Comparing Chinese and United States lake management and protection

As shared through a sister lakes program

Lake Pepin, Minnesota

Liangzi Lake, Hubei Province

Minnesota Pollution Control Agency

May 2016

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Document number: wq-s1-91

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Abstract

The United States (U.S.) and China entered into a cooperative framework agreement focused on sustaining a partnership in the area of energy and the environment. One area of emphasis was water quality, with lakes being a specific focus. A Sister Lakes Program provided a basis for this collaboration.

The two lakes selected for this partnership were Lake Pepin in the U.S. (State of Minnesota) and Liangzi Lake in China (Hubei Province). This required a collaborative effort between the U.S. Environmental Protection Agency (USEPA) and Ministry of Environmental Protection (MEP) of China and the State of Minnesota and Hubei Province.

Representatives from Minnesota and Hubei Province visited both lakes, and a formal memorandum of cooperation and workplan was developed. The memorandum described specific areas of cooperation, including scientific research on restoration and protection of lakes with a focus on Liangzi Lake and Lake Pepin. Potential topics to be included were water quality assessment, biological monitoring, and pollutant source identification and pollutant trading. Of particular interest to the Chinese partners, was development of Total Maximum Daily Loads (TMDLs) and the planning and implementation associated with that.

This report represents a starting point for this effort. We provide comparisons between the two lakes and demonstrate similarities and differences in approaches. This report sets the stage for further work and the opportunity to learn from each other with the intent of improving the management and protection of both lakes.

Introduction

In December 2007, the third U.S.-China strategic and economic dialogue determined the 10 years cooperative framework agreement of energy and environment between the two countries. The two governments agreed to a partnership in the area of environmental protection for an extended period. In April 2008, a consensus was reached on the cooperation in protection and use of clean water. On December 4, 2008, the Ministry of Environmental Protection (MEP) of China with the U.S. Trade and Development Agency and the United States Environmental Protection Agency (USEPA) signed the "Clean Water Plan of Action" (http://www.state.gov/e/oes/eqt/tenyearframework/141878.htm).

On July 7, 2011, the conference on policy of water environment protection of China and the U.S. was held in the city of Wuhan in Hubei Province. Protection policies for the ecology of lakes in China was discussed along with details on environmental protection, environmental monitoring, and the comprehensive improvement of rural environmental of Liangzi Lake and Bositeng Lake. U.S. representatives described relative technologies of environmental protection and several successful cases. The representatives reached a consensus about rehabilitation of natural lakes. This meeting also called for site visits in China to Liangzi Lake in October 2012 and a reciprocal visit to a U.S. lake in late 2012. USEPA selected Lake Pepin in Minnesota to be the sister lake for this partnership

The 7th Policy and Technical Workshop on Sino-U.S. Clean Water Action Plan was held in Wuhan, Hubei Province on October 30 and 31, 2012. The Minnesota Pollution Control Agency (MPCA) provided state-level participation at the request of USEPA. The two sides exchanged their experiences of protecting lake-based water sources, and started discussion on the Sister Lake Partnership Initiative (http://www.epa.gov/international-cooperation/epa-collaboration-china). Following the workshop, U.S. representatives made a visit to Hubei Province and Liangzi Lake to become more familiar with important features of the lake and work activities underway. Chinese representatives made a reciprocal visit in January 14-16, 2013 to Minnesota to visit Lake Pepin and discuss further development of the Sister Lakes Project.

The Department of Environmental Protection (DEP) of Hubei Province and the MPCA signed a memorandum of cooperation on July 2013. The memorandum described specific areas of cooperation, including scientific research on restoration and protection of lakes with a focus on Liangzi Lake and Lake Pepin. Potential topics to be included were water quality assessment, biological monitoring, and pollutant source identification and pollutant trading. Of particular interest to the Chinese partners was development of Total Maximum Daily Loads (TMDLs) and the planning and implementation associated with that. A subsequent workplan described potential work products.

This report represents a starting point for this effort. We provide comparisons between the two lakes and demonstrate similarities and differences in approaches. This report sets the stage for further work and the opportunity to learn from each other with the intent of improving the management and protection of both lakes.

Description of the lakes and their watershed

Describing the morphometry and watershed characteristics (Table 1) of the two lakes is essential to understanding their water quality, overall ecology, and individual management challenges. Climatic differences are an important consideration as well, given the differences in latitude of Lake Pepin and Liangzi Lake (Figure 1). In our approach, we provide paired descriptions of each lake, which later allow for comparisons and discussion on their management.

Figure 1 Location of Minnesota.

The red star is the approximate latitude of Wuhan, Hubei Province, which is similar to New Orleans, Louisiana.

Table 1 Lake and watershed characteristics for Pepin and Liangzi Lakes

	Lake Pepin[1]	Liangzi Lake[2]
Surface area (km^2)	103	304
Mean depth (m)	5.4	3.0
Maximum depth (m)	17.0	6.2
Maximum width (km)	3.3	12.3
Maximum fetch (km)	19.0	18.3
Length (km)	33.5	31.7
Volume (hm^3)	556	912
Watershed area (km^2)	126,910	3,265
Watershed: Lake surface area	1,232:1	11:1
Mean hydraulic retention time	0.04 year (16 days)	0.53 year (193 days)

1 Lake Pepin values as summarized in Larson et al. 2002.

2 Liangzi Lake values from Hubei DEP and Sumin, W. and Hongshen, D. 1998. Lakes in China. Beijing Science Press.

Lake Pepin

Lake Pepin is a natural lake on the Mississippi River, formed about 10,000 years ago by a glacier. This lake is the only natural impoundment on the Mississippi River, the rest being the result of a series of locks and dams built in the 1930s for commercial navigation. Lake Pepin is referred to as a "run-of-the-river reservoir," given its location on the mainstem of the river.

The lake has a surface area of about 103 square kilometers (km) and a mean depth of 5.4 meters (m). Its watershed is about 122,000 square km, which is approximately half of Minnesota's total land area plus a portion of Wisconsin (Figure 2). Its drainage area includes the Upper Mississippi River, St. Croix River, and Minnesota River Basins, with a total watershed to lake surface ratio of about 1,200:1 (Table 1). Based on area, the three major basins (in order) comprise about 42%, 36%, and 16% of Lake Pepin's watershed. Relative contributions to the flow into Lake Pepin vary annually; however, on average their relative contributions are 48%, 24%, and 28% respectively.

Lake Pepin is comprised of two somewhat distinct segments (

Figure 3); the Upper where the Mississippi River flows into the lake is smaller and shallower, whereas the Lower is longer, deeper, and wider. These distinct segments influence the water quality monitoring site selection as described later.

Figure 2 Lake Pepin watershed with major basins

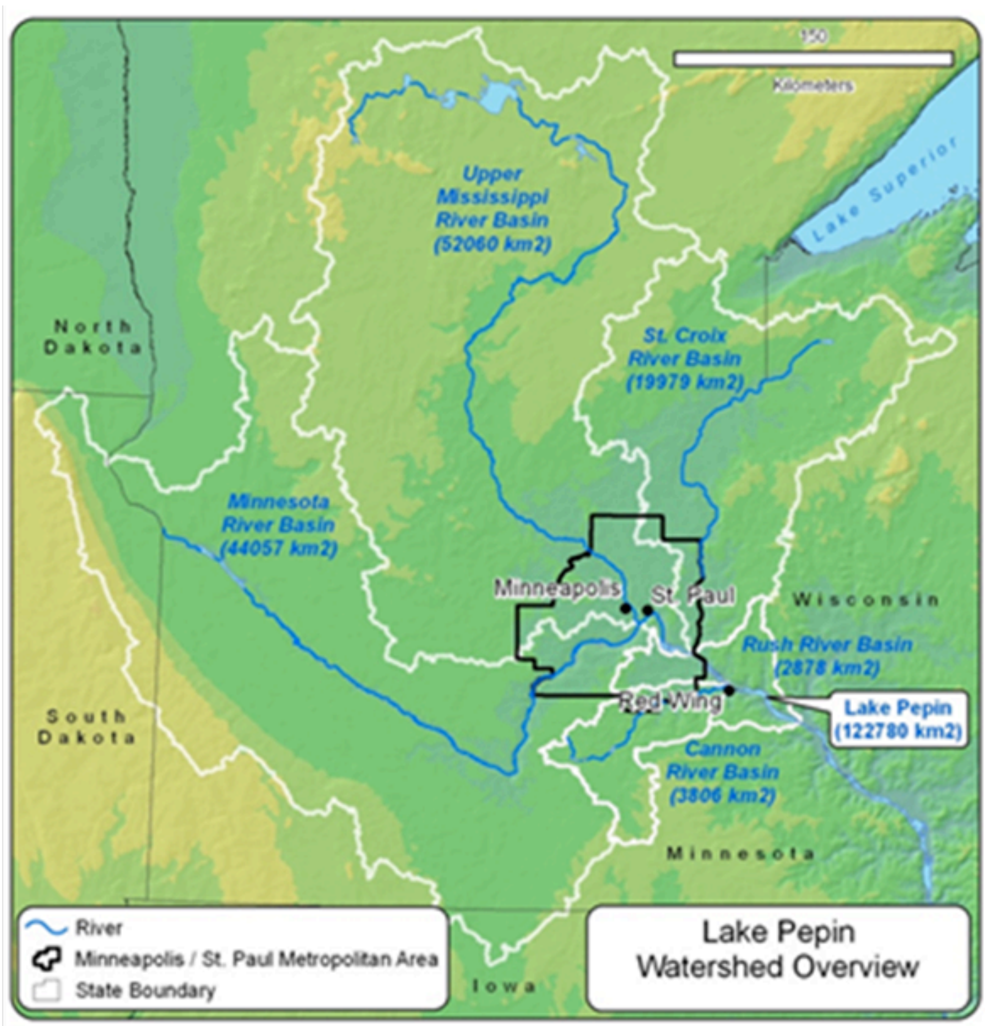
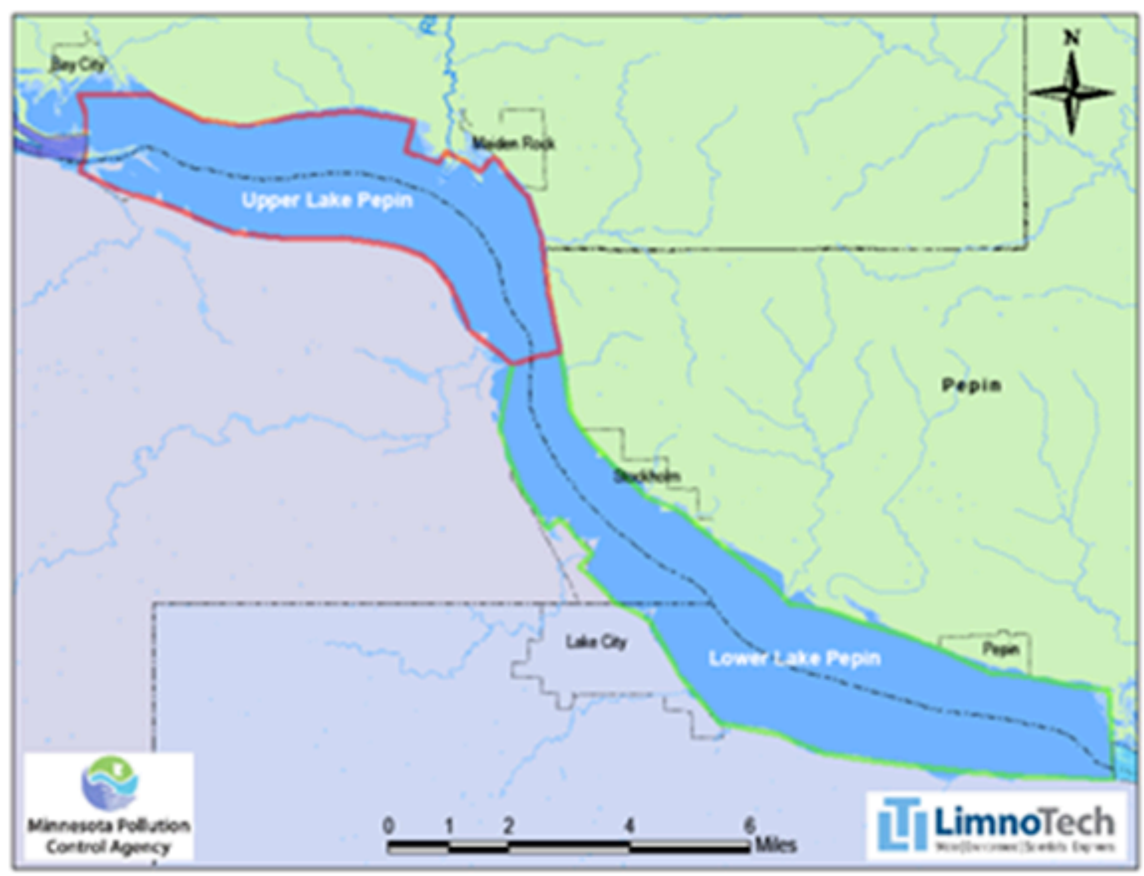


Figure 3 Lake Pepin map showing Upper and Lower Segments

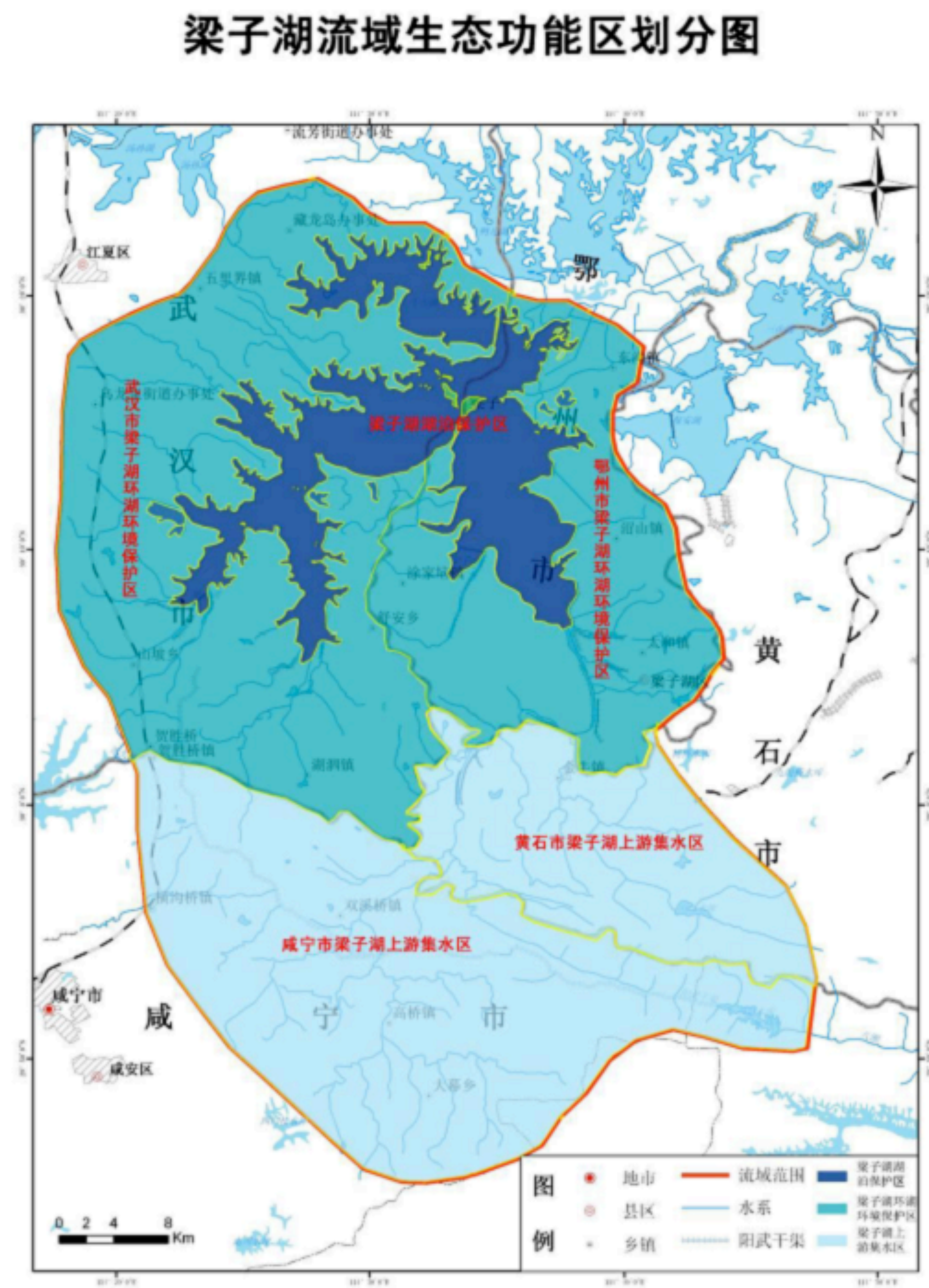


Liangzi Lake

The shoreline of Liangzi Lake is 636 km, and there are a total of 316 lake forks or bays. Liangzi Lake system is composed of Liangzi Lake, Ya'er Lake, Sanshan Lake, and Bao'an Lake (Figure 4). The total watershed area of the system is 3,265 km^2; the watershed area of Liangzi Lake is 2,085 km^2. Liangzi Lake is bounded by Liangzi Island in the center, divided into two lakes: East Liangzi Lake and West Liangzi Lake. East Liangzi Lake includes Tu Zhen Lake, East Lake and West Lake and other 20 sub-lakes, and belongs to Ezhou City; West Liangzi Lake includes Niushan Lake, Qianjiang Lake, Zhangqiao Lake, and other 18 sub-lakes, and belongs to Jiangxiao District.

There are more than 30 rivers flowing into Liangzi Lake, the largest being the Gaoqiao River. Gaoqiao River runs from the Gaoqiao Town in Xianning City, is 64.4 km in length, and has 26 tributaries. The river catchment is 893 km^2, and accounts for half of the catchment area of Liangzi Lake and more than 50% of the water that flows to the lake. In the control section (Gang Bridge) at Gaoqiao River, the width is 20 m and average water depth is 2 m. Annual average flow rate is 14.8 m^3/s; the flow rate in the middle reach is 10.4 m^3/s. The river discharged to the Chang River. The Chang River connects Liangzi Lake in Donggou Town of Ezhou City, flows through Donggou, LuXi Kou, Xia Jia Gou, and Lu Kou, to Fankou gate into the Yangtze River, for a total length of 46.6 km.

Figure 4 Liangzi Lake watershed. The watershed extends across Wuhan, Ezhou, Huangshi, and Xianning Cities. Drainage area of 2,085 km^2. Outlets to Yangtze River through Changang Canal.



Climate and hydrology comparisons

The climate, geography, and related factors are substantially different between these two lakes. When combined with the watershed area and land use composition, this influences the hydrology, water, and pollutant loading to each. Table 2 summarizes important climate and hydrologic data for each lake.

Table 2 Climate and flow summaries for Liangzi and Pepin. Temperature and precipitation data for City of Red Wing (Pepin) and City of Wuhan (Liangzi)

	Lake Pepin	Liangzi Lake
Precipitation		
Summer (June-Sept.)	0.4 m	0.6 m
Annual	0.8 m	1.27 m
Evaporation		
Annual	0.9 m	0.95 m
Temperature		
Annual average max	12.8 C	29.8 C
Annual average minimum	0.9 C	4.6 C
Surface water inflow		
Summer flow rate (June-Sept.)	686[a] m^3/sec	130 m^3/sec
Annual flow rate	660[a] m^3/sec	[b.]
Total annual runoff volume	15,768 hm^3	1,092 hm^3
Typical annual runoff depth	0.15 m	0.52 m

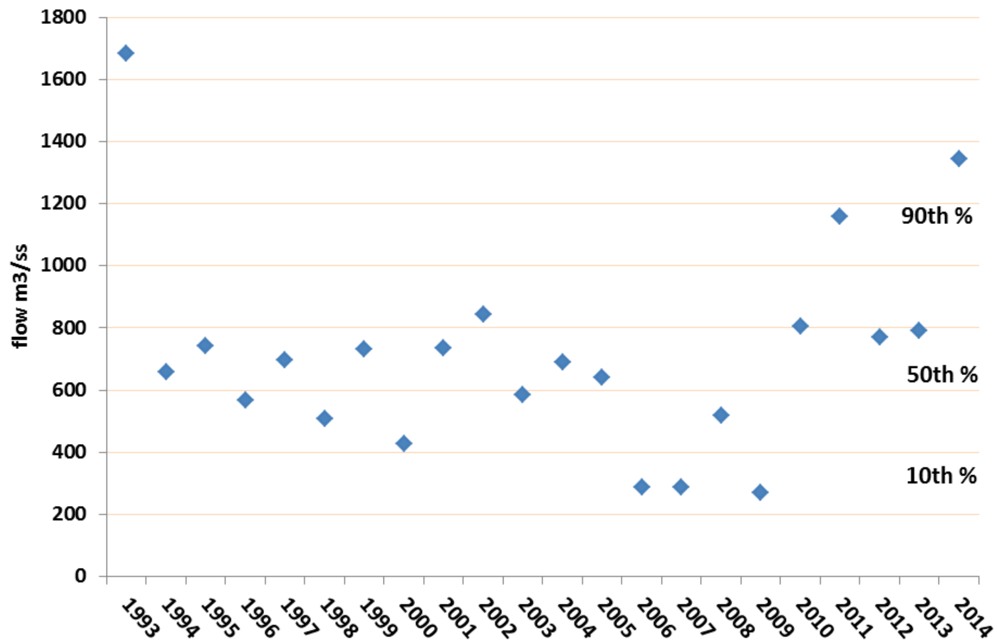
[a.] Mississippi River above Pepin, recent 22-yr record b. Highly variable so no value given

Lake Pepin

Rainfall and runoff varies annually across Lake Pepin's watershed and may vary substantially among the three major basins that comprise its watershed in any given year. A recent 22-year record (1993-2014), as summarized by the Long Term Resource Monitoring Program (LTRMP), provides a basis for describing river flow and water quality for Lake Pepin (Figure 5).

During this 22-year period, summer-mean Mississippi River flow varied from about 270 m^3/s (9,500 cfs, 2009) to almost 1,700 m^3/s (60,000 cfs, 1993), with a median of about 680 m^3/s (24,000 cfs). Water residence time in Lake Pepin is a direct function of Mississippi River flow (Heiskary and Walker 1995). During the extreme high flow of 1993 (100th percentile for this 22-year record), residence time was about 5 days, while at low flow of 2009 (0 percentile for this 22-year record) residence time was about 25 days. Based on long-term records, average residence time is about 16-19 days (Larson et al. 2002).

Figure 5 Summer-mean flow of Mississippi River at Prescott (upstream of Lake Pepin) for the period from 1993-2014



Liangzi Lake

The annual runoff depth in Liangzi Lake district is 523.9 mm, the related total amount of annual runoff is 10.92 * 10^8 m^3. The maximum measured annual runoff depth is 1239.1 mm; the related total amount of annual runoff is 27.02 * 10^8 m^3, which is 4.3 times of the normal lake volume. During the period when outlet-structure gates are open, the average annual flow of Liangzi Lake is 52.01 m^3/s, the maximum daily average flow of 395 m^3/s.

The annual average level of Liangzi Lake is 17.81 m; the lowest water level occurs in March (16.69 m), while the highest (18.78 m) occurs in August. Because annual precipitation variability is large in Liangzi Lake watershed, the difference between the low and high levels of the lake can be very great. For example, in 1968, because of the drought, the highest level of Liangzi Lake was only 17.45 m, even lower than the average level of 17.81 m. The highest level the following year was 21.05 m, which is a difference of 3.6 m for the two years.

Watershed land use and demographic comparisons

Lake Pepin

Since over 60% of Minnesota drains through Lake Pepin, the relative composition of land use is somewhat reflective of Minnesota as a whole. The single largest land use is cultivated land (Table 3) and a majority of this is in the highly agricultural Minnesota River Basin (Figure 2).

Forest and wetland land uses dominant the upper portions of the Upper Mississippi River Basin. While urbanized (developed) land use is a small percentage, a majority of this is in the Twin Cities Metropolitan Area, which includes Minneapolis and St. Paul and is immediately upstream from Lake Pepin (Figure 2). Over one-half of Minnesota's population is located in this metropolitan area as well.

The St. Croix River Basin has a mix of land uses with forested use being prominent throughout much of the basin. The differences in land use composition among the three basins strongly influences phosphorus and sediment loads from each and their relative significance to Lake Pepin water quality problems as will be discussed later.

Table 3 Watershed land use composition and population for Pepin and Liangzi Lakes

Land use (%)	Lake Pepin (MN side)	Liangzi Lake
Urban/residential	7.4	15.0[a]
Cultivated	50.6	70.0[b]
Pasture/grassland	5.0	<1.0[c]
Forest	19.5	15.0[d]
Wetland/water	17.5	
Population	4,351,000	737,000

a. dry land, b. paddy, gardens, c. grass, d. forest & orchard

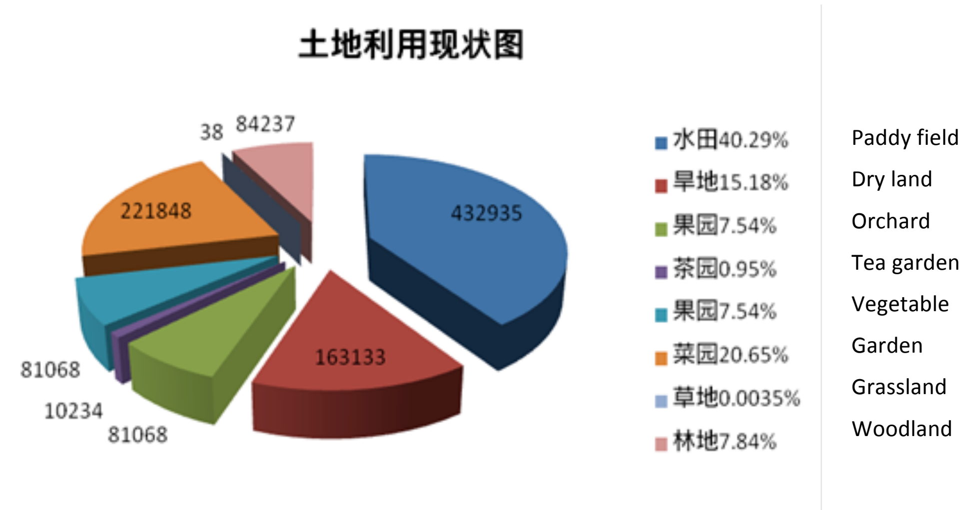
While Lake Pepin is not a source of municipal drinking water, the Mississippi River upstream of Lake Pepin is an important source of drinking water for a number of cities, including Minneapolis and St. Paul. Many cities in Iowa (downstream) rely on the water exiting Lake Pepin as a drinking water source. With the Twin Cities Metropolitan Area in close proximity to the lake, Lake Pepin is a popular recreational destination as reflected by the pictures in Figure 6.

Figure 6 Lake Pepin Photos. #4 courtesy of John Sullivan, WDNR

Liangzi Lake

The land area of Liangzi Lake Basin is 2,474 km^2, accounting for 1.23% of the land area of Hubei Province. Most of the land is in agricultural and aquatic use. Farmland consists of paddies, orchards, vegetable fields and gardens and accounts for 398 km^2, and of this, the majority was paddy field.

Figure 7 Liangzi Lake watershed land use composition



Liangzi Lake watershed contains Wuhan, Ezhou, Daye (a county-level city in Huangshi City), Xianning Four Cities and 19 towns and 344 villages. The total population was 754,200, and the land area was 2,474 km^2.

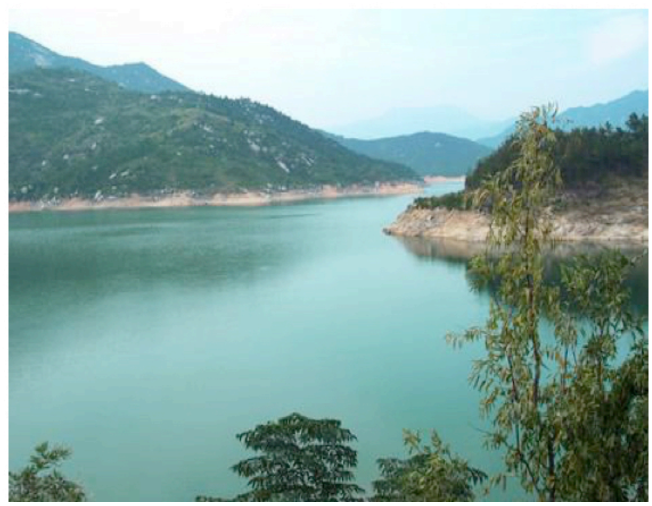
In recent years, because of its unique advantages in rich resources and favorable location, and convenient transportation, the primary (agricultural and fishery), secondary (industry), and third industry (e.g. transportation, communication, and service) developed rapidly in Liangzi Lake Basin. According to the latest survey results, the GDP of 19 towns in Liangzi Lake watershed reached 77.554 billion yuan in 2011, of which the first, second, and the third industry accounted for 13.50%, 56.87%, and 29.62% respectively. The per capita net income of farmers was 6126.6 yuan, a large gap with the average level of the province's 7851.7 yuan.

Liangzi Lake is one of the emergency sources of drinking water for Wuhan City. Its tributary Gaoqiao River is the drinking water source of the Shuangxiqiao Town and Gaoqiao Town of Xianning, Qiuchuan River is the source of drinking water for Jinniu Town of Ezhou. There are two centralized drinking water sources in Liangzi Lake Basin, serving a population of 21,600.

The lakeshore sediments of Liangzi Lake are composed of red clay, yellow clay, clay and silt loam in general. The slope of lakeshore is gentle and suitable for the growth of a variety of aquatic and wetland plants, resulting in high species richness.

The tourism industry of Liangzi Lake Basin is mainly concentrated in the Liangzi Town, Liangzi Lake Scenic Area, and Shaoshan Forest Park. Ezhou Liangzi Lake ecological tourist zone was named a national AAA level scenic spots in September 2006. Liangzi Lake's tourism consists of sightseeing, catering, and accommodation. Annually, 500,000 tourists visit the area. The total output value of the tourism industry in 2011 amounted to 320 million yuan. Pictures taken near the lake demonstrate scenic values and usage of the lake (Figure 8).

Figure 8 Pictures of Liangzi Lake.
Photos 1-3 from Steve Heiskary, October 2012. Photo 4 from Hubei MEP presentation October 2012.



Comparison of lake ecology

Rooted aquatic vegetation (macrophytes) is essential to the overall ecology and water quality of lakes. Both lakes have had surveys of the emergent and submergent macrophytes and the lakes' fish. Survey techniques vary between the two lakes and only general qualitative descriptions are included here. We do not provide quantitative comparison between the two lakes.

Macrophyte composition and distribution

Lake Pepin

Submersed rooted vegetation in Lake Pepin varies among the Upper and Lower segments of the lake. This is in part because of the difference in depth but also is a function of elevated suspended sediment in the Upper segment, which limits light for plant growth. A good data record is available for the period 1998-2015. Percent frequency of macrophytes is one measure used to describe plant abundance and distribution across each segment (Figure 11).

The Lower segment percent frequency is consistently higher, with but a few exceptions (in this record) and averaged 29% as compared to 20% for the Upper segment. Percent frequency varies from year-to-year. A distinct increase for 2006-2010 was noted in both segments; followed by a decline in 2011. This was followed by lower but stable amounts in 2012-2015.

The most common forms are sago pondweed (*Potamageton pectinatus*), wild celery (*Vallisneria americana*), water stargrass (*Heteranthera dubia*), and coontail (*Ceratophyllum demersum*), (in that order). The peak value of 74% in 2010 in the Lower segment is largely attributed to extensive growth of Canadian waterweed *(Elodea canadensis*) and water stargrass.

Liangzi Lake

In summer, the lakeside zone is rich in aquatic plants, including emergent, floating leaf, and submerged plants. Among 22 sample plots, only one found no aquatic plants. The lakeside zone found 52 families, 128 genera, and 182 species of plants. Compared with the results of the previous investigation, the dominant species had changed, the represent species including barnyard grass, Bermuda grass, *Conyza canadensis*, *Hydrilla verticillata*, *Vallisneria spiralis*, *V. siderite,* and a few other forms.

In autumn and winter, some species in the nearshore zone senesce, but are replaced by different species, such as *Galium aparine*, Ji Ye Jincai. Aquatic plants decreased significantly in Beizui (North mouth), where a survey of 17 sample plots of aquatic plants found there were only seven plots with aquatic plants, including one plot, which only occasionally had a few reeds. Representative species include Bermuda grass, *Carex leucochlora*, and *Hemarthria altissima*, to name a few.

According to the summer lakeside-zone survey results, the species structure is not complete currently. Some areas of southwest lack submersed and floating-leaf plants and the emergent vegetation coverage rate was low over most of the lakeside zone.

The species structure of lakeside zone in autumn and winter was quite limited as compared with summer, especially the submersed and floating-leaf plants. In autumn and winter, both were in low numbers and generally scattered around the lake. Because of the low coverage of plants in autumn and winter, ecological function of lakeside zone is decreased.

Fish composition and fishery activity

Lake Pepin

Lake Pepin has an extremely diverse fish population that reflects both river and lake influences. The Minnesota Department of Natural Resources (MDNR), using various techniques, samples its fish population routinely. The lake is an extremely popular destination for anglers, and angler effort averages about 460,000 hours annually and has been as high as 660,000 hours. This works out to an average of about 13.5 hours of fishing activity for each acre of water on an annual basis. A June 2014 MDNR sampling effort provides the basis for describing Lake Pepin's fish population (**Error! Reference source not found.**). These data and the summary that follows were derived from the MDNR web page located at http://www.dnr.state.mn.us/lakefind/showreport.html?downum=25000100.

Summary and Highlights from 2014 Lake Pepin Large Lake Survey

By total number, Sauger (*Stizostedion canadense*) and White Bass (*Morone chrysops)* are the most commonly caught and harvested species. Walleye (*Stizostedion vitreus)* are generally third or fourth in total number. Bluegill (*Lepomis macrochirus*), Black Crappie (*Pomoxis nigromaculatus*), Yellow Perch (*Percina caprodes*), and Northern Pike (*Esox lucius*) have all experienced excellent year classes in the recent past due to clear water and abundant aquatic vegetation and will continue to provide excellent opportunities in the next several years. There are also many other fish species in Lake Pepin and there are over 120 fish species known to exist in this portion of the Mississippi River.

Toward the end of 2013, anglers began reporting better catches of Sauger. This is likely due to the growth of age-2 Sauger to acceptable size (0.33-0.36 m). Angling for Walleye and Sauger improved over the course of 2014, as smaller individuals of both species grew to sizes acceptable to anglers. Though angling improved during 2014, the numbers of larger Sauger and Walleye anglers had become accustomed to seeing in the 2008-2010 period remained relatively rare. A combination of several poor year classes in the early 2010s, the disappearance of several strong year classes from the early 2000s due to natural mortality, and record catches of young-of-year (YOY) Gizzard Shad (*Dorosoma cepedianum*) providing abundant forage likely have contributed to this lower success. Angling for Walleye and Sauger should continue to improve in 2015 and into the next several years as the predicted strong 2013-year class recruits to the fishery.

Smallmouth Bass (*Micropterus dolomieu*), Largemouth Bass (*Micropterus salmoides*), Yellow Perch, Northern Pike, Black Crappie, and Bluegill should continue to provide excellent angling opportunities during 2015, based on the numbers of adult and juvenile fish sampled. A recent tagging study involving White Bass from Pool 4 has shown that the White Bass population in Pool 4/Lake Pepin is very mobile, with individuals tagged in Pool 4 moving as far upstream as the Apple River (via St. Croix River) in Wisconsin and as far downstream as Pool 6 (below Lake Pepin). This long distance movement, contributed to rapid swings in gill-net catch rates from year to year, and indicates care must be taken when evaluating White Bass populations using Lake Pepin gill net catch rates.

The consistent Bluegill and Yellow Perch reproduction observed since 2004 should continue to provide good angling opportunities with quality-sized fish available in 2014. Three apparent strong year classes (2012-2014) of Black Crappies will enhance an already productive crappie fishery with individuals recruiting to the creel for the next four years.

Table 4 Fish Sampled In Lake Pepin for the 2014 Survey Year by MDNR.

Species	Gear used	Number of fish per net		Average fish weight (lbs)	Normal range (lbs)
		Caught	Normal range		
Black Crappie	Gill net	5.38	0.1 - 0.7	0.25	0.2 - 0.5
Blue Sucker	Gill net	0.04	N/A	6.04	N/A
Bluegill	Gill net	0.04	N/A	0.52	N/A
Bowfin (dogfish)	Gill net	0.04	0.0 - 0.1	5.96	3.0 - 4.3
Channel Catfish	Gill net	2.25	N/A	1.13	N/A
Common Carp	Gill net	0.04	0.0 - 2.3	2.68	2.3 - 10.8
Flathead Catfish	Gill net	0.25	N/A	1.82	N/A
Freshwater Drum	Gill net	9.75	0.8 - 11.9	0.36	0.4 - 0.8
Gizzard Shad	Gill net	17.29	N/A	0.13	N/A
Golden Redhorse	Gill net	0.08	N/A	3.31	N/A
Goldeye	Gill net	0.04	N/A	2.07	N/A
Lake Sturgeon	Gill net	0.12	N/A	1.20	N/A
Mooneye	Gill net	5.96	N/A	0.55	N/A
Northern Pike	Gill net	1.46	0.9 - 4.3	5.57	2.4 - 4.3
Paddlefish	Gill net	0.04	N/A	0.83	N/A
Quillback	Gill net	0.08	N/A	3.12	N/A
River Carpsucker	Gill net	0.04	N/A	0.99	N/A
Rock Bass	Gill net	0.83	0.1 - 1.1	0.34	0.3 - 0.6
Sauger	Gill net	20.50	10.2 - 18.6	0.89	0.5 - 0.6
Shorthead Redhorse	Gill net	2.67	0.1 - 0.9	1.57	0.9 - 2.5
Shovelnose Sturgeon	Gill net	0.04	N/A	1.66	N/A
Silver Chub	Gill net	0.04	N/A	0.08	N/A
Silver Redhorse	Gill net	0.54	N/A	3.64	N/A
Smallmouth Bass	Gill net	0.33	0.0 - 0.2	0.74	0.8 - 1.5
Smallmouth Buffalo	Gill net	0.08	N/A	0.10	N/A
Spotted Sucker	Gill net	0.08	N/A	3.19	N/A
Walleye	Gill net	5.33	3.3 - 14.8	1.34	0.9 - 1.5
White Bass	Gill net	4.04	3.2 - 6.3	1.01	N/A
White Crappie	Gill net	0.42	0.1 - 0.5	0.08	0.2 - 0.4
White Sucker	Gill net	1.25	0.8 - 2.4	2.28	1.6 - 2.1
Yellow Perch	Gill net	9.08	9.9 - 57.1	0.40	0.2 - 0.3

Normal ranges represent typical catches for lakes with similar physical and chemical characteristics.

Liangzi Lake

Surveys compiled by Mr. Cao Wenxuan from the Institute of Hydrobiology, Chinese Academy of Sciences, provided the basis for various research reports and other information on the fish of Liangzi Lake. Based on these reports, there were 94 fish species, belonging to 10 orders and 20 families. However, because of the separated lake and other effects, the current total fish species was more than 70 in Liangzi Lake. The fish that account for most numbers in the lake are Cyprinidae, and in terms of biomass account for 67% of the total fish numbers.

Fishing and aquaculture are important to the local economy and influences the ecology of the lake. There were numerous branches (bays) and rich resources in Liangzi Lake, which made it very suitable for development of aquaculture. At present, there are 96 fence-breeding spots, a total area of 80,593 acres, involving 318 families and 1,543 people, of which 1,296 are fishermen and 274 farmers. There are 260 motor fishing boats for aquaculture production, with a total power of 1120.6 hp.

The breeding varieties mainly are crab, with an appropriate mix of silver carp. The production of crab farming for five consecutive years was stable at 300,000 kg/a; the yield of fish is about 4,000,000 kg/a; the total output was about 21 million, accounting for about 20% of the total output value of the lake.

Shoreland and migratory bird composition

Lake Pepin

The entire reach of the Mississippi River above and below Lake Pepin supports a wide variety of birds, including numerous shorebirds and waterfowl. It is an important corridor for migrating waterfowl (over 600,000 in one day in fall 2005), particularly Canvasbacks (over 50% of North American population), Tundra Swans (over 20% of Eastern North American population), and nesting water birds (http://mn.audubon.org/minnesota-important-bird-areas). Bald Eagles routinely nest and overwinter in this area and are a common sight.

An important reason to reduce suspended sediments in Upper Lake Pepin is to allow for more macrophyte growth, which will attract more waterfowl to the area. Complete listings of all birds sighted in the Lake Pepin area is at http://mn.audubon.org/sites/default/files/documents/birdlistformat_lakepepiniba.pdf

Liangzi Lake

There were 166 kinds of birds, including 50 kinds of resident birds, accounting for 30.12%; 41 kinds of summer migrants, accounting for 24.69%; 69 kinds of winter migratory birds, accounting for 41.56%; and 6 kinds of passing migrant, accounted for 3.16%. Winter migratory birds were dominant.

Among the 91 kinds of resident birds and summer migratory birds, there were 42 species of Oriental realm, accounting for 47.25% 20 species of Palearctic realm, accounting for 21.97%; 28 species of both Oriental and Palearctic realms, accounting for 30.76%. The Oriental realm species was dominant.

Description and comparison of water quality

Monitoring approaches

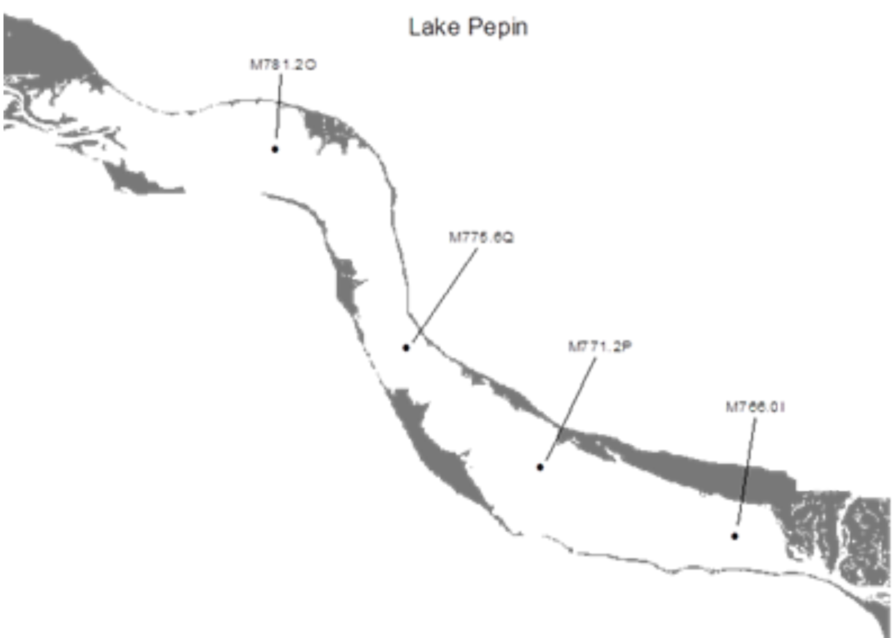
Lake Pepin

Because of its elongate morphometry and the Mississippi River being the primary driver of water quality and quantity, MPCA and MDNR established fixed sites along the length (thalweg) of the lake. These four sites (Figure 9) have been sampled long-term and provide a good basis for assessing trends over time and across different flow regimes. These sites also allow for assessment of changes in water quality from the inflow portion of the lake (Upper segment) to the outflow portion (Lower segment). Use of consistent sites was important for developing water quality models and is critical to assessing lake water quality as compared to the water quality standards.

Monitoring at these sites is part a broader partnership between the Federal government and the states that border the Mississippi River, Lake Pepin, and the navigational pools. This joint effort is referred to as the Long Term Resource Monitoring Program (LTRMP).

Minnesota conducts a majority of its lake water quality monitoring in the summer months of June through September, with collections typically once or twice per month. The emphasis on summer is two-fold, as this is the season of highest recreational use of the waters for swimming, boating and fishing and this is the time of year when pollutants like excess phosphorus and nitrogen have their greatest impact on water quality. In lakes with short water residence time, like Pepin, there are numerous flushing events over the summer period.

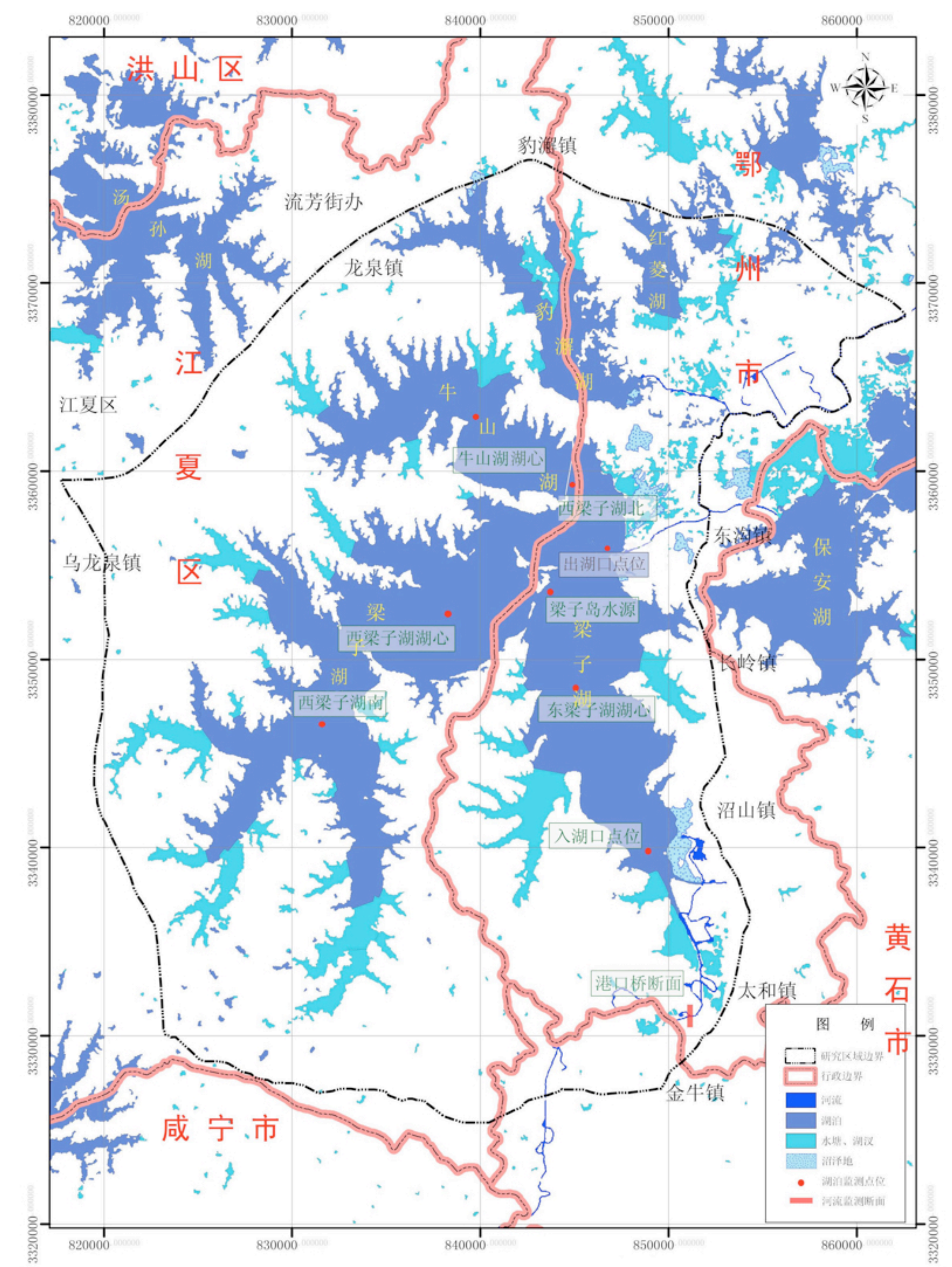
Figure 9 Lake Pepin long-term water quality monitoring sites



Liangzi Lake

Because it has numerous bays or fingers, there is a need to sample a variety of locations across Liangzi Lake to describe spatial patterns and to characterize its overall quality. The approach taken in the 2013-2015 monitoring was to sample along the length of the main bays of the lake (Figure 10). This provides a good basis for evaluating any gradients in water quality as water moves through the lake.

Figure 10 Liangzi Lake map and monitoring sites: NW bay [Niushan Lake] (1), SW bay (2), SE bay (3), center of the lake, and outlet (1).



Water use classifications and water quality standards

Minnesota, USA

The basis for judging or assessing the quality (condition) of waters varies according to national, state, or provincial approaches. In the U.S., water quality standards (WQS) are developed in support of the Federal Clean Water Act (CWA) and are often the primary basis for assessing the condition of waters.

Numeric and narrative standards provide a basis for determining if a lake or river meets its designated uses and are the basis for the CWA 303(d) "impaired waters" assessments. WQS are developed by the USEPA or by the states. When states develop WQS, the standards are often based on USEPA guidance and generally require USEPA approval after they have become successfully promulgated (placed in rule) at the state level. Minnesota's lake nutrient WQS (lake eutrophication standard) is one such example (Heiskary and Wilson 2008) and is considered an aquatic recreation-based standard.

Use classifications are an integral part of Minnesota's water quality standards. A general description, as drawn from MN Rule Ch 7050.0140, follows.

- **Class 1 waters,** domestic consumption. This includes all waters that are or may be used as a source of drinking water.
- **Class 2 waters,** aquatic life, and recreation. This includes all waters that support or may support fish, other aquatic life, bathing, boating, or other recreational purposes. Most of Minnesota's natural lakes and rivers have this class designation.
- **Class 3 waters**, industrial consumption. Includes all waters that are or may be used as a source of supply for industrial process or cooling waters.
- **Class 4 waters**, agriculture, and wildlife. Includes all waters that are or may be used for any agricultural purposes.
- **Class 5 waters**, aesthetic enjoyment, and navigation. Includes all waters that are or may be used for any form of water transportation
- **Class 6 waters**, other uses, and protection of border waters. Includes all waters that serve the purposes of Classes 1-5 and where there is a need to conform with requirements of any other state, province, or nation.
- **Class 7 waters**, limited resources value waters. Include waters that have been subject to use attainability analysis and found to have limited value as a water resource.

All surface waters are protected for multiple uses, and specific numeric WQS are developed to protect those uses. Water quality standards may apply to broad classes and uses of waters. For example, Minnesota's 5 mg/L dissolved oxygen (DO) standard, as a minimum to support aquatic life, is applied broadly to all Class 2B waters (Minn. Rule Ch 7050). Class 2b includes a majority of Minnesota's rivers and lakes. Minnesota also employs site-specific standards. This type of WQS considers specific characteristics of a waterbody, which may make it distinctly separate from other waterbodies in its class.

Hubei, China

China assigns waters to various classes and then uses the "class" as a basis for describing water quality. As drawn from MEP (2002), "The water bodies are divided into five classes according to the utilization purposes and protection objectives."

- **Class I** is mainly applicable to the water from sources, and the national nature reserves.
- **Class II** is mainly applicable to first class of protected areas for centralized sources of drinking water, the protected areas for rare fishes, and the spawning fields of fishes and shrimps.
- **Class III** is mainly applicable to second class of protected areas for centralized sources of drinking water, protected areas for the common fishes, and swimming areas.
- **Class IV** is mainly applicable to the water areas for industrial use and entertainment, which is not directly touched by human bodies.
- **Class V** is mainly applicable to the water bodies for agricultural use and landscape requirement."

Standards are developed in support of each class and they specify the water quality items, standard values, water quality evaluation, and analysis method of the water quality items. They also address implementation and supervision of standard, based on the five applicable functions for surface water. Examples of standards that are relevant to Liangzi Lake are included in Table 5.

If we compare China's classes with those used in Minnesota's rule (MN Rule Ch 7050.0140) the following similarities are apparent:

- Class I is similar to Minnesota's Outstanding Value Water Resources (ORVW).
- Class II is similar to Class 1 (drinking water) and Class 2A for support of coldwater fish.
- Class III is most comparable to Class 2B, which supports both aquatic recreation and aquatic life. Lake Pepin is a 2B water.

Table 5 Standard values of basic water quality variables (Index) in China's environmental quality standard for surface water (mg/L) (from Ban et al. 2014)

Index	Class I	Class II	Class III	Class IV	Class V
DO	7.5	6.0	5.0	3.0	2.0
COD_{Mn}	2.0	4.0	6.0	10.0	15.0
NH3-N	0.15	0.50	1.00	1.50	2.00
TP	0.010	0.025	0.050	0.100	0.200
TN	0.20	0.50	1.00	1.50	2.00

Water quality assessment

Lake Pepin

Lake Pepin was listed as "impaired for nutrients" in Minnesota's 2002 CWA 303(d) assessment, based on the narrative WQS in place at that time. That listing required development of a total maximum daily load (TMDL) for phosphorus to determine the magnitude of phosphorus reductions needed to bring it in compliance with the standard.

As a part of the TMDL process, a science advisory panel (SAP) was convened to help develop and review the science and policies associated with the TMDL development. While Minnesota had developed lake eutrophication standards in 2008 (Heiskary and Wilson 2008) and river eutrophication standards were under development (Heiskary and Bouchard 2014), Lake Pepin was deemed to be somewhat intermediate between a lake and a river. As such, the SAP agreed that site-specific eutrophication standards would be appropriate for the lake.

Heiskary and Wasley (2011) describe the process that was used and the multiple lines of evidence including monitoring, modeling, and lake-sediment core reconstruction to arrive at site specific standards of TP - 100 µg/L (ppb) and chlorophyll-a - 28 µg/L (MN Rule Ch7050.0222). This WQS is intended to ensure Pepin is suitable for contact recreation and that nuisance algal blooms are kept to a minimum. These site-specific numeric standards were included in the WQS rulemaking for the river eutrophication WQS and were formally promulgated in Minnesota's Rule Ch 7050 in 2014 (https://www.revisor.leg.state.mn.us/rules/?id=7050).

The development of the Lake Pepin excess nutrient TMDL is well underway. A mechanistic model framework was developed by Limno Tech Inc. that provides various scenarios for phosphorus reductions and the predicted in-lake response to those reductions (Limno Tech 2008). These scenarios help guide development of the TMDL.

Another WQS that has great relevance to the health of Lake Pepin is the site-specific total suspended solids (TSS) standard. This WQS was established specifically for the Mississippi River from Pool 2 (Metro Area in Figure 2) through Lake Pepin. A primary focus of this WQS was to improve transparency to allow for submerged aquatic vegetation (SAV) growth, which serves to stabilize sediments and provide valuable food and habitat for waterfowl and fish. Technical justification of the WQS may be found at http://www.pca.state.mn.us/index.php/view-document.html?gid=10530. Based on multiple lines of evidence, it was found that a summer average TSS of 32 mg/L, for this reach (Pool 2 through Lake Pepin), would allow for significant expansion of SAV across shallower portions of Pool 2 and the Upper segment of Lake Pepin.

LTRMP provides an excellent source of data for assessing current and past water quality conditions in Lake Pepin. This program was initiated in 1993 and summer-mean data from 1993-2014 is used to describe status and trends for Lake Pepin. We focus on those parameters directly associated with the nutrient and sediment impairments in Lake Pepin: total phosphorus (TP), chlorophyll-a (Chl-a), and total suspended solids (TSS).

Mean TP ranged from 150-200 ppb during most summers and averaged 160 ppb over this record (Figure 12). Since 2009, mean TP has declined below 150 ppb; however, values remain above the 100 ppb WQS. TP varies somewhat from the inflow of the lake (Mile 781) to the outflow of the lake (Mile 766). Early in this record (1993-2005), Upper segment TP was higher than Lower segment TP (Figure 13); however, since 2006, Lower segment TP has been higher than Upper segment TP. The decrease in Upper segment TP relates to reductions in P loading from upstream wastewater treatment facilities (described further in following section); however, internal recycling of soluble ortho phosphorus from the sediment, in the Lower segment, contributes to the elevated TP at Mile 766 (Figure 13).

Chlorophyll-a (Chl-a) provides a measure of algal biomass and is an important and routinely measured parameter for assessing lakes in Minnesota. While in most cases Chl-a can be estimated simply based on TP (e.g., Carlson 1977, Heiskary and Wilson 2008), in Lake Pepin we have found that Chl-a varies not only as a function of TP but also water residence time and to some degree, inorganic turbidity (Heiskary and Walker 1995).

Data from the most recent ten-year period is routinely used to assess lake condition relative to WQS (28 ppb Chl-a for Lake Pepin) and summer-mean data are represented in Figure 14. Chl-a is typically highest in years of lower flow when water residence time is longer and suspended sediment (turbidity) is often lower. For example, high Chl-a was noted in 2006-2009 during years of low flow (Figure 5), in contrast to 2010, 2011, and 2014 when flow was high.

Chl-a varies somewhat from the inflow (M781) to the outlet (M766) of Lake Pepin (Figure 15); however the pattern is not consistent from year to year. During the low flow years of 2006-2009 Chl-a remained relatively high and consistent across the lake, in contrast to higher flow summers like 2010-2014 when Chl-a declines in the Lower segment. Because Lake Pepin residence time is relatively short during most summers, algal production in the Mississippi River is a large source of the measured Chl-a in the Upper segment. As water flows to the deeper Lower segment, much of this algae sediments to the bottom of the lake, in particular during years of high flow (low residence time).

Total suspended solids (TSS) concentrations are highest at the inflow of the lake and decline over the length of the lake (Figure 16). In most summers, TSS averages 15-20 ppm in the Upper segment and declines to 8-10 ppm near the outlet of the lake. TSS in the Mississippi River upstream of Lake Pepin (M786, 5 miles (8 km) upstream of Lake Pepin) is high, averaging 35 ppm in the most recent 10-year period, and is above the 32 ppm WQS in most summers (Figure 16). This excessive loading of suspended sediment contributes to the infilling of Lake Pepin, limits light which in turn limits the growth of rooted macrophytes, and serves as an important source of phosphorus to the lake as well.

Figure 11 Lake Pepin percent frequency of macrophytes for Upper and Lower lake. Data supplied by Megan Moore, MN Department of Natural Resources (UMRR-LTRM).

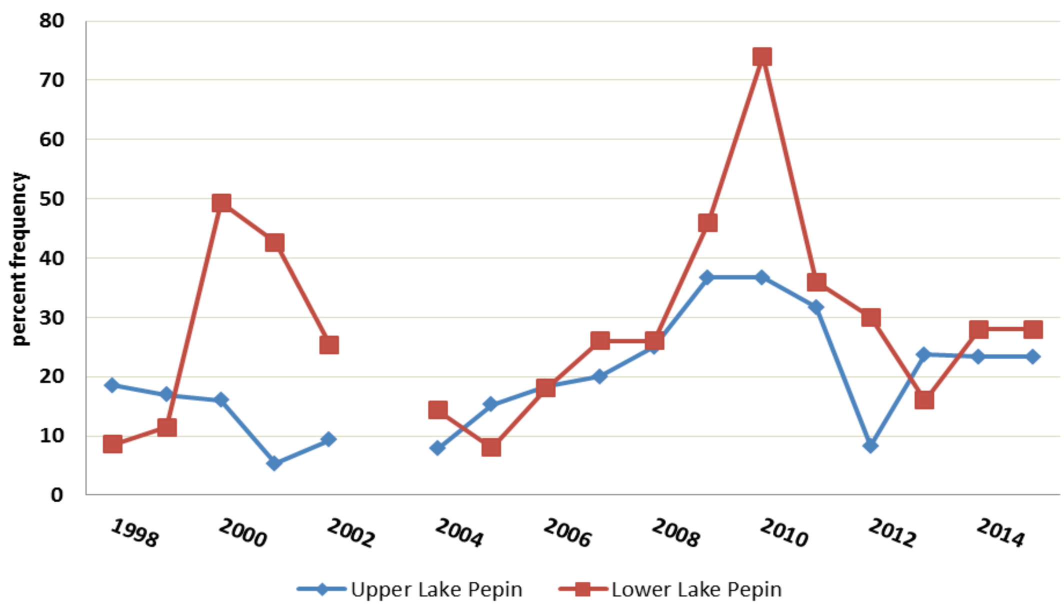


Figure 12 Lake Pepin TP trends over time: a) Summer-mean ±SE for 4 stations on Pepin. Data from LTRMP. Red line = long-term mean of 160 ppb.

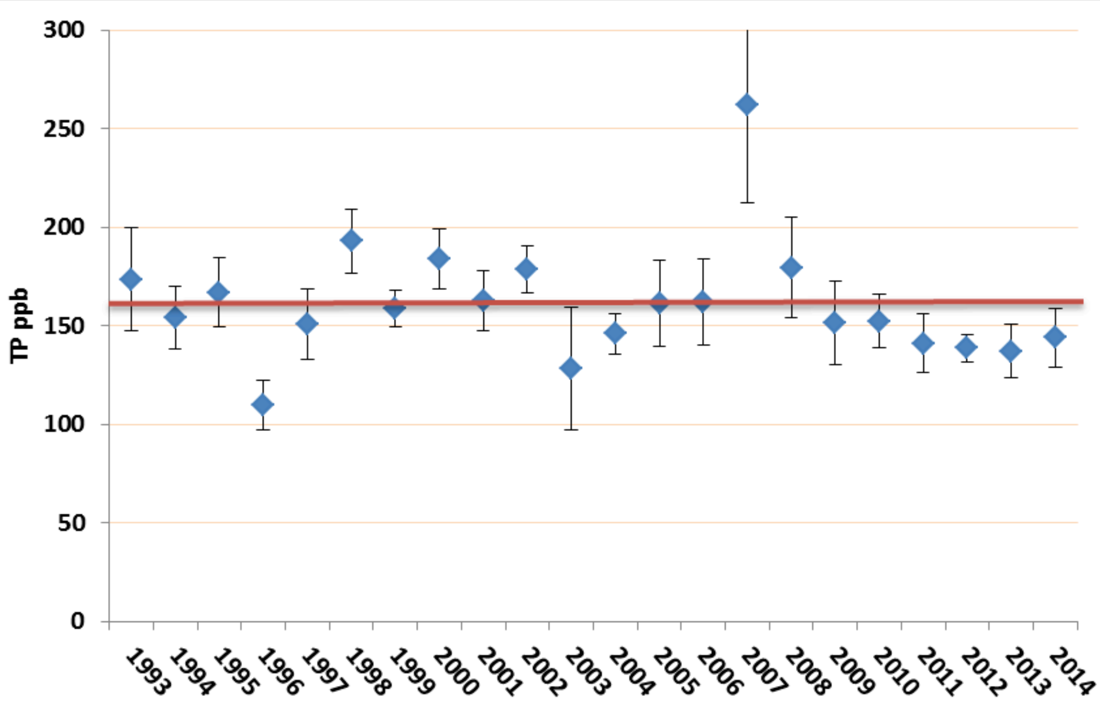


Figure 13 Summer-mean total phosphorus for inflow site (Mile 781 Upper Segment) and outflow site Mile 766 (Lower Segment).

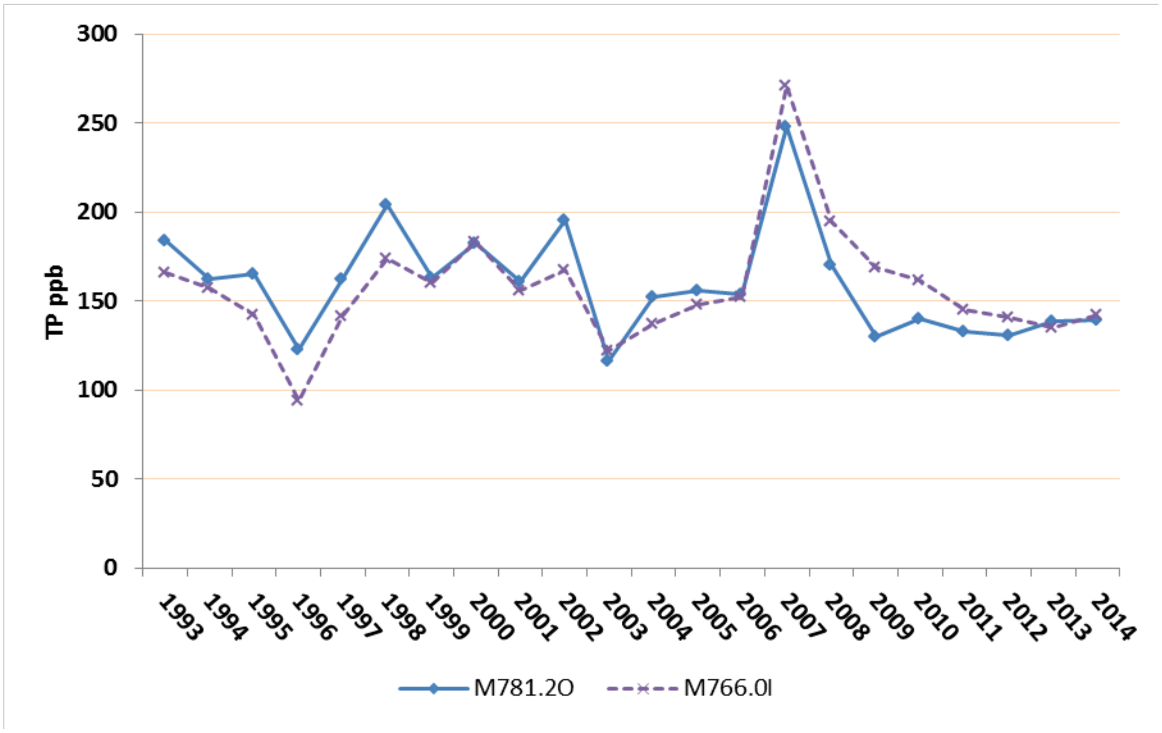


Figure 14 Lake Pepin Summer-mean Chl-a for 2005-2014 and 10-year mean. Site-specific Chl-a WQS noted with red line.

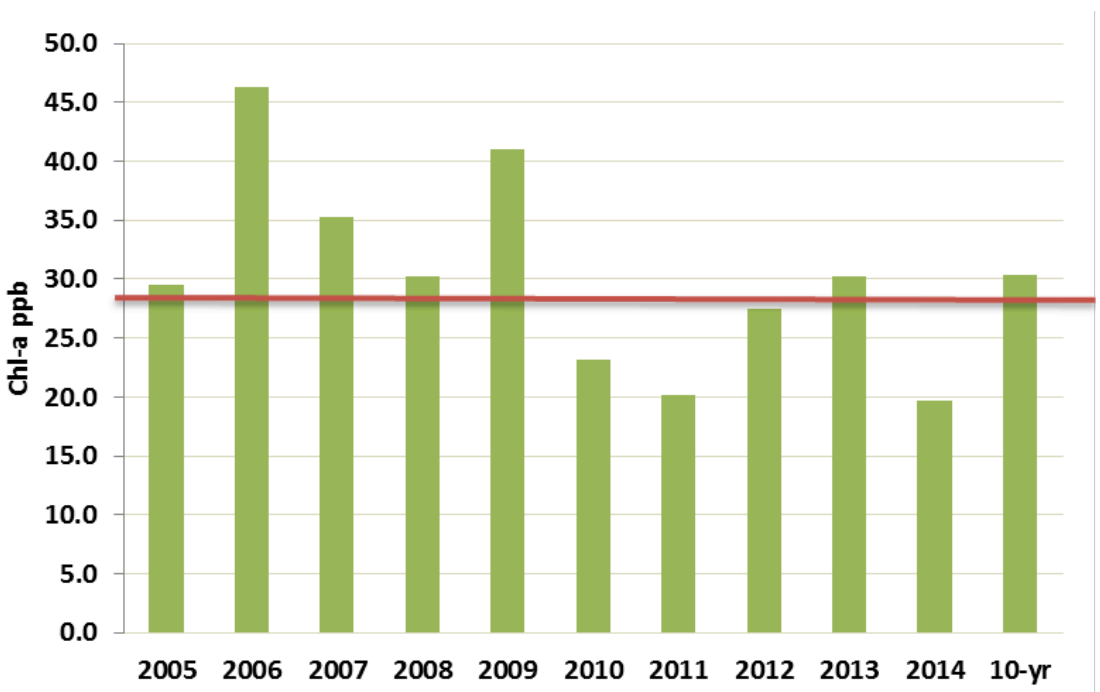


Figure 15 Lake Pepin Summer-mean Chl-a by Site. M781 (inflow) through M766 (outlet).

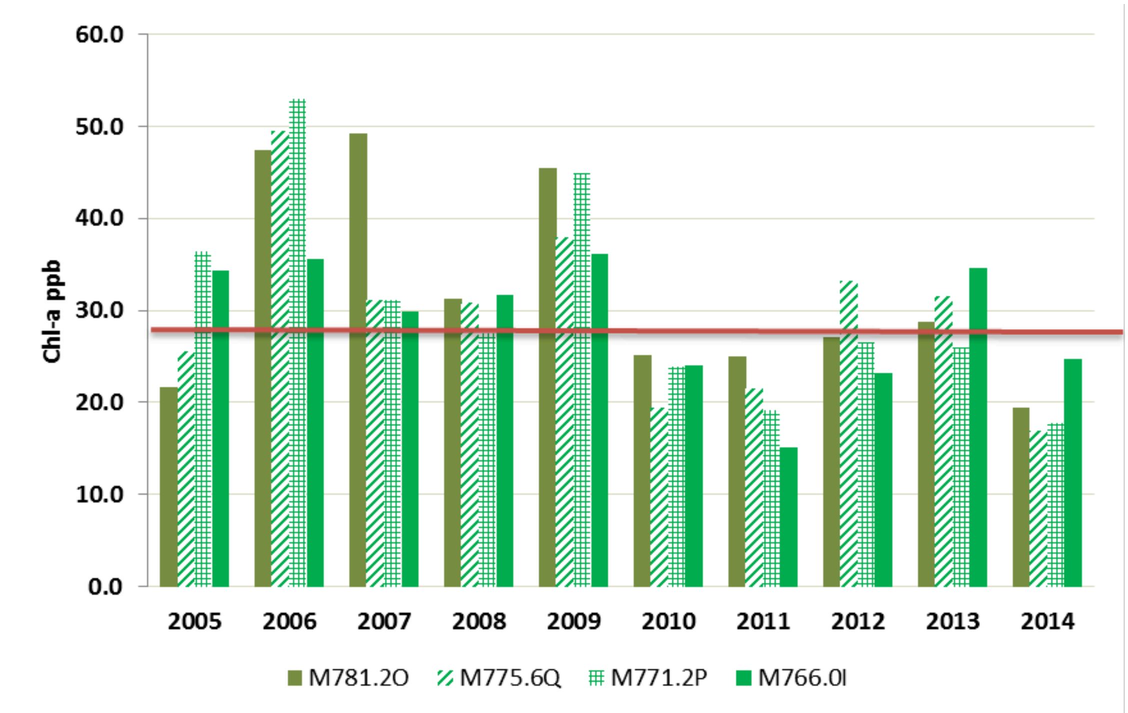
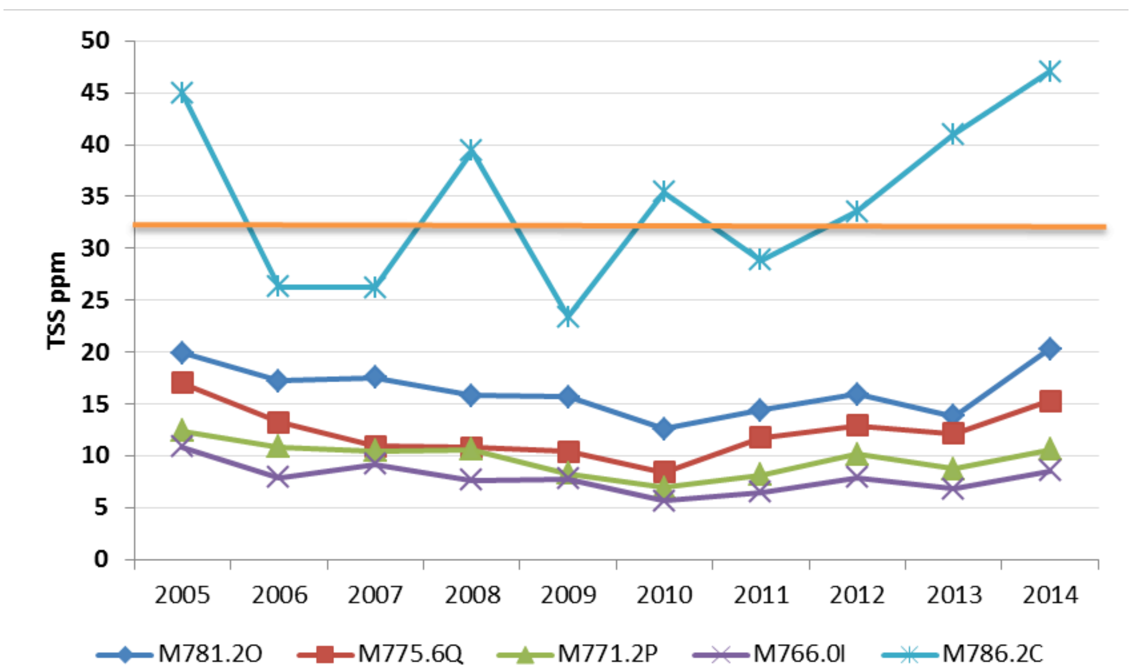


Figure 16 Lake Pepin (sites M781-M766) and Mississippi River (M786) total suspended solids. Summer average values from LTRMP. Site specific WQS of 32 mg/L represented by solid line.



Liangzi Lake

A basic description of the water quality of Liangzi Lake, based on monitoring from 2013-2015, precedes a discussion based on classes. An overall summary of data is compiled in Table 6.

The 2013 TP and TN data are used to demonstrate spatial and seasonal patterns for Liangzi Lake (Figure 17). In general, TP is relatively low in Liangzi Lake with most measurements between 0.010-0.03 ppm (mg/L) [*note many of the previously noted concentrations for Lake Pepin were in ppb or µg/L; 1,000 ppb=1ppm*]. The southeast bay (East Liangzi Lake inflow) exhibits a slight increase in TP from March through June, but remains low thereafter. The west bay (North and South mouth in West Liangzi Lake) exhibits a lesser increase over this period and likewise is rather stable from June through December. TN is rather low as well, and there are no strong seasonal patterns (Figure 17); however, TN is higher in East Liangzi Lake as compared to West Liangzi Lake.

In the summer, the water quality of Liangzi Lake maintained in Class III in general, partly Class IV. Class IV water was mainly distributed around Laowuxia of Niushan Lake west, Tuditang Lake of West Liangzi Lake, Manjiang Lake of East Liangzi Lake, and east area of Gaotang Lake. Class V and worse than Class V water was mainly distributed in the west area by the Niushan Lake Dam (Figure 10) and around Limujiang area of West Liangzi Lake. Class II water mainly distributed in the Zhangqiao Lake and the south area of Shanpo Lake in West Liangzi Lake.

The lake outlet site (Figure 10) represents the cumulative or overall condition of Liangzi Lake and provides a good basis for comparing among years (Figure 18). TP is rather consistent among years and most measures range between 0.015-0.025 ppm. No consistent seasonal pattern was evident. TN is very consistent across seasons and years, and averaged about 0.44 ppm over this three-year record (Table 6). COD_{Cr} averaged about 12 ppm at the outlet and exhibited minimal variability (Figure 18). BOD_5 varied somewhat among the three years; however, there was not a distinct seasonal pattern.

A discussion based on class provides further perspective. In the fall, the water quality of Liangzi Lake was generally in Class III (accounting for 75% by area); the second was Class II (accounting for 25% of the lake). Class III water was mainly distributed in Niushan Lake and East Liangzi Lake, Class II water was mainly distributed in the West Liangzi Lake.

In the winter, the water quality of Liangzi Lake in general was in Class IV (accounting for the 70%), the second was Class III (accounting for 27%), and the remainder Class V. Class III water was mainly in Qianjiang Lake, Tuditang Lake, and Shandi Lake of West Liangzi Lake. The Class V water was mainly in south Zhangqiao Lake of West Liangzi Lake and the southwest corner in Gaotang Lake of East Liangzi Lake.

In the spring, the water quality of Liangzi Lake, in general, was in Class III, the second was Class II, and Class IV, occasionally Class V. The Class IV water was mainly in Niushan Lake West (Fu Jiaju, Da Wu Chen, and Xibianfang), the center in Houhai Lake of East Liangzi Lake and around Taihe River of Gaotang Lake. The Class V water was primarily in the east area of Niushan Lake Dam and the center of Manjiang Lake, and around Shujiaya in Zhangqiao Lake of West Liangzi Lake.

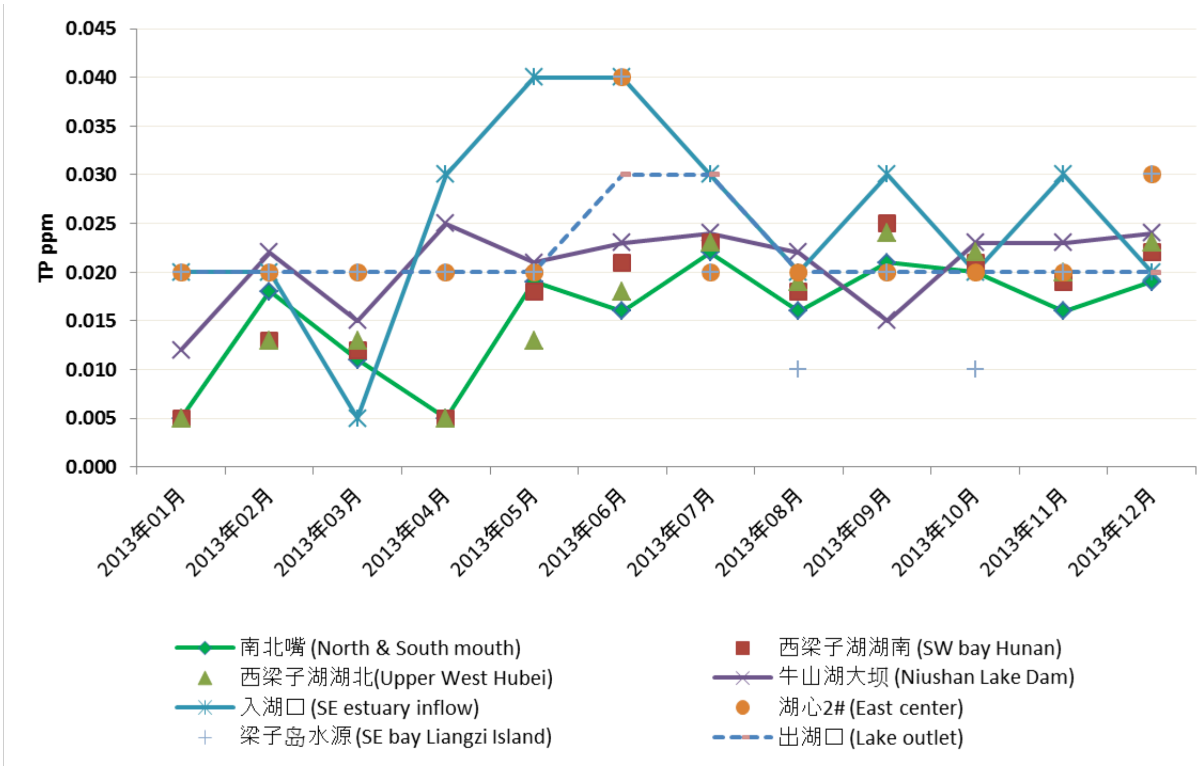
There are more than 30 rivers flowing into Liangzi Lake. The main rivers are Gaoqiao River, Jinniu River, and Chaoying River to name a few. Gaoqiao River was 64.4 kilometers in length; its watershed area was 893 square kilometers, accounting for half of Liangzi Lake's watershed area, its flow accounted for more than 50% of the water flowing into lake. Two monitoring sections were set in Gaoqiao River, the annual average of these two sections in 2015 showed pH of 7.83, DO of 9.1 mg/L, COD of 12.1 mg/L, BOD_5 of 2.3 mg/L, NH_3-N of 0.28 mg/L, TP of 0.07 mg/L, which indicated that the water quality was Class II.

In July and October, the water quality of most of the inflowing rivers was Class III and the remainder Class IV. In December, the water quality was generally Class V or worse, the remainder Class V. In March, the water quality was Class V or worse, the second was Class V. In October, the water quality of 54% rivers into the lake was good, higher than 11%, 46%, and 54% of July, December, and March respectively. In December, the water quality of 85% rivers into the lake was bad, higher than 51%, 69%, and 3% of July, October, and March respectively. In general, the water quality of many of the inflowing rivers was good in autumn and poor in winter and spring.

Table 6 Liangzi Lake water quality summary for 2013-2015 (units are ppm [mg/L])

Sites	2013	COD_{Mn}	COD_{Cr}	BOD_5	NH_4-N	TP	TN
南北嘴 (N & S mouth)		2.8	11.5	1.5	0.158	0.016	0.334
西梁子湖湖南 (SW bay Hunan)		2.9	12.1	1.6	0.169	0.017	0.360
西梁子湖湖北 (Upper W Hubei)		2.9	11.9	1.6	0.165	0.016	0.354
牛山湖大坝 (Niushan Lake)		3.4	13.7	1.9	0.209	0.021	0.401
入湖口 (SE inflow)		3.1	12.3	1.4	0.217	0.025	0.466
湖心 2# (East center)		2.7	11.5	1.4	0.201	0.022	0.438
梁子岛水源 (SE bay Liangzi I)		2.8	11.2	1.5	0.204	0.021	0.446
出湖口 (Lake outlet)		3.0	11.9	1.4	0.208	0.022	0.448
	mean	3.0	12.0	1.5	0.192	0.020	0.406
	max	3.4	13.7	1.9	0.217	0.025	0.466
	min	2.7	11.2	1.4	0.158	0.016	0.334
	2014	COD_{Mn}	COD_{Cr}	BOD_5	NH_4-N	TP	TN
南北嘴 (N & S mouth)		2.8	10.2	1.3	0.204	0.017	0.382
西梁子湖湖南 (SW bay Hunan)		2.9	11.1	1.4	0.211	0.019	0.397
西梁子湖湖北 (Upper W Hubei)		2.9	11.1	1.4	0.211	0.019	0.422
牛山湖大坝 (Niushan Lake)		3.4	14.0	1.8	0.305	0.022	0.460
入湖口 (SE inflow)		3.1	12.3	1.4	0.211	0.022	0.439
湖心 2# (East center)		2.9	11.8	1.2	0.196	0.020	0.432
梁子岛水源 (SE bay Liangzi I)		2.9	11.5	1.3	0.197	0.020	0.441
出湖口 (Lake outlet)		3.1	12.4	1.3	0.203	0.020	0.439
	mean	3.0	11.8	1.4	0.217	0.020	0.427
	max	3.4	14.0	1.8	0.305	0.022	0.460
	min	2.8	10.2	1.2	0.196	0.017	0.382
	2015	COD_{Mn}	COD_{Cr}	BOD_5	NH_4-N	TP	TN
南北嘴 (N & S mouth)		3.7	12.6	1.0	0.302	0.027	0.510
西梁子湖湖南 (SW bay Hunan)		3.5	11.7	0.9	0.310	0.026	0.508
西梁子湖湖北 (Upper W Hubei)		3.5	12.1	0.9	0.290	0.026	0.500
牛山湖大坝 (Niushan Lake)		3.6	12.5	0.8	0.304	0.027	0.504
入湖口 (SE inflow)		3.1	12.3	1.7	0.167	0.021	0.405
湖心 2# (East center)		3.6	14.6	2.3	0.236	0.024	0.479
梁子岛水源 (SE bay Liangzi I)		3.2	12.6	1.8	0.181	0.022	0.434
出湖口 (Lake outlet)		3.2	12.5	1.7	0.180	0.023	0.438
	mean	3.4	12.6	1.4	0.246	0.025	0.472
	max	3.7	14.6	2.3	0.310	0.027	0.510
	min	3.1	11.7	0.8	0.167	0.021	0.405

Figure 17 Liangzi Lake 2013 total phosphorus and total nitrogen spatial and seasonal (January through December) trends.



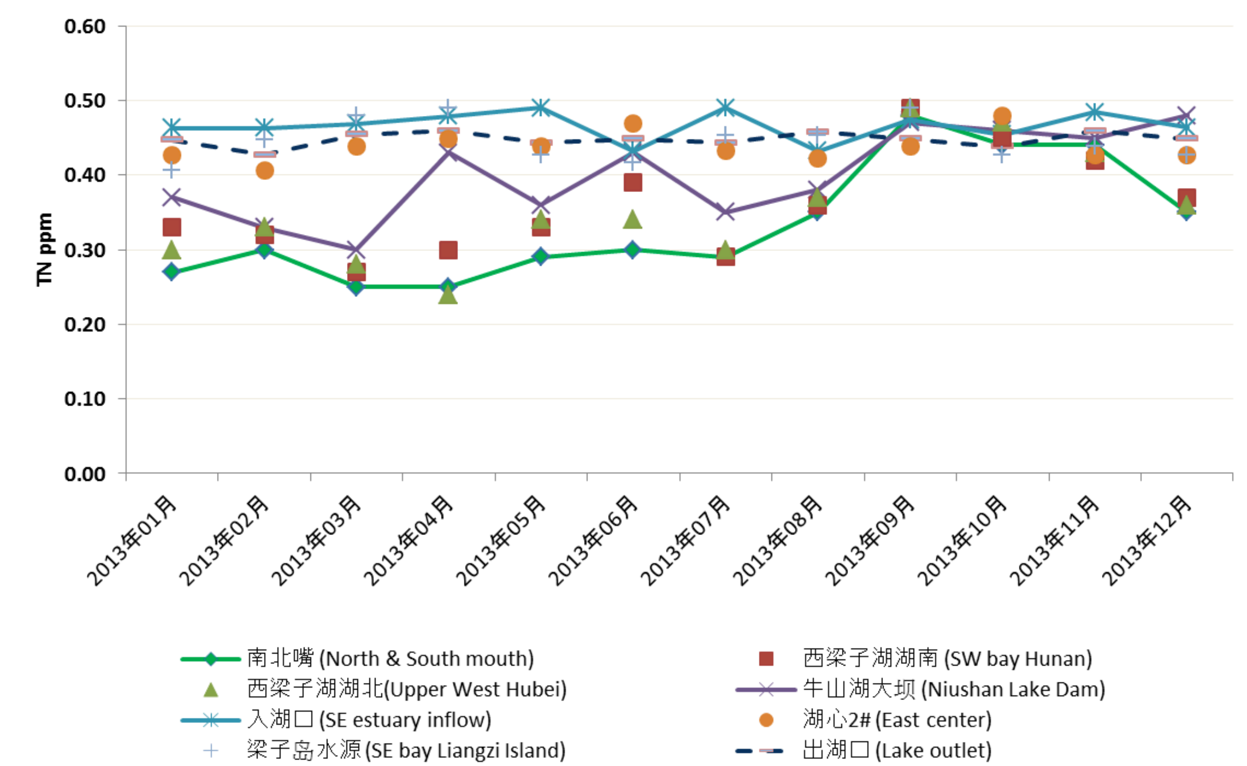
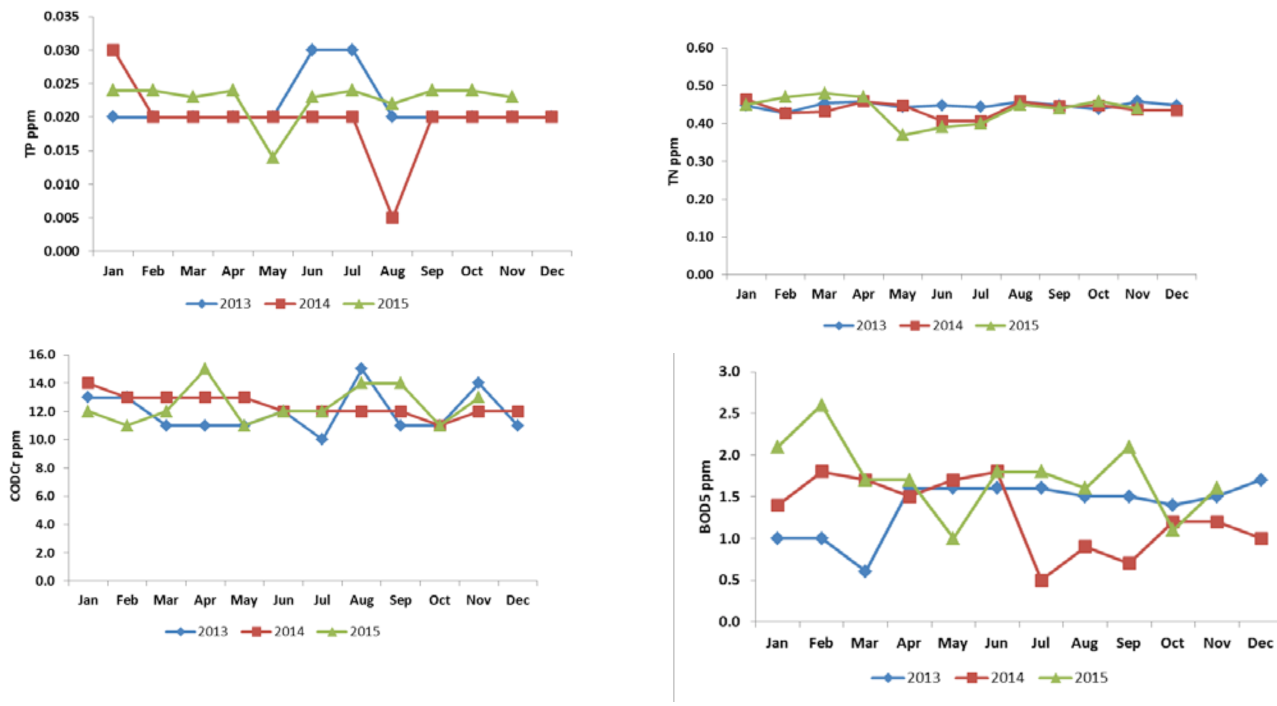


Figure 18 Liangzi Lake 2013-2015 outlet TP, TN, COD_{Cr}, and BOD_5 monthly measurements.



Water pollution concerns and reduction strategies

Both lakes have a wide range of land uses and point sources that contribute to the pollution of the lakes. Various forms of agricultural land uses are common in both watersheds (Table 3). Agricultural land uses (e.g., cultivated land, paddies, or gardens) all have the potential to export excess nutrients, specifically phosphorus and nitrogen, which can contribute to the eutrophication (nutrient overenrichment) of lakes. In addition, it is common to have excess amounts of suspended sediment in runoff from this type of land use.

Watersheds for both lakes also have numerous cities, with homes, industry, buildings, and extensive road networks and parking areas. These impervious surfaces allow for excessive runoff and transport of pollutants to the rivers that drain these landscapes and that eventually flow to Liangzi Lake and Lake Pepin. In addition, wastewater treatment facilities contribute nutrients as well.

Lake Pepin Basin

Both point and nonpoint sources of pollution contribute to the impairment of Lake Pepin's water quality. Point sources refer to a specific discharge point, such as a pipe, and are often regulated through water quality permits. Nonpoint sources refer to overland runoff, erosion, streambank sloughing, and various sources that are typically not regulated.

Phosphorus is the primary pollutant associated with the eutrophication of surface waters in Minnesota. Four principal external sources of phosphorus in Lake Pepin include the Upper Mississippi, St. Croix and Minnesota rivers as well as the Twin Cities Metropolitan Area (Figure 2). In addition to these external sources, internal recycling of phosphorus from lake sediments is a significant source as well.

The Minnesota River contributes 75% or more of the suspended sediment that enters Lake Pepin (Gunderson et al. 2015). Primary sources of TSS in the Minnesota River Basin include overland runoff from cultivated fields, ravine erosion, and streambank sloughing. The suspended sediment also provides a significant source of plant nutrients. At low flow, the nutrients accelerate phytoplankton (algae) growth. At higher flows, suspended sediment is a major cause of turbidity. The fine particles suspended in the water settle out in the Upper segment of the lake and represent a third problem for Lake Pepin – an accelerated infilling of the lake. Studies of Lake Pepin sediment cores have shown that, at current sedimentation rates, the Upper segment of Lake Pepin will fill in within 100 years and the lower portion will disappear within 340 years. Once the lake disappears, its function as a protector of downstream water quality will disappear as well.

Point source dischargers (e.g. municipal wastewater facilities [WWTF]) require National Pollutant Discharge Elimination System (NPDES) permits to discharge to public waters. Many NPDES permits in Minnesota include limitations on the amount of phosphorus discharged to surface waters. This is particularly true for WWTF that discharge to or are upstream of nutrient impaired lakes or rivers. There are numerous WWTF in the Lake Pepin watershed (Figure 19). As their NPDES permits are renewed, most are required to treat for phosphorus. Phosphorus effluent limits of 1 ppm or less are increasingly common throughout the Lake Pepin watershed. Significant reduction in P loading to Lake Pepin has occurred because of this.

Very significant TP reductions have been made at the WWTFs in and near the Twin Cities Metropolitan area (Figure 20). The largest reduction was at the MCES Metro Plant, which treats about one-half of the entire volume of wastewater in Minnesota. The reductions from that WWTF, alone, have been tremendous and account for much of the reduction in point source P loading to Lake Pepin. From ~2000-2011, effluent P concentrations at the Metro Plant were reduced from about 3.0 ppm to less than 0.3 ppm. Further reductions are ongoing at many of these facilities.

Figure 19 NPDES wastewater discharges in the Lake Pepin watershed and annual phosphorus loading from municipal and industrial dischargers.

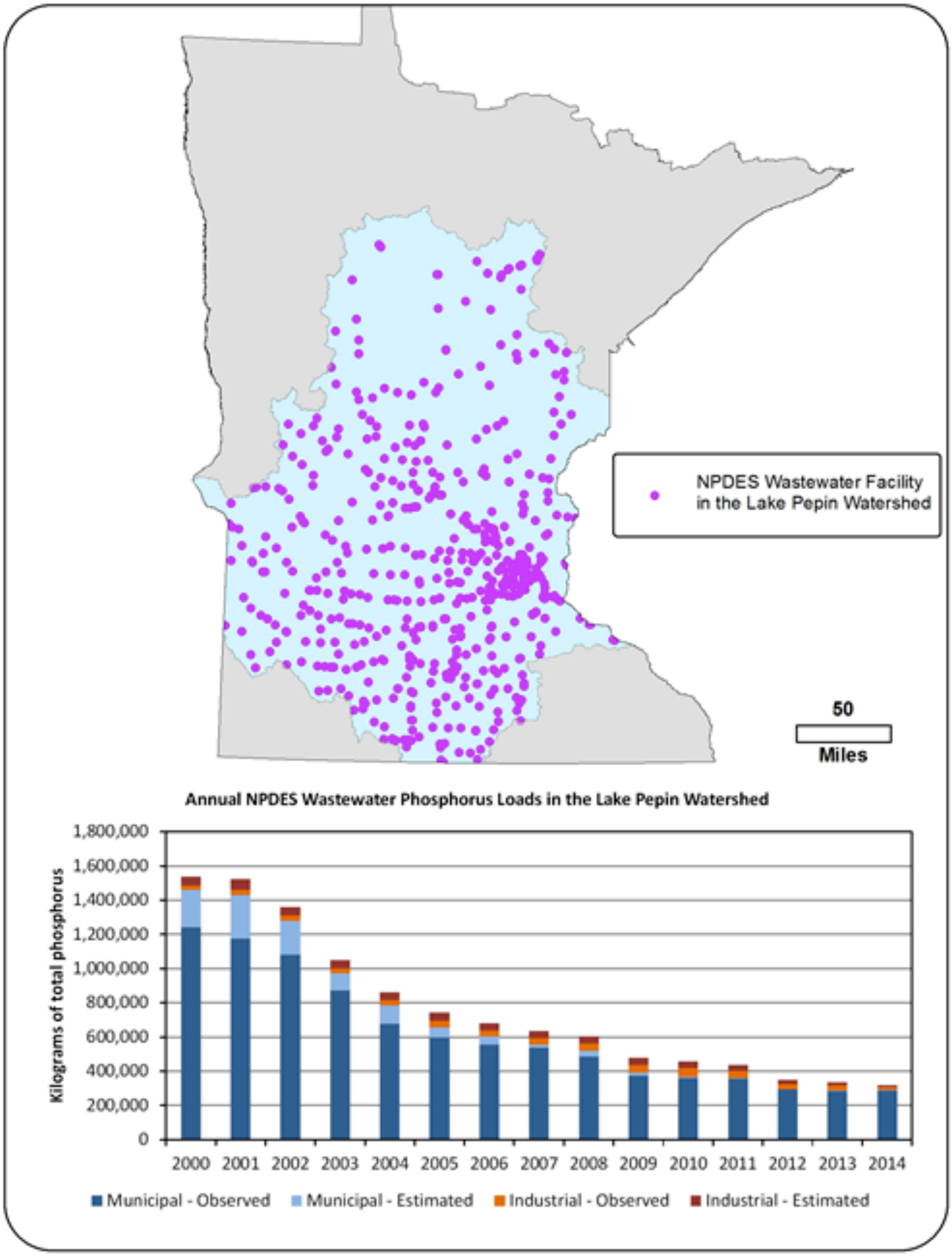
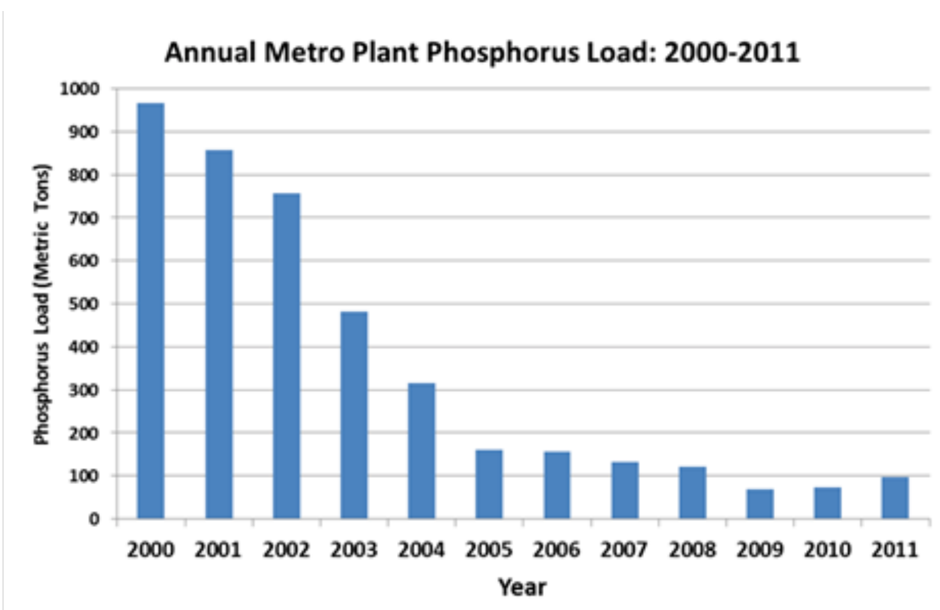


Figure 20 Major wastewater treatment facilities (WWTF) in and near the Twin Cities Metropolitan Area that discharge to rivers that eventually flow to Lake Pepin (a). The MCES Metro Plant is the largest WWTF in Minnesota at 250 MGD design flow and ~190 MGD average daily discharge. Phosphorus load reductions from 2000-2011 noted (b).

a)

b)



Liangzi Lake Basin

The annual COD emission of 19 villages in Liangzi Lake Basin was 12,380.34 tons, total nitrogen was 2,029.77 tons, and total phosphorus was 414.57 tons.

The COD, total phosphorus, total nitrogen emissions of Jiangxia District were the largest; pollutant load sharing rate were 40.29%, 41.50% and 39.45% respectively. The COD, total phosphorus, total nitrogen emissions of Xian'an District was the second; pollutant load sharing rate were 32.15%, 30.80%, and 30.93% respectively.

There are several sources of phosphorus loading to Liangzi Lake. Based on source category, total phosphorus emissions from the livestock industry were the largest, accounting for 52.62%, followed by urban sewage at 25.80%. Total nitrogen emissions was dominated by livestock and poultry breeding, with 34.14% of the TN load, followed by agricultural non-point source pollutant loading at 33.19%. COD emission was dominated by urban domestic sewage at a rate of 43.19% of the total load.

Discussion

Lake Pepin and Liangzi Lake are both very important resources and are highly valued by local communities and the broader state or provincial governments. There are numerous differences between these two lakes, which influence how water quality and ecological monitoring is conducted and how data is assessed. Approaches vary in part, because of distinct morphometric and watershed differences between the lakes, as well as differences in how Minnesota and Hubei Province conduct this type of work. A brief comparison follows.

Lake Pepin is a large mainstem lake on the Mississippi River. As such, it has a very large watershed and a huge watershed to lake ratio, as compared to Liangzi Lake (Table 1). This results in high water, phosphorus, and sediment loading from its watershed, with the Mississippi River serving as the primary inflow to the system. This also means that reliable estimates of flow, nutrient, and sediment loading may be obtained by monitoring the Mississippi River upstream of Lake Pepin. The high watershed to lake ratio also results in very short water residence time. Consideration must also be given to high flow versus low flow years and their impact on pollutant loading, processing (sedimentation and algal uptake), and in-lake response. Given its linear configuration, water quality monitoring sites were established along the thalweg of the lake, which provides a basis for assessing in-lake processing of nutrients and sediment as water moves through the lake. Algal production varies as well across this gradient.

Liangzi Lake in contrast, has a small watershed relative to its surface area and a longer water residence time (Table 1). However, Liangzi has numerous branches or bays where water quality may vary. These small branches feed into three large bays: southeast, southwest, and northwest that flow toward the outlet in the northeast corner of the lake. As such, sample sites were arrayed along the length of each to allow for accurate characterization of the water quality of each and the overall lake. In addition, there are numerous tributaries, which can make it challenging to obtain accurate estimates of water and nutrient loading (as compared to Lake Pepin with one major inflow).

Climatic differences are significant as well. The climate of the Liangzi Lake watershed is more similar to that found in far southeastern U.S. (Figure 1), with much warmer temperatures and higher rainfall as compared to Lake Pepin with cooler temperatures, less precipitation, and distinct seasons (Table 2). Minnesota conducts most eutrophication-related water quality monitoring in the summer months of June-September because this is the time of greatest recreational use of lakes and the response of algae and plants to excess nutrients is most pronounced (e.g. production of harmful algal blooms). In a warmer climate, like that of Liangzi Lake, it is important to monitor the lake throughout the year.

It is difficult to make direct comparisons of the water quality of Lake Pepin and Liangzi Lake because water quality monitoring programs and parameters measured vary between the two lakes (

Table 7). Based on the parameters both lakes had in common, it appears that nutrient concentrations (TP and TN) are higher in Lake Pepin as compared to Liangzi Lake. This makes sense given that Lake Pepin's watershed is much larger than that of Liangzi Lake and Liangzi Lake's volume is greater (Table 1).

In the U.S. (Minnesota), designated uses and WQS are important drivers of monitoring and assessment efforts. In Minnesota, WQS are developed specific to the designated use classes. China (Hubei) also has defined classes for its waters, which are intended to protect specific uses of those waters and they have developed standards for that purpose. Some relevant parallels between the two "use" class approaches were noted.

Site-specific standards are developed in the U.S. (Minnesota) when a waterbody is unique or there are factors that may make the exising WQS not applicable to the waterbody in question. That was the case for Lake Pepin, which is intermediate between free-flowing rivers and lakes. The site-specific WQS and guidance associated with its implementation dictates the number of samples, location, timing, and type of sampling that is required to determine if Lake Pepin meets the WQS.

In Minnesota, water quality data are summarized, as required in guidance associated with the WQS, and compared to the WQS to determine if the water complies with the WQS. Waters that do not meet standards are designated as "impaired" on Minnesota's CWA 303(d) list. As a part of the 303(d) listing, TMDLs are required for these waters to determine the pollutant reductions needed to bring the water into compliance. This step is now underway for Lake Pepin.

Lake Pepin has numerous WWTF discharges in its watershed, and the NPDES permit process has been extremely successful in obtaining reduced P loading from WWTF throughout the watershed, with the single biggest reductions made at the Metro Plant immediately upstream from Lake Pepin. The TMDL, once complete, will have a detailed accounting of further reductions needed to bring the water quality of Lake Pepin into compliance with the WQS.

Liangzi Lake, by comparison, does not have extensive WWTF discharges, though future development in the watershed raises the possibility of new discharges in the watershed. Both lakes have extensive amounts of agriculture in their watersheds (Table 3). Agricultural lands have the potential to export excess nutrients and sediments to lakes in the form of overland runoff or through ditches, tributaries, or other conveyances. Based on personal communication during the mutual visits, it appears both the U.S. and China lack formal regulations to limit runoff from agricultural lands, and this appears to be a challenge both countries face when attempting to improve or protect water quality.

This report provides some useful comparisons between Lake Pepin and Liangzi Lake and can serve as a base upon which future cooperation can be attained. Each lake has distinct management challenges, and this report serves to call out similarities and differences in approaches to monitoring and management. Both lakes are valuable resources, and their protection and improvement is important. Ideally, the Sister Lakes Program will continue and be of benefit to both lakes.

Table 7 Water quality summaries for each lake.
Values for Pepin based on LTRMP data from 2005-2014 (10-yr summary consistent with lake 303(d) assessments). Upper and Lower segment values provided for perspective. Liangzi Lake data averaged from 8 sites, monthly monitoring from 2013-2015.

Parameter	Lake Pepin whole	Lake Pepin Upper	Lake Pepin Lower	Liangzi Lake whole
Total phosphorus (µg/L)	163	154	166	22
Total nitrogen (mg/L)	3.6	3.7	3.6	0.4
Chlorophyll-a (µg/L)	30	32	30	7.0[1]
Total suspended solids (mg/L)	12	16	10	--
Carbonaceous oxygen demand (mg/L) COD_{Cr}				12.3
Carbonaceous oxygen demand (mg/L) COD_{Mn}	--	--	--	3.1
Biochemical oxygen demand (mg/L)				1.5
Secchi (m)	0.76	0.55	0.82	--
Turbidity (NTU)	10	15	9	--

1 Estimated based on TP using Carlson's TSI (Carlson 1977)

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