Long-term Trends in Water Quality in a New England Hydroelectric Impoundment

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Abstract - Lake Lillinonah, a hydroelectric impoundment on the Housatonic River, CT, is characterized by frequent and extensive algal blooms during the summer months, and historical accounts from the lake's early years document the fact that algal blooms (dominated by cyanobacteria) have been a concern since the lake's creation in 1955. Algal blooms create lethal oxygen conditions for aquatic organisms, impair recreation, and produce toxins that are harmful to people, pets, and wildlife. To help understand current and future trends in water quality, we reconstructed the historical water quality of Lake Lillinonah from 1974 to 2009. Our results suggest that water temperature, phosphorus concentration, and nitrogen concentration all play a role in determining summer water clarity. Additionally, although total phosphorus concentration has decreased since the early 1970s, total nitrogen concentration has remained constant likely due to differences in watershed nutrient-management strategies, and water clarity in the lake remains poor. We suggest that a continued effort to reduce both nitrogen- and phosphorus-loading is necessary in order to improve water clarity, particularly considering the observed increase in storm-loading events and warmer temperatures predicted as the climate warms.

Introduction

Freshwater lakes and impoundments are key components of both human and natural systems, providing critical ecosystem services including drinking water, recreation, hydropower generation, flood control, transportation, and food (Hassan et al. 2005). Because many freshwater ecosystems have been altered by human activity, monitoring and active management of water quality are necessary to maintain desired ecosystem services (Carpenter et al. 2011). Within-lake water quality is regulated by a host of factors, including watershed land-use (Downing and McCauley 1992), food-web structure (Carpenter and Kitchell 1996), and lake morphometry (Noges 2009).

Water quality is a relative measure of the suitability of water for a particular use and can be measured in a number of different ways. Some common metrics used to quantify and monitor water quality include nutrient concentration, water clarity, dissolved oxygen concentration, and presence/absence of certain indicator species (Ahuja 2013). Identifying historical trends in water quality is crucial when trying to understand current impacts and how changes in drivers such as land use and climate will affect future water quality. For example, a recent study used historical patterns in the relationship between cyanobacterial blooms and lake temperature to model future bloom prevalence given predicted climate change (Wagner and Adrian 2009).

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To help understand current and future trends in water quality, we reconstructed the historical water quality of Lake Lillinonah, a hydroelectric impoundment on the Housatonic River, from its creation in 1955. Lake Lillinonah is a eutrophic system with a history of frequent and extensive algal blooms during the summer months. Historical accounts from the lake's early years document that algal blooms have been a concern since the lake's creation. Water-quality data have been collected on Lake Lillinonah intermittently since the early 1970s, but there has been no comprehensive analysis of the entire time-series. Our objectives were to assess whether water quality in Lake Lillinonah has changed over time and to identify whether there was a relationship between nutrient concentration and water clarity during the history of the lake. In addition, we examined whether any patterns in water quality could be explained by hydrologic events or changes in nutrient management within the watershed.

Methods

Site description

Lake Lillinonah is an impoundment on the Housatonic River, in western central Connecticut (Fig. 1). The Housatonic River is one of 3 major tributaries of Long Island Sound (CTDEP and NYSDEC 2000). In the watershed above Lake Lillinonah, much of the underlying geology is metamorphic schist and granite with some areas of marble (Bell 1985). The large (~360,000 ha) watershed includes parts of western

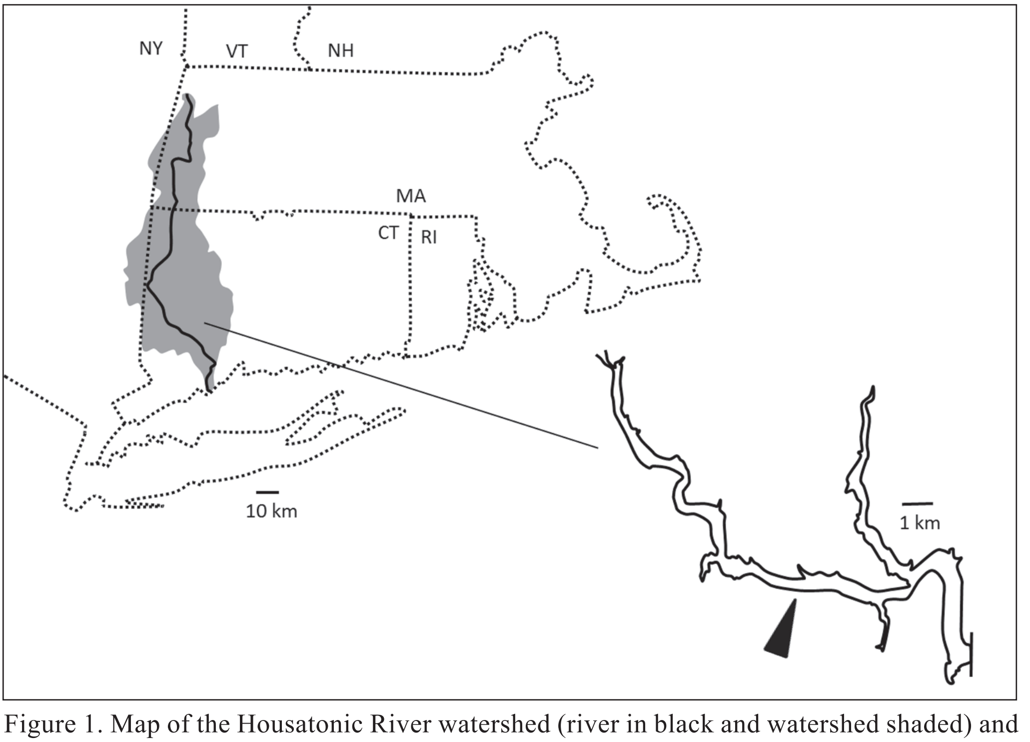


Figure 1. Map of the Housatonic River watershed (river in black and watershed shaded) and Lake Lillinonah (inset). The central lake sample station is marked with an arrow.

Massachusetts, eastern New York, and much of western Connecticut (Fig. 1). It includes backwaters from the Housatonic and Shepaug rivers. The lake was created following construction of Shepaug Dam in 1955 by Connecticut Light and Power and is used for hydroelectric generation and recreation. The 626-ha lake has a maximum depth of 30.5 m near the dam (Healy and Kulp 1995) and a mean depth of 13.4 m (Klug et al. 2012). Residence time is relatively short but highly variable depending on river flow and hydropower generation. Published values for average residence time range from 17–24 d (Healy and Kulp 1995, USEPA 1975a). The impoundment is used to alleviate flooding in times of high flow, and the water level is lowered up to 3 m preceding predicted heavy rain. Land use in the watershed is a mix of forested and developed areas with some agriculture.

Recent environmental history

Historically, Pittsfield, MA, New Milford, CT, and Danbury, CT, had significant industrial activities in the watershed above Lake Lillinonah (Fredette 1992). One legacy of this activity is elevated concentrations of polychlorinated biphenyls (PCBs) in the sediments of the Housatonic River and its impoundments. From 1932 to 1977, a General Electric (GE) plant in Pittsfield, MA, discharged PCBs into the river as a byproduct of electrical-transformer manufacturing. In 1999, GE reached a settlement with the US Environmental Protection Agency (USEPA) and the states of Massachusetts and Connecticut, and agreed to pay for remediation of contaminated sediments as well as restoration of natural resources along the entire river. Significant sediment remediation of a short river section near the plant was completed in 2007 (USEPA 2009). Remediation in the rest of the river has focused on habitat restoration and sediment containment and is ongoing (Sperduto 2013). Despite these efforts, concentrations of PCBs in some fish species are still elevated and restrict their availability for human consumption for much of the river and its impoundments (CTDPH 2013).

Another legacy of human activity in the watershed is excessive loading of nitrogen and phosphorus from both point and nonpoint sources. Point sources within the watershed include municipal wastewater-treatment plants and industrial discharge. Nonpoint sources include atmospheric deposition, fertilizer and manure runoff, and urban stormwater runoff (Trench 2000). By the early to mid-1970s, researchers had established that excessive nutrient loading, primarily phosphorus, was the cause of eutrophication in lakes worldwide (Schindler 1974, USEPA 1975a, Vollenwieder 1976), and efforts to reduce phosphorus loading in the Housatonic River were intensified (Fredette 1992). By the late 1980s, phosphorus removal was implemented at least seasonally at municipal wastewater-treatment plants throughout the Lake Lillinonah watershed, and agricultural best-management practices were implemented in parts of the watershed (Fredette 1992). More recently, during the 2000s, there have been regional efforts to reduce nitrogen loading in inland waters as part of a plan to reduce nitrogen concentrations in Long Island Sound (CTDEP and NYSDEC 2000). When all planned upgrades are complete, it is expected that the wastewater-treatment plants in the Connecticut portion of the Lake Lillinonah watershed will have reduced their nitrogen discharges by 50–66% (CTDEEP 2013).

Along with efforts to reduce nutrient loading, steps have been taken to mitigate some of the impacts of eutrophication in Lake Lillinonah. To reduce algal blooms temporarily, copper sulfate was applied as an algaecide at intermittent intervals for at least 35 y (Norvell and Frink 1975; S. Young, Lake Lillinonah Authority, Brookfield, CT, pers. comm.). In addition, because water at the Shepaug Dam turbine gates is frequently hypoxic, power generation led to poor oxygen conditions and fish kills in the downstream basin, Lake Zoar (CTDEP and NU 1988, Fredette 1992). In 2006, a liquid-oxygen diffuser was installed at the bottom of Lake Lillinonah near the dam to oxygenate the water before sending it through the turbines to Lake Zoar (FLPR 2007).

Data sources

To examine historical water quality, we compiled nutrient data for 24 y from the 36-y period between 1974 and 2009 (1974–1991, 2002–2003, and 2006–2009). The number of data points per year (May–September) for total phosphorus (TP) and total nitrogen (TN) ranged from 2 to 15 with a median of 7 for TP and a median of 5 for TN. Secchi depth data was available for 17 years during that time period (May–September, n = 2–15, median = 6).

We gathered data from a number of sources (Table 1). There were several studies conducted in the 1970s and 1980s designed to assess the impacts of wastewater-treatment plant upgrades on water quality in the lake (CTDEP and NU 1988; Fredette 1983, 1986, 1987, 1988; Jones and Lee 1981; Smith and Brown 1978; USEPA 1975a). In addition, the US Geological Survey (USGS) conducted routine monitoring in the lake from 1974–1991, and we obtained those data from the USGS

Table 1. Sources of data used in this study. x indicates which parameters were available from each source. CTDEP = Connecticut Department of Environmental Protection, FOTL = Friends of the Lake, NU = Northeast Utilities, LLA = Lake Lillinonah Authority, USEPA = US Environmental Protection Agency, USGS = United States Geological Survey.

		Parameter				
Source	Date range	Secchi depth	Total phosphorus	Total nitrogen	Surface-water temperature	Turbidity
CTDEP unpubl. data	1980	x			x	
CTDEP unpubl. data	1983	x	x		x	
CTDEP and NU 1988	1984–1985	x	x	x	x	
FOTL unpubl. data	2006, 2008	x	x		x	
Fredette 1983	1981–1982	x	x			
Fredette 1986, 1987, 1988	1986–1988	x	x			
Klug unpubl. data	2003	x	x	x		
Knoecklein 2004	2002–2003	x	x	x	x	
LLA unpubl. data	2006–2009	x	x	x	x	
Smith and Brown 1978	1976–1977	x	x	x	x	
USEPA 1975b	1975		x	x	x	
USGS unpubl. data	1974–1991	x	x	x	x	x

online data-repository. Much of the data from the 2000s was from monitoring studies commissioned by (1) Friends of the Lake, a local non-profit environmental organization and (2) Lake Lillinonah Authority, the municipal management board funded by the 6 surrounding towns. These monitoring studies were conducted by limnological consulting companies (Northeast Aquatic Research, LLC and HydroTechnologies, Inc.). J. Klug provided unpublished data from 2003. We also retrieved reports (Norvell and Frink 1975), data sheets from state monitoring efforts, and anecdotal evidence related to lake-water quality from the files at the Connecticut Department of Energy and Environmental Protection (formerly the Connecticut Department of Environmental Protection). To study the effects of river flow, we used USGS discharge data from the closest station (#01200500), located approximately 5 km upstream on the Housatonic River at Gaylordsville, CT.

Sampling and analytical methods followed standard limnological practices but varied depending on the data source. All nutrient samples were analyzed at state- or federally certified laboratories according to their standard operating procedures. Most of the studies we used were of fairly short duration (1–3 years). The USGS, the source of our longest data record (19 years), analyzed whether changes in their methods affected the interpretation of historical data. For the period we studied (1974–1991), there were no changes in USGS methods that would bias our interpretations (Trench 1996).

Data analysis

To analyze historical water quality, we chose one central location (Fig. 1) that was a common sampling site in both historical and current studies. We analyzed surface samples—defined as samples taken at between 0 and 1 m depths—from May to September. We chose May–September as our focal period because those were the most common months represented in our data set. In addition, May–September coincides with the period of most-intense algal blooms and recreational use.

Visual inspection of scatter plots showed several outliers in discharge, turbidity, and nutrient concentration in the days and weeks following Hurricane Belle in 1976. Although extreme events play an important role in water quality, we were most interested in factors driving water quality during more typical conditions, thus we removed the post-Hurricane Belle data points from the analysis described below. Following removal of outliers, the data were normally distributed and we did not transform the data.

To identify trends in historical water quality, we calculated average summer values of TP concentration (mg/L), TN concentration (mg/L), TN:TP ratio, and Secchi-disk depth (m). Due to several temporal data gaps in the record, we did not conduct statistical trend analysis and instead discuss patterns over time based on visual inspection.

We used Pearson correlation analysis with a conservative 2-tailed test to explore associations between variables (TN, TP, Secchi depth) and factors potentially affecting them (water temperature, discharge, turbidity).

Results and Discussion

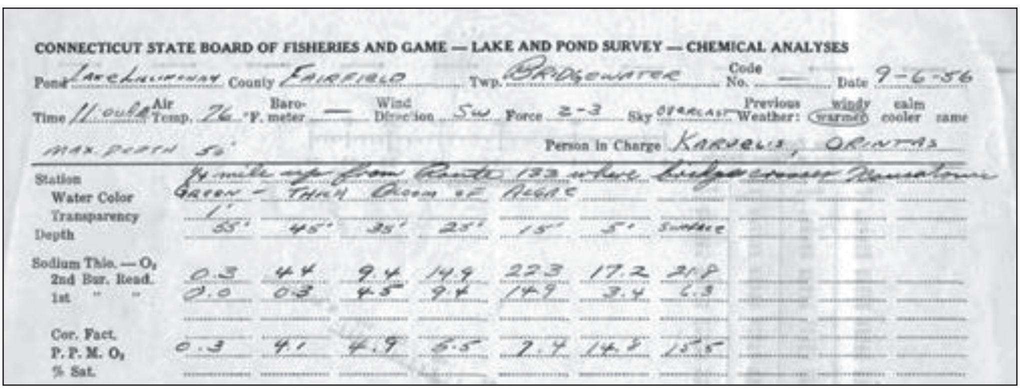
Historical trends in water clarity

Lake Lillinonah has shown symptoms of eutrophication since its creation in 1955. The first known data sheet, from 1956 (Fig. 2), recorded a Secchi depth of 0.3 m (1 ft) and 0.3 mg/L dissolved oxygen on the bottom. We did not find Secchi depth or nutrient data from the 1960s, but notes on other data sheets suggest similar poor conditions. For example, a fisheries data sheet from 31 August 1963 noted a "dense bloom of algae". Similarly, a letter from a limnological consultant to the State Water Resources Commission described a 6 July 1970 boat ride during which the observer recorded "very heavy bloom conditions" throughout the entire mainstem arm of the lake and near the dam (Benoit 1970). A report prepared for the National Eutrophication Survey identified high nutrient loading and concentration within the lake and concluded that recreation within the lake was impaired by "blue-green" algal blooms (USEPA 1975a).

Average summer Secchi depth was variable across years (range = 1.2 m in 1986 to 2.8 m in 2003) but showed no trend over time (Fig. 3). Turbidity at the mid-lake station was generally low (97% of samples on record were <10 NTU) indicating that the variability in summer water clarity was due to variability in algal biomass. Under the trophic-status classification used by the Connecticut Department of Energy and Environmental Protection (CTDEP 1991), the lake was consistently eutrophic (Secchi depth < 2 m) throughout the period of record (CTDEP 1991) except 5 years which were more characteristic of late mesotrophic conditions (Secchi depth = 2–3 m in 1981, 1982, 1983, 1987, and 2003). Secchi-depth data was only available for ~70% of the years in which we had nutrient data, which limited our ability to compare patterns with the nutrient-concentration time-series. In addition, average water clarity may have been affected by treatment of the lake with the algaecide copper sulfate in some years (Norvell and Frink 1975; S. Young, pers.comm).

Historical trends in nutrient concentration

Average summer TP concentration in Lake Lillinonah trended downward from 1974 through 1991 (Fig. 4a). This period corresponded with significant efforts to


CONNECTICUT STATE BOARD OF FISHERIES AND GAME — LAKE AND POND SURVEY — CHEMICAL ANALYSES

Pond LAKE LILLINONAH County FAIRFIELD Twp. BRIDGEWATER Code No. — Date 9-6-56

Time 11 o'clock Air Temp. 76 °F. Barometer — Wind Direction SW Force 2-3 Sky OVERCAST Previous Weather: windy calm warmer cooler same

MAX. DEPTH 56' Person in Charge KARVELIS, ORINTAS

Station	¼ mile up from Route 133 where bridge crosses Housatonic						
Water Color	GREEN – THICK BLOOM OF ALGAE						
Transparency	1'						
Depth	55'	45'	35'	25'	15'	5'	Surface
Sodium Thio. — O_2 2nd Bur. Read.	0.3	4.4	9.4	14.9	22.3	17.2	21.8
1st " "	0.0	0.3	4.5	9.4	14.9	3.4	6.3
Cor. Fact.							
P.P.M. O_2	0.3	4.1	4.9	5.5	7.4	14.8	15.5
% Sat.							

Figure 2. Earliest known data-sheet recording Lake Lillinonah water quality on 6 September 1956.

reduce point-source loading of phosphorus from municipal wastewater-treatment plants in the watershed (Fredette 1992) and is consistent with a regional trend identified by Trench (1996). Trench (1996) analyzed trends in water-quality data for the period 1975–1988 for 30–40 sites in Connecticut (primarily rivers) and found a downward trend in TP concentration at 70% of the sites, including a site in Lake Lillinonah and 1 on the mainstem of the Housatonic River just upstream. TP concentration during the 2000s was lower than the 1970s but higher than concentrations in the early 1990s (Fig. 4a).

Despite substantial reductions in point sources, it is likely that nonpoint phosphorus loading increased in the latter part of the record as population size in the area increased. For example, Danbury, the largest city in the watershed, grew by 25% from 1990 to 2010 (US Census Bureau 2014). Under the trophic status classification used by the Connecticut Department of Environmental Protection (CTDEP 1991), the lake was consistently eutrophic (TP > 0.03 mg/L) or hypereutrophic (TP > 0.05 mg/L) during the period of 1979–1989. In 1990 and 1991, TP concentrations fell into the late mesotrophic category. During the 2000s, TP concentrations hovered near the 0.03-mg/L boundary between late mesotrophic and eutrophic conditions. The change in trophic status highlighted the decline in TP concentration over time but also the increase in the 2000s.

There was no apparent trend in average summer TN concentration during the period of record (Fig. 4b). This result is not surprising given that nutrient-reduction strategies in the watershed were focused on phosphorus (Fredette 1992). Regional cross-site studies of water quality, primarily using river sites, detected either no

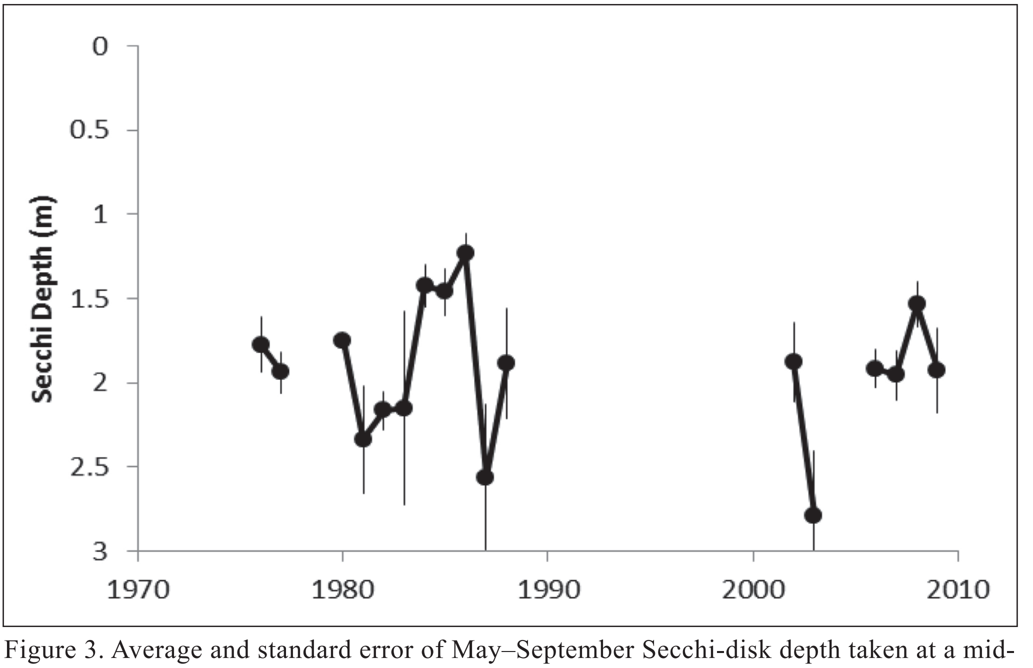


Figure 3. Average and standard error of May–September Secchi-disk depth taken at a mid-lake station in Lake Lillinonah.

statewide trend (Colombo and Trench 2002, Trench 1996) or increasing TN concentrations (Trench 1996) depending on the time period studied. Trench (1996) analyzed data from a site within the lake and 2 sites in tributaries and found an increase in TN concentration during 1975–1988 but no trend during 1981–1988. In contrast, Colombo and Trench (2002) found no trends in TN concentration from 1992–1998 at 4 tributary sites. Using the trophic-status rubric based on TN, the lake was consistently eutrophic (TN > 0.6 mg/L) with a few hyperutrophic (TN > 1 mg/L) years and 1 late mesotrophic year.

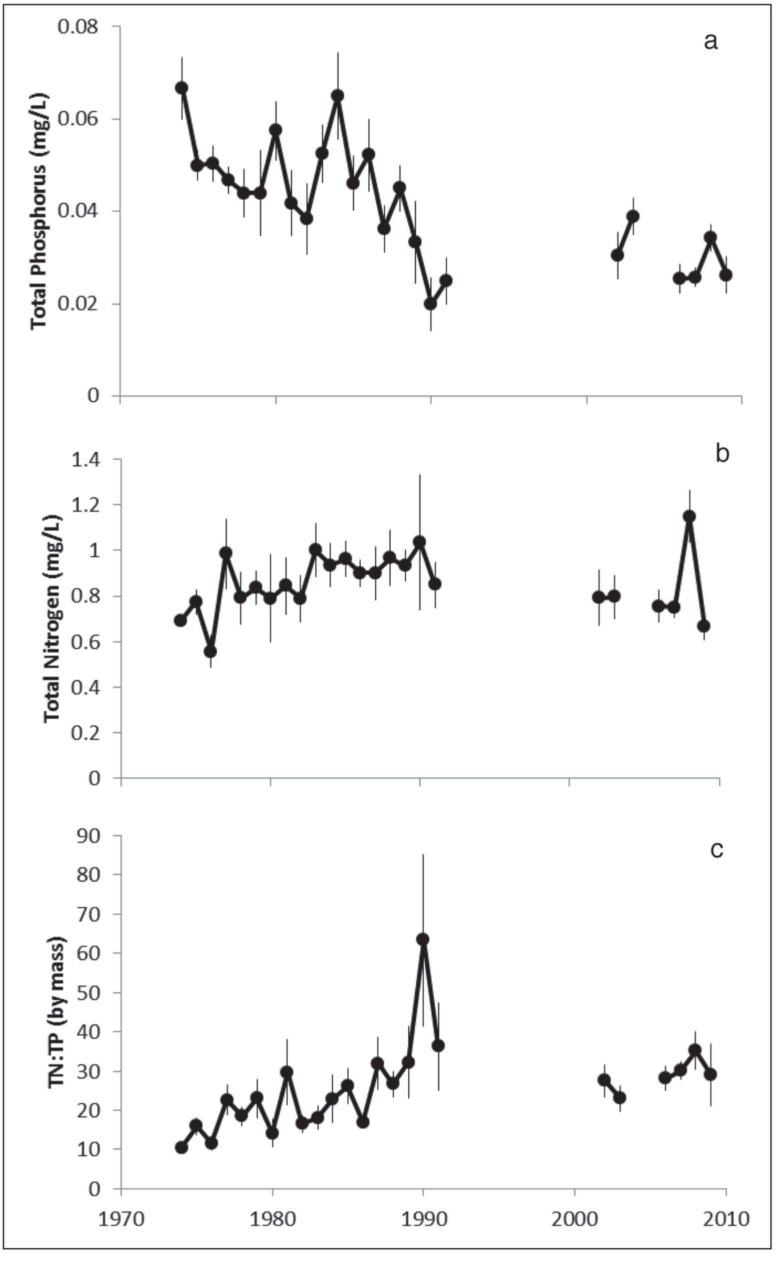


Figure 4. Average and standard error of May–September (a) total phosphorus concentration, (b) total nitrogen concentration, and (c) total phosphorus-to-total nitrogen ratio in surface (0–1 m) samples taken from a midlake station in Lake Lillinonah.

The decline in TP coupled with stable TN resulted in an increase in the TN:TP ratio between 1974 and 1991 (Fig. 4c). This result is consistent with other studies that found an increase in TN:TP ratio in areas where the target for reduction was phosphorus (Jeppesen et al. 2005) and comparative studies that showed that TN:TP ratios were lower in lakes with high TP (Downing and McCauley 1992). The ratio stabilized in the 2000s at ~30 TN:TP by mass. Reviews of nutrient-limitation studies suggested that algal communities would likely have been limited by phosphorus at ratios observed in the 2000s (Guilford and Hecky 2000).

Relationships between variables

Across all years, Secchi-disk depth was negatively correlated with TP (r = -0.27, P = 0.006, n = 111), TN (r = -0.29, P =0.01, n = 75) and surface-water temperature (r = -0.25, P = 0.02, n = 68). Thus, water clarity was lower when nutrient concentration and water temperature were higher. These results correspond with our general understanding of the physiological factors regulating algal growth and are consistent with the indication that variability in water clarity in Lake Lillinonah is driven by variability in algal biomass and not turbidity (see above). A large body of comparative work shows that algal biomass increases as both TN and TP concentration increase (e.g., Guilford and Hecky 2000, Mazumder and Havens 1998) and that nitrogen, phosphorus, or both limit algal growth (e.g., Elser et al. 2007). Similarly, an increase in temperature generally increases algal growth and an increase in algal blooms is one predicted consequence of warming due to global climate change (Jeppesen et al. 2009, Johnk et al. 2007, Moss et al. 2011).

After we removed the post-Hurricane Belle data points from our analysis (see methods), TP and TN were not correlated with turbidity or discharge (P > 0.05 in all cases). Interestingly, there was no significant correlation between TN and TP concentration (P > 0.05). Large-scale comparative studies have found TN and TP correlated across lakes (Bachmann et al. 1996, Downing and McCauley 1992). Because much of the historical focus on nutrient reduction has been on phosphorus but not nitrogen, the concentrations in Lake Lillinonah are uncoupled (Fig. 4a, b). The decoupling is evident in the increasing trend in TN:TP throughout the early part of the record (Fig. 4c). Although the TN:TP ratio stabilized in the 2000s, the current efforts to substantially reduce nitrogen loading to the rivers that feed Long Island Sound (CTDEP and NYSDEC 2000) will likely lead to a future decrease in the TN:TP ratio if phosphorus loading is not reduced at the same rate. Phytoplankton community structure is strongly influenced by resource ratios (Smith and Bennett 1999, Tilman 1982) and cyanobacteria typically dominate at low TN:TP ratios (Elser 1999, Smith 1983). Although the summer phytoplankton community in Lake Lillinonah is already dominated by cyanobacteria (J. Klug, unpubl. data), blooms may be exacerbated by further reduction in TN:TP when physical conditions are favorable (Elser 1999).

Impacts of extreme hydrological events

On 10 August 1976, Hurricane Belle made landfall on Long Island, NY and passed over Connecticut bringing high winds and heavy rainfall (Lawrence

1977). The USGS sampled Lake Lillinonah on 11 August 1976 (the day after Belle) and 14 September 1976 (~1 month after Belle) (Fig. 5). We did not include post-Belle samples in our analysis of long-term trends because the values were not representative of 1976 summer conditions. Both samples had very high turbidity and total phosphorus concentrations (Fig. 5) reflecting high sediment and nutrient loading to the lake following the storm. Values returned to near the 1976 baseline by 18 October 1976. A recent study documented a similar pattern following Tropical Cyclone Irene in 2011 (Klug et al. 2012). The impact of these loading events on water quality depends on how much of the phosphorus is retained within the system relative to that flushed downstream during the period of high flow. After Belle, both turbidity and TP remained elevated a month after the storm despite a reduction in discharge, indicating that some of the storm-related nutrients were retained. This observation underscores one of the challenges of detecting the influence of extreme events. Because extreme hydrological events are rare, high-frequency regular monitoring or targeted sampling is necessary to better understand the effect of these events on overall water quality. Extreme events have increased in frequency in much of the US (Diffenbaugh et al. 2005, NCIA 2006) suggesting that planning for increases in storm-driven phosphorus loading is essential (Jeppeson et al. 2009).

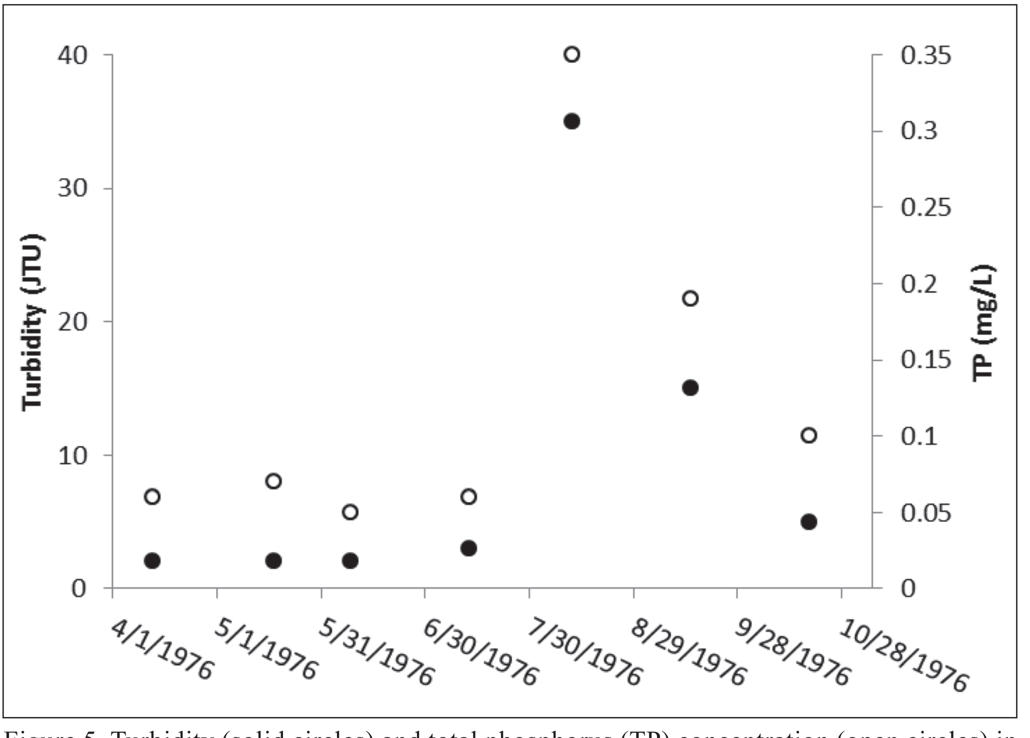


Figure 5. Turbidity (solid circles) and total phosphorus (TP) concentration (open circles) in surface samples taken from a mid-lake station in Lake Lillinonah as part of the US Geological Survey (USGS) water-quality monitoring program. Hurricane Belle hit the area on 10 August 1976.

Future considerations

By establishing a baseline dataset for 1974–2009, this study lays the groundwork for future studies of water quality in Lake Lillinonah. Our results demonstrate that both in-lake nutrient concentration (TP and TN) and weather conditions (water temperature) are important in determining water clarity in Lake Lillinonah. Despite historical reductions in phosphorus and other pollutants (e.g., PCBs), Lake Lillinonah is still listed as impaired for recreation and fish consumption under section 303(d) of the Federal Clean Water Act (CTDEEP 2012). Recreational impairment is caused by excess nutrients and algal growth (CTDEEP 2012); further reductions in nutrient loading are necessary to improve water quality.

There are a number of significant recent changes in the Lake Lillinonah watershed that will likely impact future water quality. Changes to permit limits and wastewater-treatment plant upgrades in the late 2000s have resulted in reduced phosphorus and nitrogen loading in Lake Lillinonah's tributaries (CTDEEP 2013, CTDEP 2008), and continued monitoring will be necessary to track whether these changes lead to reduced in-lake concentrations and improved water clarity. Other factors which may influence future water quality include the recent (~2010) invasion of zebra mussels (Biodrawversity 2011) and future increases in water temperature and frequency of extreme loading events due to ongoing climate change (Jeppeson et al 2009).

Acknowledgments

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