Dolichospermum* has the genes capable of producing Microcystin. Initial results suggest that this strain in Lake George does not possess the genes required to produce Microcystin. However, tests for other toxins have not yet been conducted so it remains unclear if the dominant taxa could produce other toxins.

***Dolichospermum* is capable of producing toxins, however, no measurable amount of toxins have been detected in samples collected from the Lake to date.**

RESEARCH EFFORTS

DFWI scientists are currently working to understand what causes blooms to form and are developing methods to predict when and where blooms may occur. Several hypotheses that may explain why blooms occur are being tested. First, streams may be a key source of nutrients that can activate the growth of cyanobacterial resting cells (akinetes) so that they grow in lake sediments before entering the water column. Researchers are trying to better understand rates of nutrient loading from streams around the Lake to identify potential nutrient hotspots (and “hot moments”).

In recent decades, Lake George has experienced an increase in precipitation especially in the form of extreme events (e.g. very large storms). Large storms mobilize more sediment and phosphorus-associated particles. Therefore, researchers hypothesize that increases in extreme storms may be mobilizing more phosphorus into the Lake to support the growth of cyanobacteria.

Cyanobacteria also thrive when nitrogen (N) is low relative to phosphorus (P). Specifically, cyanobacteria do best when the N:P ratio is below 30. Long-term monitoring has shown that nitrogen has declined over time, and the ratio of N:P has also declined as a result. The Lake now regularly has N:P ratios below 30, especially in the South Basin of the Lake. Together, the declining N:P ratio, and increases in storm severity and precipitation may be factors that are stimulating blooms to occur.

RECOMMENDATIONS FOR FUTURE WORK AND MANAGEMENT NEEDS

Researchers at DFWI are conducting research to understand the triggers for algal blooms, study the factors that may lead to toxin production, and develop models to forecast when and where blooms will occur. In addition to understanding the ultimate factors explaining why blooms occur, researchers are exploring the proximate factors that explain the specific conditions when cells aggregate at the surface. Blooms tend to occur in warm, sunny, calm conditions, but how warm, sunny, and calm is enough? By modeling the hydrodynamics of the Lake, researchers are exploring how day to day and seasonal variations in weather can create conditions favorable for bloom formation. Recent work suggests that weather conditions that can cause a strengthening of stratification often precede late fall blooms. In 2023, these models were successfully used to predict multiple HAB events on Lake George.

Once forecasts for the timing of blooms prove reliable, researchers hope to engage with outreach and management agencies and other organizations to provide early warnings of the likelihood of blooms. Additionally, if researchers can couple weather forecasts with 3-dimensional hydrodynamic models, specific locations where blooms are likely to form can be created. This could provide accurate predictions for the timing and location of algal blooms in Lake George.

Research to better understand the relationship between stream flow, stream volume, and nutrient loads will likely improve both HAB forecasting as well as increase our understanding of nutrient sources and budgets for the Lake. Additionally, research to understand if changes in nutrient forms, ratios, or concentrations may stimulate blooms or toxin production is a high priority.

MICROPLASTICS

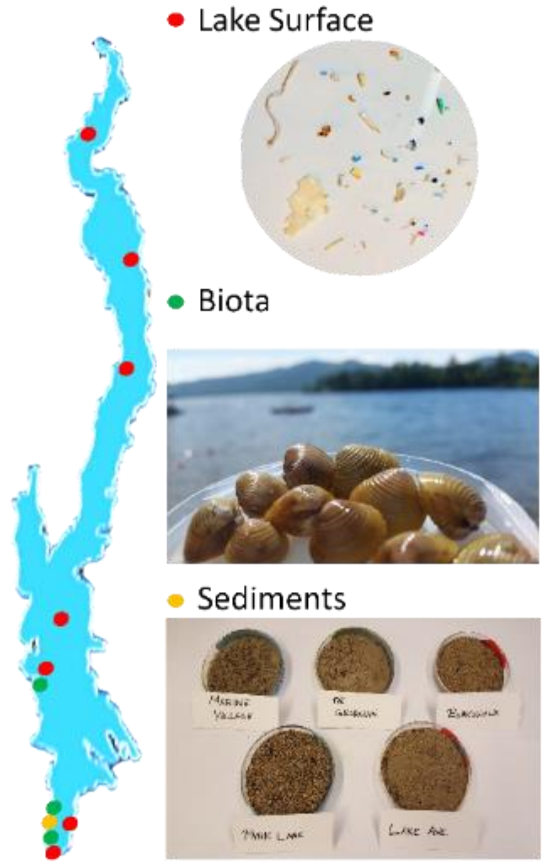
BACKGROUND AND CONCERN

Microplastics are small plastic particles up to 5 millimeters in size that include plastic pellets, chips, microbeads, synthetic fibers, lines, rope and styrofoam. Microplastic particles make their way into waterbodies and can negatively impact water quality, wildlife, and human health. Microplastics enter lakes through numerous pathways including from the atmosphere, runoff, or direct discharge. They can be broken down from larger plastics or have been produced for purposes such as cosmetics and personal care products. In collaboration with other researchers, DFWI scientists have shown that microplastics often form when larger plastic pieces are broken down after being exposed to UV light and mechanical action (e.g., waves and wind).

SCIENTIFIC STUDIES

LAKE SURFACE SAMPLES

Surface samples were collected at 7 sites throughout Lake George using a manta net attached to the front of a boat. Samples were processed by chemically burning off all organic material so that microplastics could be enumerated microscopically. Microplastic densities were found to be comparable to Lake Erie and greater than abundances observed in Lake Superior and Lake Huron.



BIOTIC SAMPLES

Native mussels and invasive clams were collected and then dissected to determine if microplastics were present. Twenty-five Asian clams ranging in size from 10-26 millimeters were sampled from three locations: Boardwalk, Park Lane, and Chelka Lodge. At all three sites a seasonal trend of decreasing microplastics was observed over the growing season. Minimal plastic contamination was observed in native mussel species whereas they were much more abundant in Asian clams with as many as twenty microplastics observed in one Asian clam. Weekly collection and analysis of microplastics in Asian clams showed a strong seasonal component to the prevalence and abundance of microplastics in these organisms.

SEDIMENT SAMPLES

Sediments were also collected and analyzed for microplastics at the three sites where Asian clams were collected. Microplastic densities in Lake George sediments ranged from 60 to 236 plastics per kilogram (p/kg) with an average of 185 p/kg. This density was generally greater than observations at locations examined in Lake Ontario. Of note, the Boardwalk location had the lowest quantities of microplastics in both the sediments and Asian clams.

RECOMMENDATIONS FOR FUTURE WORK AND MANAGEMENT NEEDS

While current efforts have shown that microplastics are in the Lake, the temporal and spatial distribution of this contamination has not yet been fully documented. The threat of microplastic contamination to organisms (e.g. in fish) or human health is also poorly understood. Monitoring activities could include repeating and expanding collections on the surface of the Lake several times per year. It could also include quantification of microplastics in each of the levels in the food web (phytoplankton, zooplankton and fish).

MERCURY

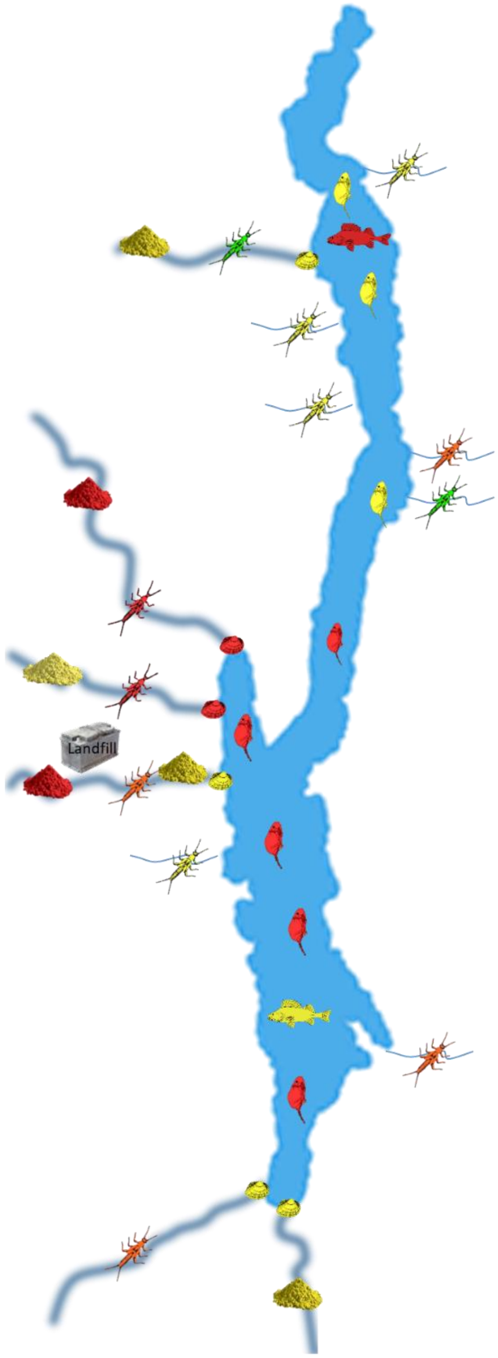
BACKGROUND AND CONCERN

Mercury is an important pollutant found throughout the world, even in polar regions far from pollution sources. Mercury can occur in multiple forms including elemental, inorganic, and organic (methylmercury). Methylmercury is considered a highly toxic form and this form represents the biggest threat to Lake George. The burning of fossil fuels is a primary source of mercury which is then transported in the atmosphere. When it is deposited, it can be converted to methylmercury by bacteria in low oxygen environments such as in lake sediments and wetlands. Methylmercury can accumulate in organisms and biomagnify within the food web, meaning that concentrations in animals increase at higher levels in the food chain. Therefore, methylmercury concentrations can reach potentially harmful levels in some large predatory fish.

SCIENTIFIC STUDIES

MERCURY IN TRIBUTARIES

An investigation into the mercury concentrations of Lake George tributaries has identified patterns of methylmercury contamination. Samples from 20 streams around the Watershed



Summary of Mercury concentrations in perch ( ), native mussels ( ), macroinvertebrates ( ), zooplankton ( ), and particle sediments ( ). Red indicates high and yellow indicates low. For macroinvertebrates there are four categories from high to low (red, orange, green and yellow).

were collected to measure baseline concentrations. Following this initial survey, a deeper investigation into mercury concentrations in macroinvertebrates, leaf litter and benthic algae from eight streams was conducted. Understanding the concentrations in these samples is essential for understanding and assessing the risk to human health from consuming fish from the Lake. Within a stream, methylmercury (biologically relevant) concentrations increased with higher trophic position. That is, mercury was lowest in leaf litter and highest in predatory macroinvertebrates with the algal and detritivore communities having intermediate concentrations. Biomagnification explained most of the variability in mercury within the studied stream food webs. The two largest stream sub-watersheds, Northwest Bay and Indian Brooks, had higher mercury concentrations than the other streams sampled. These two streams have substantial wetlands throughout their headwaters, which serve as potential sites for mercury methylation. Factors associated with the increased mercury concentrations include dissolved organic carbon (DOC) and shallow sub-watershed slopes that slow water transport, thereby allowing bacteria more contact time with the mercury for methylation to occur in low oxygen environments.

MERCURY IN BENTHIC ORGANISMS

Researchers at DFWI have collected and analyzed over 80 samples of benthic organisms from the Lake bottom in over 20 nearshore sites. There were four main groups of benthic macroinvertebrates collected that included native mussels, banded mystery snails, worms, and emergent insects. There were no significant spatial or temporal trends detected among benthic invertebrates for any forms of mercury that were measured. The lack of differences could be due to the longer life span of benthic invertebrates relative to phytoplankton or zooplankton. Mercury concentrations of benthic invertebrates collected from Lake George were similar to, or lower than, concentrations reported from other studies, but followed similar patterns of increasing concentrations in organisms with more predatory feeding behaviors.

MERCURY IN ZOOPLANKTON

Zooplankton samples from deep water areas in conjunction with the long-term monitoring programs were collected and analyzed. Zooplankton in Northwest Bay exhibited higher mercury concentrations than those at other sites. Significantly higher concentrations were observed in the South Basin relative to the North Basin during the spring months. Interestingly, the zooplankton mercury concentrations correlate with chlorophyll-*a* concentrations in the North but not the South Basin. Mercury supply via tributaries, higher productivity, and seasonal oxygen depletion could all be influencing spatial and temporal variations. Overall, in Lake George, zooplankton mercury concentrations (mean 63 ng/g, range 24-140 ng/g) were within the range reported for other studies in Adirondack lakes and Lake Superior.

MERCURY IN FISH

In the last decade, researchers at DFWI have analyzed over 400 fish tissue samples from Lake George including nearshore fish (e.g., Yellow perch, Yellow bullhead, Pumpkin seed, and Rock bass) and sport fish (Lake trout, Largemouth bass, Smallmouth bass, and Landlocked salmon). A pattern of bioaccumulation (increased concentration related to increased size) in each species was observed. A general trend of elevated mercury in fish was also observed in the Dome Island sub-basin relative to the north and south ends of the Lake. Fish in the Dome Island sub-basin area are likely impacted by elevated mercury loading coming from Northwest Bay and Indian Brooks.

Researchers compared mercury concentrations in Lake George fish with two regional synoptic studies and found that warm water fish from Lake George had similar or lower concentrations. The sportfish generally exhibited similar concentrations to these synoptic studies, with a single Lake trout exceeding the NYS DOH advisory limit of 1000 ng/g.

RECOMMENDATIONS FOR FUTURE WORK AND MANAGEMENT NEEDS

Quantifying mercury concentrations is essential to understanding the threat posed by mercury pollution to organisms and human health. Due to the size of the Lake George watershed, mercury concentrations in organisms in and around the Lake can be variable. Understanding changes in the environment that may alter methylation rates of mercury would help identify potential future concerns for the ecosystem and human health. Specifically, areas of study should include quantifying changes in dissolved organic carbon loading, residence times of water in wetlands, and hypoxia duration. Future studies should also focus on the interconnection between mercury from the terrestrial to aquatic webs and continued monitoring of fish to assess potential human exposures.

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