Onondaga Lake: A Restoration Success Story

David Glaser, Elizabeth Moran, James R. Rhea, and Christopher Gandino

Introduction

The Clean Water Act has improved water quality across the nation. Among the many success stories is the restoration of New York's Onondaga Lake, once called "the most polluted lake in the U.S." The regulatory requirements and state and local funding included in the Act were fundamental to attainment of the lake's designated uses. Although the engineering successes and water quality improvements of the past decades are well described (Effler et al. 2013; Matthews et al. 2015, Murphy et al. 2015; Hurley and Gandino 2017; OCDWEP 2020a), we want to highlight the Onondaga Lake story from another perspective: the cascading impacts of nutrient reductions on the entire ecosystem. A central paradigm in lake management is the importance of controlling phosphorus and nitrogen inputs. The Onondaga Lake story illustrates the significance of considering the complex interplay between nutrient control and both top-down and bottom-up influences on ecosystem structure and function.

The Syracuse Metropolitan Wastewater Treatment Plant (Metro), an 85 million-gallons-per-day tertiary treatment facility, discharges to Onondaga Lake. Contravention of the New York State water quality guidance value of 20 micrograms per liter (µg/L) total phosphorus and the state standards for dissolved oxygen, ammonia, and nitrite led to an Amended Consent Judgment (ACJ) requiring advanced treatment of ammonia and phosphorus at Metro. In addition, Onondaga County was required to design and implement a comprehensive ambient monitoring program (AMP) to document the lake's response. The County constructed a biological treatment system to oxidize ammonia and a physical-chemical treatment system to remove phosphorus. The biologically activated filter (BAF) system for ammonia went online in 2004 and brought the lake into compliance with ammonia standards while substantially increasing water column nitrate concentrations. The high-rate flocculation settling (HRFS) system to treat phosphorus was completed in 2005. In 2009, the County initiated its *Save the Rain Program*, which includes green and gray infrastructure to reduce discharges from combined sewer overflows. Onondaga Lake responded to the reduced ammonia and phosphorus loadings with decreased water column productivity, decreased ammonia toxicity, and increased water transparency which promoted changes in the lake ecosystem.

Decades of intensive lake monitoring before and after the Metro upgrades have documented the ecosystem's response to these changes in the inputs and chemical forms of phosphorus and nitrogen. Onondaga County led an AMP to monitor changes in the lake's water quality, habitat, and biological resources (OCDWEP 2020b) and to provide insights into the effects of invasive species and a warming climate. The information presented here is supported by more than 50 published technical articles documenting the lake's restoration, including Effler (2013), Matthews (2015), and Murphy (2015).

Environmental setting

Onondaga Lake is in central New York State, northwest of Syracuse (Figure 1). It measures approximately 7.6 kilometers long, between 1 and 2 kilometers wide, and has a surface area of 11.7 square kilometers. The lake's maximum depth is 19.5 meters, and it averages 10.9 meters deep. Ambient data to track compliance and trends are collected at the lake's deepest point, South Deep. The Onondaga Lake watershed is highly urbanized compared with other lakes in the region, with approximately 20 percent urban, 40 percent forest, and 30 percent agricultural land cover.

In addition to inflows from four major and several minor tributaries that direct runoff from the 642-square-kilometer watershed, the lake receives treated effluent from Metro that originates both inside and outside the basin. Metro effluent contributes about 20 percent of the total lake inflow in an average hydrologic year, and about 50 percent in summer. Because of the lake's large watershed, inputs of water from outside the watershed via Metro, and small volume, lake water residence time is short, about three to four months. The lake discharges into the Seneca River, which flows into Lake Ontario. Due to downstream flow control and associated changes in surface water elevation, the Seneca River periodically backflows into Onondaga Lake, ecologically linking the two systems.

The lake's narrow littoral zone, where light reaches the sediment surface, typically extends a few hundred meters out from the shoreline to a water depth of approximately six meters.

Onondaga Lake undergoes thermal stratification each summer when the dissolved oxygen (DO) of the cooler lower water is depleted, restricting the biological community to the warmer upper water. The lake mixes each fall, entraining cooler low-DO hypolimnetic water with the surface water. Although portions of the lake freeze in the winter, total ice cover is rare.

Nutrient reduction

Phosphorus

Treated wastewater contributed 40 percent to 60 percent of Onondaga Lake's external total phosphorus (TP) load in the

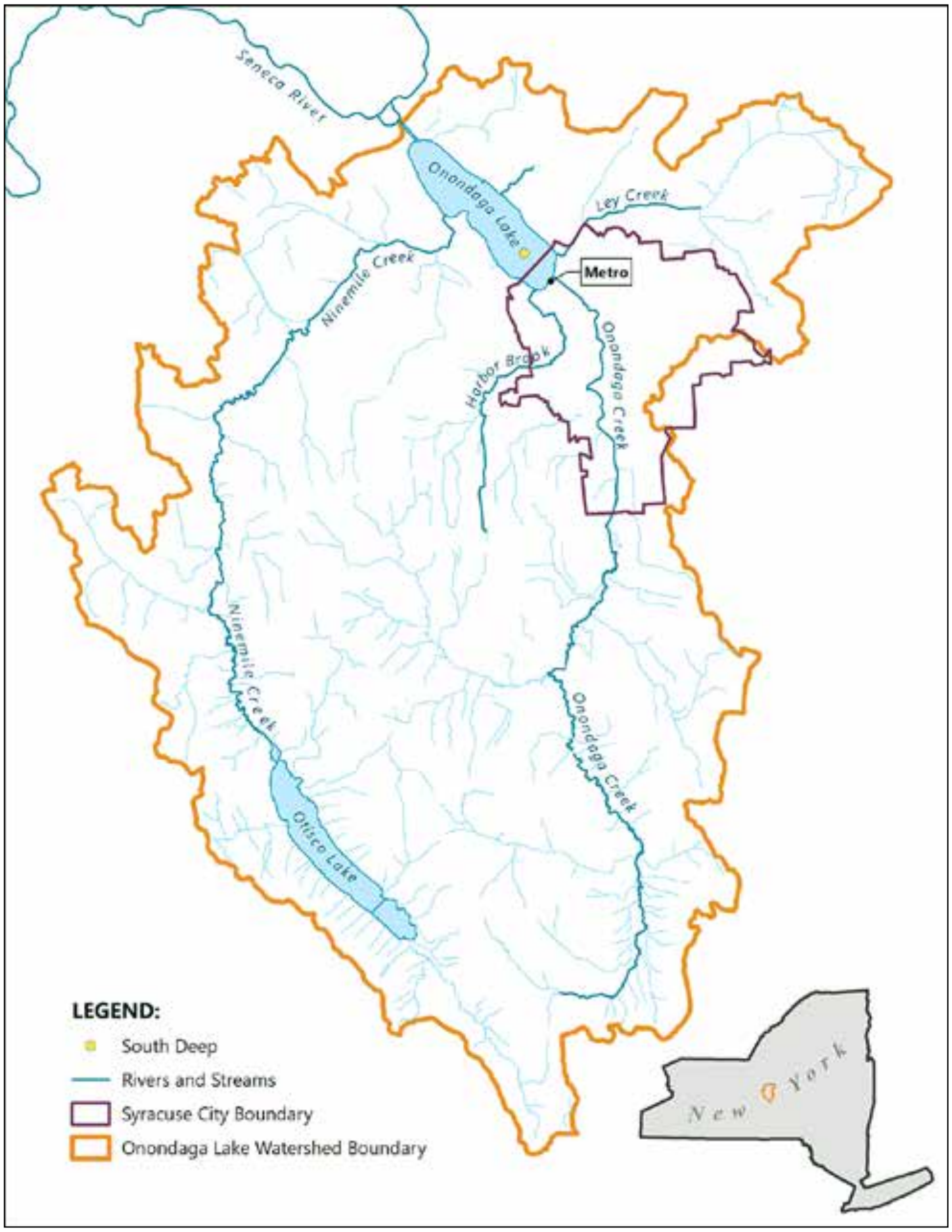

Figure 1. Onondaga Lake and its watershed.

1990s. Metro's contribution was especially significant during the summer, when inflows from the tributaries were low. The result was hypereutrophic conditions: elevated phosphorus and chlorophyll, low Secchi disk transparency, cyanobacteria dominance of the phytoplankton community, rapid DO loss, and accumulation of reduced species such as hydrogen sulfide in the hypolimnion during the summer. When the lake cooled and mixed in the fall, DO levels throughout the water column fell as the reduced species were entrained and oxidized.

Tertiary phosphorus removal using HRFS began in 2004 (Figure 2) and had a rapid, positive impact on the lake's trophic state. Since 2007, average summer TP concentrations have been close to meeting the state's regulatory guidance value of 20 µg/L for recreational waters (Figure 3). With Metro's HRFS system producing consistently low effluent TP, the year-to-year variability in lake phosphorus levels largely reflects changes in weather (the tributaries deliver more phosphorus during wet years) and food web structure.

Nitrogen and its Forms

Historically, Onondaga Lake was impaired by elevated concentrations of ammonia-N (NH_3-N). About 90 percent of the external ammonia load came from Metro. Concentrations of this potentially harmful form of nitrogen exceeded the ambient water quality standard for protection of aquatic life. The County upgraded aeration treatment at Metro in the 1990s and in 2004 implemented BAF technology, which converts ammonia to nitrate year-round in a process known as nitrification (Figure 4). Ammonia-N concentrations in the upper waters of the lake were reduced significantly (Figure 5), and in 2008 the lake was removed from New York State's 303(d) list of impaired waterbodies for this water quality parameter. The lake remains in full compliance with this ambient water quality standard.

Efficient year-round nitrification at Metro resulted in increased nitrate (NO_3-N) concentrations in Onondaga Lake. Essentially, NH_3-N and nitrite (NO_2-N) were replaced by NO_3-N, leaving the concentration of total nitrogen (TN) approximately the same (Figure 5). This led to diminished releases of

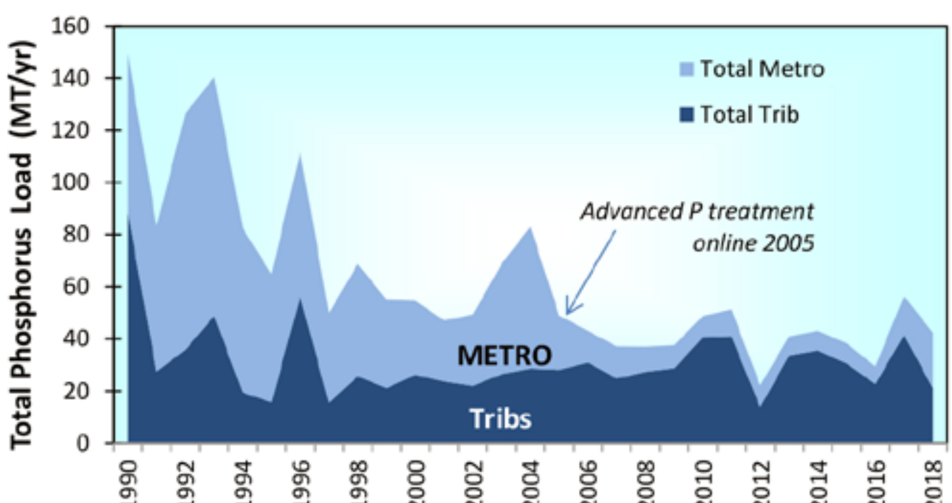

Figure 2. Annual discharge of total phosphorus (TP) to Onondaga Lake from metro and tributaries, 1990-2018.

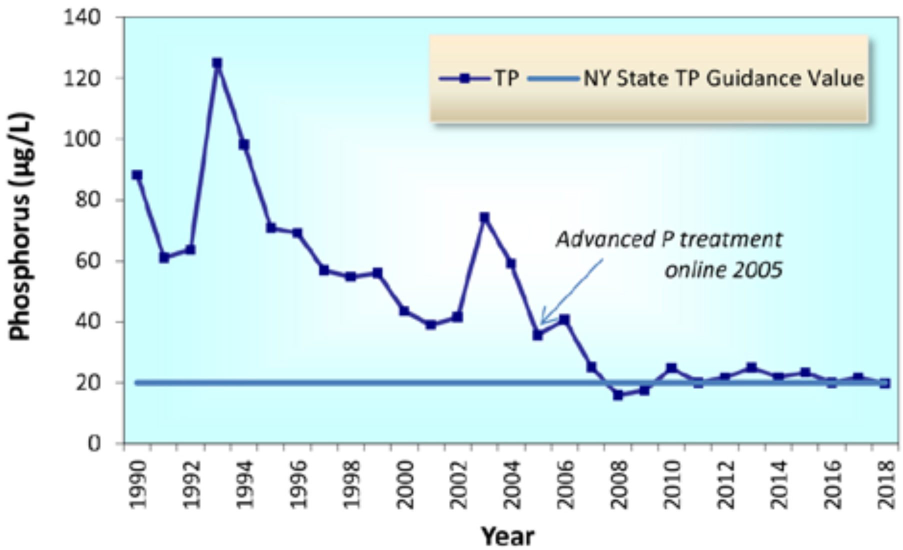

Figure 3. Summer average total phosphorus concentrations in the upper waters, 1990-2018.

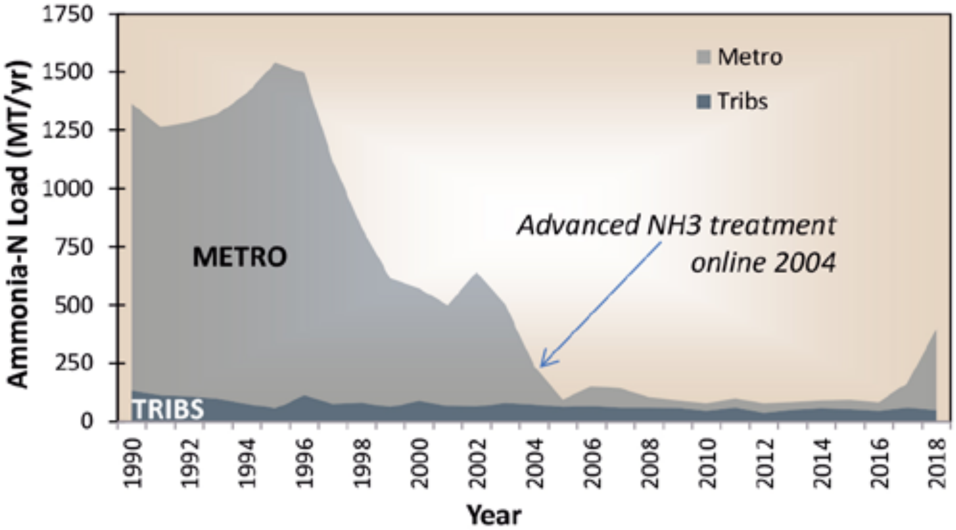

Figure 4. Annual discharge of Ammonia-N (NH_3-N) to Onondaga Lake from metro and tributaries, 1990-2018

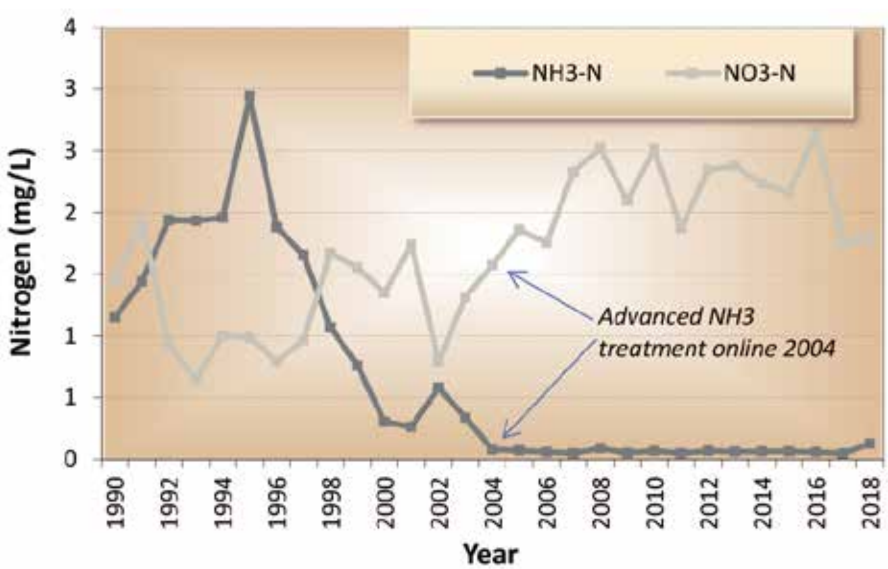

Figure 5. Summer average ammonia and nitrate concentrations in the upper waters, 1990-2018.

phosphorus and mercury from the sediments during intervals of anoxia (Matthews et al. 2013). As part of an effort under Superfund to further abate sediment releases of methylmercury, nitrate has been added to the lake in summer since 2011 (Matthews et al. 2013).

Ecosystem response

Primary Producers: Phytoplankton and Macrophytes

The supply of the major plant nutrients nitrogen and phosphorus is an important determinant of phytoplankton community composition and the risk of cyanobacterial blooms.

Maintaining high nitrogen-to-phosphorus ratios in the upper waters of Onondaga Lake has long been a strategy to reduce the risk of cyanobacterial blooms. As reported by Smith (1983), data from a wide range of temperate lakes suggest that a total N to total P ratio (TN:TP) of 29:1 (by mass) differentiates lakes with cyanobacteria dominance (TN:TP<29:1) from lakes without such dominance (TN:TP>29:1).

The time series of the summer average (June 1 to September 30) TN:TP ratio for the lake's upper waters from 1995 to 2018 is shown in Figure 6. The TN:TP ratio has remained above the literature N:P threshold for increased risk of cyanobacteria dominance since 1995. The higher values after 2007 reflect systematic decreases in total phosphorus loading from Metro, with mostly unchanging TN concentrations.

Recent literature also emphasizes the importance of the form of nitrogen in controlling phytoplankton populations, community structure, and the potential toxicity of cyanobacterial blooms (Glibert et al. 2014).

Summer average concentrations of chlorophyll-*a* (Chl-a) in Onondaga Lake have declined substantially since the early 2000s, particularly in response to the HRFS upgrade at Metro (Figure 7). Chl-*a* concentrations, which commonly exceeded a summer average of 15 µg/L from 1990 to 2004, have remained below 12 µg/L since 2007. Summer data (June to September) are used to track the lake's suitability for recreational uses. The New York State Department of Environmental Conservation (NYSDEC) defines suitable Chl-a thresholds for recreational use as follows: above 8 µg/L recreational uses are stressed; above 12 µg/L they are

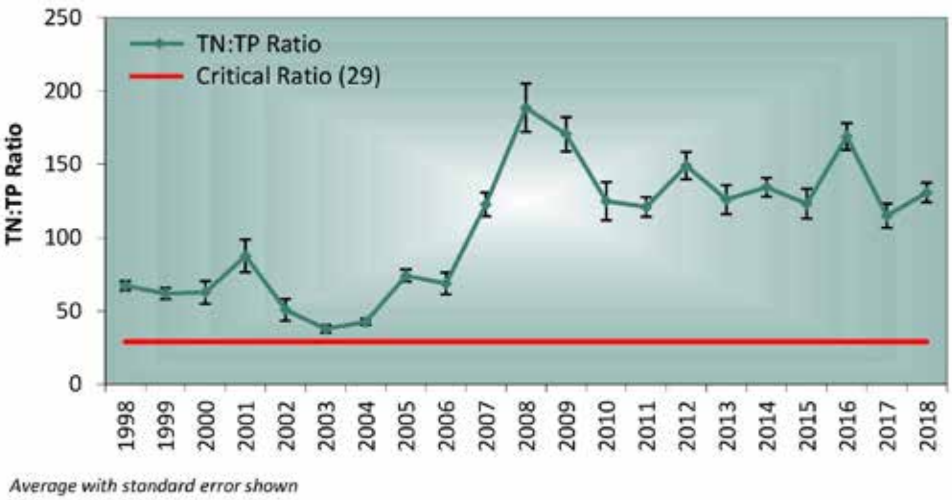

Figure 6. Summer average total nitrogen to total phosphorus (TN:TP) ratio in the upper waters, 1998-2018.

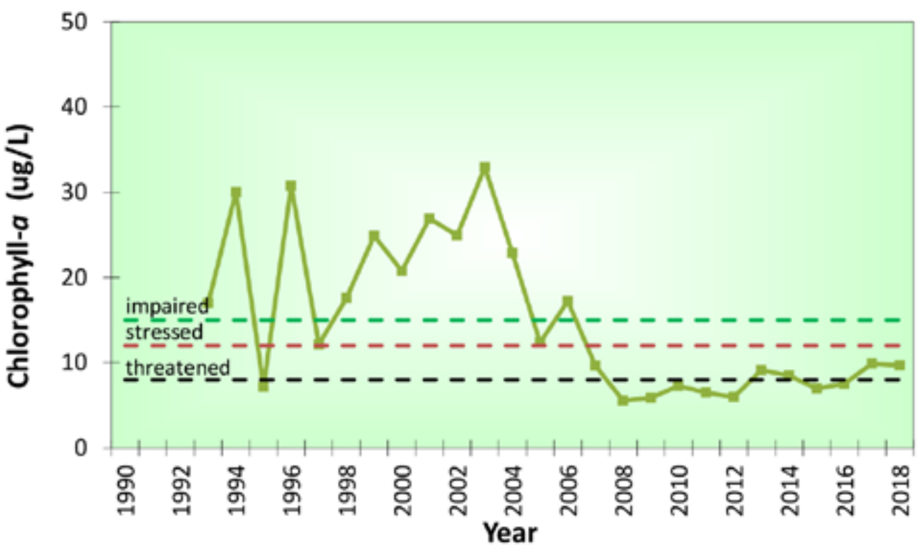

Figure 7. Summer average chlorophyll-a concentrations in the upper waters, 1990-2018.

threatened; and above 15 µg/L the uses are impaired. Thus, the lake has improved from "impaired" prior to 2004, past "threatened," to "stressed" in 2008; in some recent years, the summer average was below 8 µg/L. As shown in Figure 7, there may be a slow upward trend in Chl-*a* since about 2008. Whether this trend is real is not yet known, but the County is not resting on its laurels; as described below, additional nutrient reduction programs are in place.

Algal blooms have also declined since 2004. In the absence of state or federal criteria, the AMP has used subjective thresholds of 15 µg/L and 30 µg/L to represent minor blooms (impaired conditions) and major blooms (noxious conditions). According to these criteria, 2005 saw the last major blooms and minor blooms have declined greatly; some recent years have seen no blooms at all.

Summer blooms of filamentous cyanobacteria were once common in the lake, but in recent years, cyanobacteria have not been an important component of the phytoplankton community. Lower P levels, higher N:P ratios, and nitrogen predominantly in the form of nitrate all contribute to this observed suppression of cyanobacteria. There is evidence of a modest increase in cyanobacteria in recent years, however, which may be related to changes in climate (notably, warmer temperatures and increased frequency of calm winds).

Macrophyte populations, including submerged, emergent, and floating species, are an important component of a healthy lake ecosystem. They support an active benthic population and are strongly correlated with the diversity and productivity of fish stocks. For decades, macrophytes were scarce in Onondaga Lake. Aquatic plants were present in only about 11 percent of the littoral zone in 2000 (OCDWEP 2020b). Sediment instability, low sediment fertility, elevated salinity, poor light availability, and elevated ammonia concentrations may have contributed to the lack of vegetation in the past. Conditions have improved dramatically; in 2018 macrophytes covered 50 percent of the lake littoral zone. This change was facilitated by the increased water clarity due to the reduction in phytoplankton brought about by the reduction in phosphorus input from Metro.

Secondary Producers: Macroinvertebrates and Dreissenids

Benthic macroinvertebrates are an important component of the aquatic food web, facilitating the cycling of energy and nutrients between the sediment and the water column. Like many components of the lake ecosystem, the macroinvertebrate community has shown signs of improvement over the past two decades. The NYSDEC Biological Assessment Profile (BAP) scores at the lake's five sampling sites have improved since 2000. By 2017, four of the five sites were either "slightly impacted" or on the line between "slightly" and "moderately" impacted. Even the site near the Metro outfall has improved from 2000, when it was characterized as "severely impacted," to 2017, when it was characterized as "moderately impacted."

The improvements in the benthic macroinvertebrate community are due, in part, to decreased nutrient loading from Metro, which has led to decreased phytoplankton growth and increased macrophyte abundance and coverage. Invasive zebra and quagga mussels (*Dreissena polymorpha* and *D. bugensis,* collectively referred to as dreissenids) may also have played a role by directing nutrients from the water column to the sediments via their pseudofeces, improving water clarity and modifying the nature of the benthic substrate. These invasive filter-feeders have been prolific in the Seneca River drainage basin since the early 1990s. The Seneca River flows past and exchanges water with Onondaga

Lake. Both mussel species were first found in Onondaga Lake in 1992. They remained rare in the lake prior to 1998 and increased once ammonia concentrations fell below levels of concern to aquatic life (Figure 8). Their populations have decreased since 2014, possibly due to the invasion of the lake by the round goby (*Neogobius melanostomus*), which consume dreissenids, in 2011.

In contrast to their muted impact on Onondaga Lake, dreissenid mussels had a profound impact on water quality in the adjacent Seneca River. They heavily colonized the hard substrate of the riverbed, effectively stymied phytoplankton production through their filtering activities, and reduced DO so much the river could not assimilate effluent Metro proposed to divert from the lake to the river (Glaser et al. 2009).

Thus, reduced NH3-N and TP inputs from Metro have resulted in bottom-up impacts (reduced primary production), top-down impacts (increased dreissenid herbivory on phytoplankton due to reduced NH3-N loads from Metro), and processes that have bottom-up and top-down components (consumption of phytoplankton by dreissenids leading to the transfer of pelagic organic matter to the sediment bed, where it feeds benthic invertebrates).

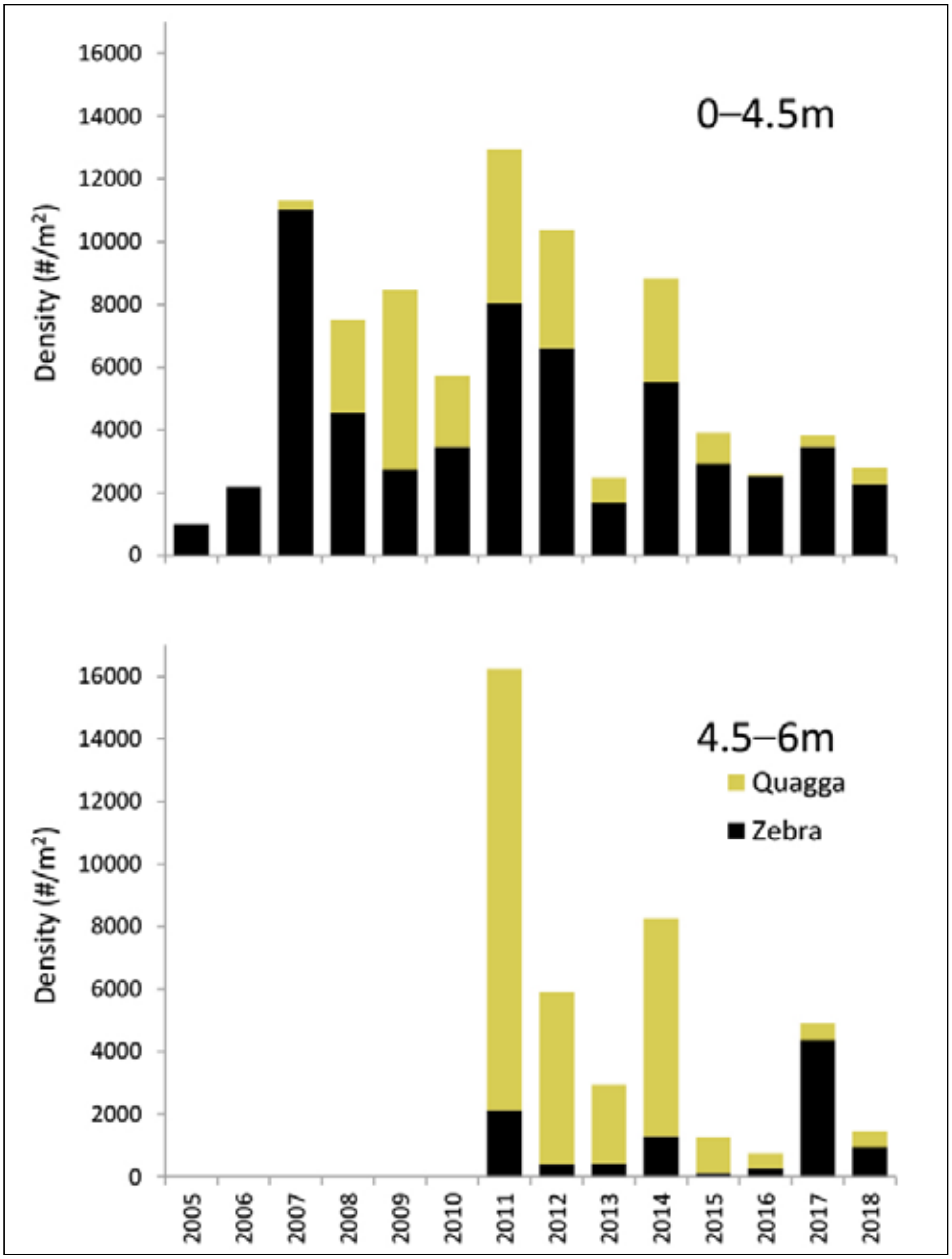

Figure 8. Average density of dreissenid mussels, 2005-2018.

Fish community

Nutrient reduction has improved fish habitat. In the past, many fish would swim from the lake during fall turnover to escape low DO concentrations. Since that time, conditions for ammonia-sensitive aquatic invertebrates and early life stages of fish have improved due to Metro's nitrogen treatment upgrades. Moreover, the expansion and diversification of the aquatic macrophyte community has provided habitat for a variety of fish species.

One of the most notable results of nutrient reductions has been the increase in water clarity and the subsequent increase in aquatic macrophytes. Numerous species of fish depend on aquatic vegetation for their survival (Valley et al. 2004). Species such as Pumpkinseed *(Lepomis gibbosus)*, Bluegill *(Lepomis macrochirus)*, Largemouth Bass, and Northern Pike *(Esox Lucius)*, depend on submersed aquatic vegetation for food and shelter. Other non-game species such as Brook Silverside *(Labidesthes sicculus)* and Banded Killifish *(Fundulus diaphanus)* depend primarily on nearshore emergent and submersed vegetation for much of their life history.

In response to improved habitat, the fish community has increased in diversity and abundance comparable to other regional lakes. Noble and Forney (1969) encountered 14 species and deemed the lake a warm water fish community. In the early 1990s, Ringler et al. (1996) sampled about 40 species of fish annually. The lake-wide biomonitoring conducted by the Onondaga County Department of Water Environment Protection has recorded since 2000, 53 species of fish. Combining all other studies since 1927, 66 species of fish have been identified in Onondaga Lake.

The fish community is affected by many factors interacting in complex ways, notably invasive species. For example, the invasion of the lake by alewife (*Alosa pseudoharengus*) has changed the species composition and average size of the zooplankton community. Alewife prey on the larger zooplankton, and the smaller species that remain are less efficient grazers of phytoplankton. The round goby affects the population of dreissenids (also invasive) by direct predation and may also have other impacts on the ecosystem.

Discussion

Onondaga Lake is a Clean Water Act success story. Investment in advanced nutrient controls has returned the lake to a mesotrophic condition. With phosphorus and Chl-*a* concentrations comparable to those of many neighboring lakes, Onondaga Lake appears to be less susceptible to the cyanobacterial blooms that have become prevalent in recent years. The high N:P ratio in the lake water, and the near absence of ammonia, benefit the plankton community by helping suppress mercury releases from legacy contamination. The benthic and fish communities are responding to the improved habitat quality of the littoral zone.

The Onondaga Lake story also contributes to our scientific understanding of lake eutrophication. The complex interplay of bottom-up forces (nutrient reduction) and top-down forces (invasive species) shows how lakes are affected by both targeted management actions and factors beyond our control. As illustrated in Figure 9, nutrient reduction affects all trophic levels of the ecosystem, including the lake's open waters and littoral zone. Water quality improvements and the Superfund cleanup intersect at NO3, with its impact on both phosphorus and mercury releases from sediments.

Over the past 10 years, the lake water quality has remained remarkably stable with little change in TP (Figure 3), NH3 (Figure 4), NO3 (Figure 5), and Chl-*a* (Figure 7) and the absence of major algal blooms. This stability prevails despite considerable variation in upper trophic level dynamics. For example, the density of the dreissenid community has varied considerably from year to year, and the species composition has changed; after being largely replaced by quagga mussels, zebra mussels returned to dominance, making Onondaga Lake the first system in which this change was documented (Strayer et al. 2018; Figure 8). Alewives, with their striking impacts on plankton populations, have varied dramatically year to year (OCDWEP 2020b).

Nonetheless, in recent years average Chl-a concentrations (Figure 7) and the frequency of blooms have appeared to trend slightly upwards. Cyanobacterial populations have also increased recently (although not to levels seen in the past). Whether these trends are statistically significant is not yet clear. Also, the potential causes are not known because TP remains low and the TN:TP ratio remains high but contributing factors may include year-to-year variation in precipitation, trends in temperature due to climate change, or complex processes involving upper trophic levels.

The County's attention is now focused on the tributary sub-watersheds to track nonpoint sources and ensure the hard-won gains in water quality, benthic habitat, and aquatic species diversity and abundance continue. County, state, and federal partners plus a diverse array of community stakeholders have worked closely over the past 20 years to realize these substantial improvements in the Onondaga Lake ecosystem. The effective partnerships among resource managers, municipalities, local universities, and the research community will help sustain the progress and facilitate adaptive management to emerging issues of invasive species and climate change.

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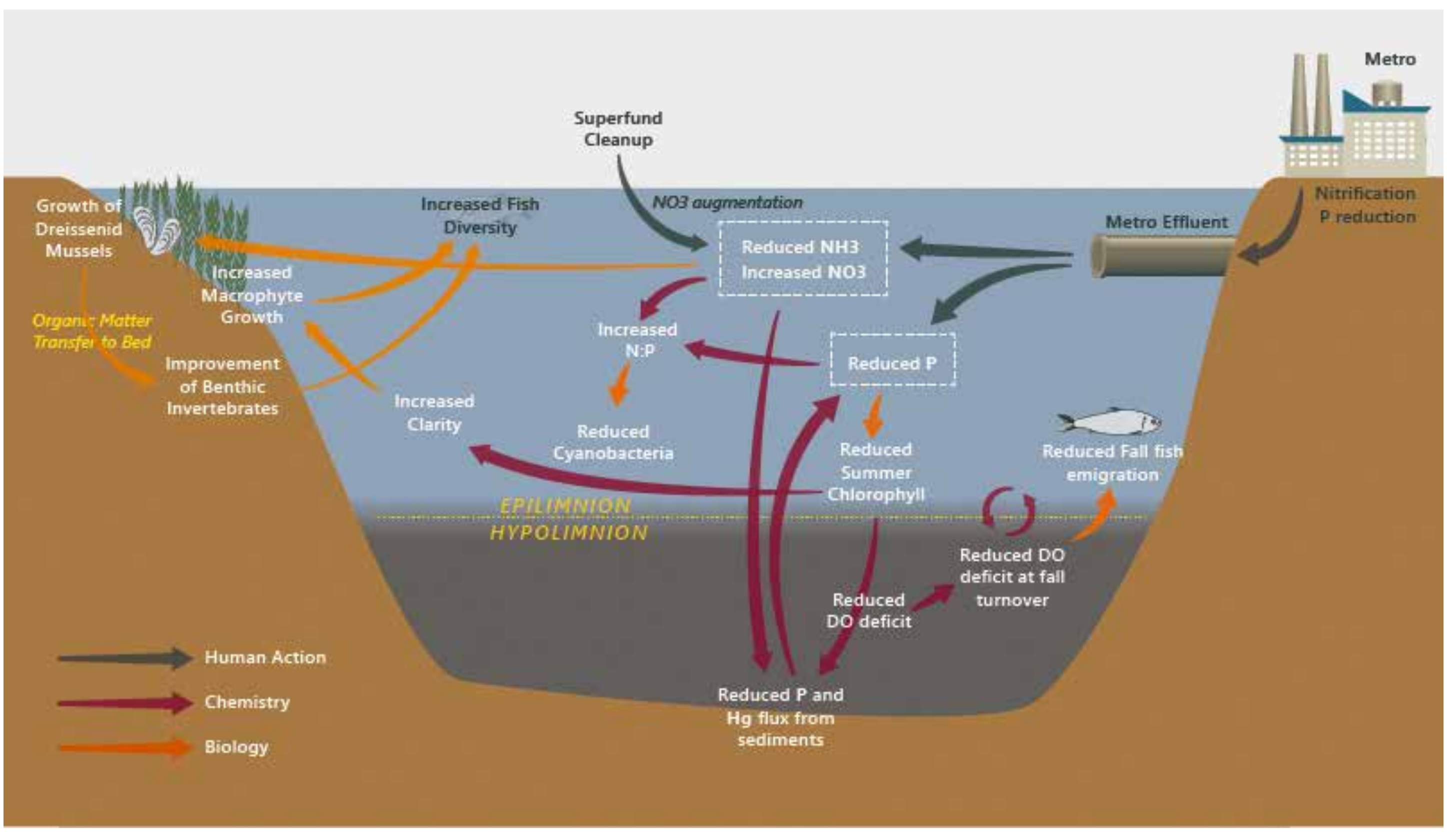

Figure 9. Conceptual model of the impacts of Metro improvements on the lake ecosystem.

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James R. Rhea, Ph.D., a founding member of Anchor QEA, LLC, has over 30 years of experience in the assessment and mitigation of water quality problems under CWA, CERCLA, and RCRA. He was the principal investigator for the development and application of a water quality modeling framework for the Onondaga Lake and Seneca River that guided the mitigation strategies for the system. He also served on the Onondaga Lake Technical Advisory Committee that oversaw the execution of the Ambient Monitoring Program that produced the physical, chemical, and biological database used to assess the impact of advanced tertiary treatment on the water quality of Onondaga Lake and its attainment of water quality standards. Jim Rhea can be reached at jrhea@anchorqea.com.

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