Lake Pepin Phosphorus Study, 1994–1998

Effects of Phosphorus Loads on the Water Quality of the Upper Mississippi River, Lock and Dam No. 1 Through Lake Pepin

by

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ABBREVIATIONS AND ACRONYMS

Chl-a	Chlorophyll *a*
DO	Dissolved oxygen
HydroQual	HydroQual, Incorporated
MCES	Metropolitan Council Environmental Services (formerly MWCC)
MDNR	Minnesota Department of Natural Resources
Metro Area	Seven-county metropolitan area of Minneapolis and St. Paul, Minnesota
Metro Plant	Metropolitan Wastewater Treatment Plant
MPCA	Minnesota Pollution Control Agency
MWBAC	Minnesota-Wisconsin Boundary Area Commission
MWCC	Metropolitan Waste Control Commission (later MCES)
N	Number of samples
NTU	Nephelometric turbidity units
NVSS	Nonvolatile (inorganic) suspended solids
P	Phosphorus
SRP	Soluble reactive phosphorus
Summer	June through September, unless otherwise noted
TP	Total phosphorus
TSS	Total suspended solids
USACE	U.S. Army Corps of Engineers, St. Paul District
USAE-WES	U.S. Army Engineer Waterways Experiment Station
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VSS	Volatile (organic) suspended solids
WDNR	Wisconsin Department of Natural Resources
WWTP	Wastewater treatment plant

MEASUREMENT UNITS AND CONVERSION FACTORS

Metric Measurements	Multiply By	To Yield U.S. Equivalents
Centimeters (cm)	0.3937	inches (in)
Meters (m)	3.281	feet (ft)
Kilometers (km)	0.6214	miles (mi)
Metric tons (mt)	1.102	short tons
Square meters (m^2)	10.76	square feet (ft^2)
Hectare (ha)	2.471	acres (ac)
Square kilometers (km^2)	0.3861	square miles (mi^3)
Cubic hectometers (hm^3)	811.0	acre-feet (acre-ft)
Milligrams per gram (mg/g)	1	part per thousand
Milligrams per liter (mg/L)	1	parts per million (ppm)
Micrograms per liter (µ/L)	1	parts per billion (ppb)
Cubic meters per second (m^3/s, cms)	35.31	cubic feet per second (cfs)
Cubic meters per second (m^3/s, cms)	22.82	million gallons per day (mgd)
Kilograms per hectare (kg/ha)	0.8921	pounds per acre (lb/ac)
Degrees Centigrade (ºC)	(9/5 * ºC) + 32	degrees Fahrenheit (ºF)

ABSTRACT

In the summer of 1988, at the height of a prolonged drought in the Upper Midwest, low river flows and high nutrient levels led to severe nuisance algal blooms in Lake Pepin, a natural impoundment in Pool 4 of the Upper Mississippi River located between Red Wing and Wabasha, Minnesota. The algal blooms caused unsightly surface scum, obnoxious odors, low oxygen levels, and localized fish kills. The Metropolitan Wastewater Treatment Plant (Metro Plant), a 250-mgd advanced secondary facility, discharges to Pool 2 of the Mississippi River in St. Paul, Minnesota, and is the largest point source of phosphorus upstream of Lake Pepin. The Metro Plant is owned and operated by the Metropolitan Council, a regional planning agency that serves the seven-county metropolitan area of Minneapolis and St. Paul, Minnesota, and provides essential services to the region. In 1994–98 the Metropolitan Council and its partners conducted studies to determine the effects of phosphorus loads from the Metro Plant and other sources on the water quality of the Mississippi River, specifically algal blooms in Lake Pepin and Spring Lake, a backwater lake in lower Pool 2.

The Lake Pepin Phosphorus Study, 1994–98, had six major components. The Science Museum of Minnesota examined sediment cores from Lake Pepin to estimate historical changes in phosphorus and sediment loads, diatom communities, and phosphorus concentrations over the past 200 years. The University of Minnesota studied historical trends in agricultural practices and wastewater discharges since 1860 to relate human activities to changes in phosphorus and sediment loads. Metropolitan Council Environmental Services assessed a 21-year water-quality database to determine sources and patterns of phosphorus, chlorophyll, and sediment loads. The U.S. Army Engineer Waterways Experiment Station conducted limnological studies of Lake Pepin to analyze fluxes of nutrients and suspended solids and examine phytoplankton dynamics. The Minnesota-Wisconsin Boundary Area Commission coordinated a volunteer monitoring program of Lake Pepin and Spring Lake to evaluate water quality from the lake users' perspective. HydroQual, Inc., developed an advanced eutrophication model to study current water-quality conditions and project future conditions under various phosphorus management strategies.

The study yielded information on past, current, and future conditions in Lake Pepin and its watershed. Over the past 200 years, algal communities in Lake Pepin have changed from clear-water benthic and mesotrophic planktonic taxa to mostly planktonic assemblages characteristic of highly eutrophic conditions. The major factors contributing to this change are likely increased phosphorus concentrations and increased light attenuation. Phosphorus loads to Lake Pepin have increased by five- to seven-fold to 4000–5500 metric tons per year (mt/yr). Increased wastewater discharges and fertilizer applications are the likely causes. Phosphorus concentrations in the lake have increased approximately four-fold, from 50 to 200 micrograms per liter (μg/L). Sediment loads have increased ten-fold to nearly 900,000 mt/yr, most likely due to increases in the amount of watershed area planted in row crops. The greatest changes in phosphorus, algae, and sediment in Lake Pepin have occurred since 1940.

Currently, nutrients are abundant in the Mississippi River from Lock and Dam No. 1 through Lake Pepin and rarely decline to concentrations low enough to limit algal growth. When physical and hydrological conditions are favorable, severe nuisance algal blooms occur especially in lower Pool 2 and Lake Pepin. Blue-green algae dominate under these conditions, and maximum

concentrations of viable chlorophyll *a* can exceed 200 µg/L. During periods of low river flows, point sources contribute the majority of phosphorus loads upstream of Lake Pepin (e.g., 89% in 1988). However, at high flows, nonpoint sources dominate phosphorus loads (e.g., 75% in 1993). At average flows, phosphorus loads are roughly split between point and nonpoint sources. The Metro Plant contributed approximately 20% of the total phosphorus and 40% of the soluble reactive phosphorus (SRP) loads during the past two decades. The Minnesota River Basin contributes the majority of phosphorus loads from nonpoint sources.

Only a small fraction of the phosphorus delivered to Pools 2–4 is retained; most is flushed through and transported downstream. During the period from 1985 to 1996, the overall phosphorus retention rate in Lake Pepin was approximately 10%. In all 12 years, Lake Pepin was a net sink of particulate phosphorus and a net source of SRP. Internal SRP loads represented approximately a tenth of the total SRP load to Lake Pepin during this 12-year period. This fraction climbed to a third in low flow years (1987–89) and two-thirds in low flow summers.

In a future low flow summer, water-quality conditions in Lake Pepin are projected to improve somewhat under various phosphorus reduction scenarios for point and nonpoint sources in the basin. In all scenarios, phosphorus concentrations in Lake Pepin would decrease dramatically but would remain high enough to support excessive algal growth. Even with phosphorus removal to 1.0 milligram per liter at all point sources in the basin and moderate phosphorus reductions from nonpoint sources, algal levels in Lake Pepin would remain excessive (i.e., viable chlorophyll *a* > 30 µg/L) over half of the summer. The main benefit of these phosphorus controls would be to reduce peak algal levels (i.e., viable chlorophyll *a* > 70 µg/L) during low flow periods. Biological phosphorus removal will be fully implemented at the Metro Plant by the end of 2003. However, long-term improvements in water quality will only be achieved through basinwide reductions in phosphorus loads from both point and nonpoint sources.

1 INTRODUCTION

The following sections provide background information on the Lake Pepin Phosphorus Study. Section 1.1 describes the poor water-quality conditions in Lake Pepin during the summer of 1988 that prompted complaints by citizens and a preliminary investigation of the cause. Phosphorus was identified as an important factor, leading to two extensive studies of the sources of phosphorus to the Mississippi River and the impact of phosphorus on water quality. Section 1.2 describes the first study, a cooperative effort by several agencies conducted during 1990–92. This initial assessment ended with a number of important findings but also several unresolved issues. These outstanding questions were addressed with additional investigations during 1994–98, which are the subjects of this report. Section 1.3 discusses the main objectives of the Lake Pepin Phosphorus Study, 1994–98, followed by descriptions of the six major study components. Finally, Section 1.4 contains a description of the study area, encompassing the Mississippi River from Lock and Dam No. 1 through Lake Pepin.

1.1 Severe Nuisance Algal Blooms in Lake Pepin, Summer 1988

In the summer of 1988, at the height of an extended drought period in the Upper Midwest, severe nuisance algal blooms occurred in Lake Pepin, a large natural impoundment (100 km^2) in Pool 4 of the Mississippi River between Red Wing and Wabasha, Minnesota (Figs. 1–3). Episodes of low dissolved oxygen (DO) concentrations and two localized fish kills were also documented. A preliminary investigation by the Minnesota Pollution Control Agency (MPCA, 1989) determined that an abundance of nutrients, combined with low river flows, provided optimal conditions for algal growth in the lake.

During June through September 1988, mean flow of the Mississippi River upstream of Lake Pepin at Prescott, Wisconsin, was 139 m^3/s (4,910 cfs), and mean water residence time in Lake Pepin was 46 days. Mean summer flows of this magnitude recur at a frequency of every 20 to 30 years (Gregory Mitton, USGS, personal communication; provisional data based on years 1928–2000). Low flows provide long residence times for algae to grow and stable conditions under which nuisance blue-green algae thrive (Paerl, 1988).

In response to complaints by citizens, the MPCA monitored the water quality of Lake Pepin on three dates in July and August 1988 (MPCA, 1989). Mean concentrations of pheophytin-corrected chlorophyll *a* and total phosphorus were 57 micrograms per liter (µg/L) and 0.49 milligrams per liter (mg/L), respectively—both indicative of a highly eutrophic system. The blooms were dominated by blue-green algae (*Aphanizomenon flos-aquae* and *Microcystis spp*.), which can produce unsightly surface mats, obnoxious odors, and toxins (Fig. 4). Through respiration and decomposition, the algal blooms likely produced transient zones of low DO concentrations that, in turn, precipitated the fish kills (Fig. 5). Phosphorus, suspended sediments, and residence time were identified by the MPCA as the three factors regulating the amount of algae produced in Lake Pepin.

Phosphorus is a common element essential for sustaining life, and as such, it is found in every living thing on earth. Phosphorus is highly concentrated in plants, animal wastes, food, fertilizers, commercial and industrial cleaners, and some consumer products. Although phosphorus is an essential element, too much phosphorus in lakes and rivers can create water-quality problems. Algae require a number of nutrients, but phosphorus is naturally scarce and often limits algal growth in freshwater lakes and rivers in northern temperate zones (Wetzel, 1975). However, many human activities increase the amount of phosphorus in lakes and rivers, thereby stimulating algal growth. An overenrichment of phosphorus can lead to an increase in the frequency and severity of algal blooms, a process known as cultural eutrophication. Sources of increased phosphorus levels in lakes and rivers include "point" or discrete sources, such as wastewater treatment plants and industries, and "nonpoint" or diffuse sources, such as runoff from rural and urban areas.

Figure 1. Photograph of Lake Pepin taken from Frontenac State Park (Courtesy of the MDNR).

Figure 2. Map of the Lake Pepin watershed, showing the Minnesota, Mississippi, and St. Croix River Basins, Twin Cities Metropolitan Area, and study area (Craig Skone, MCES).

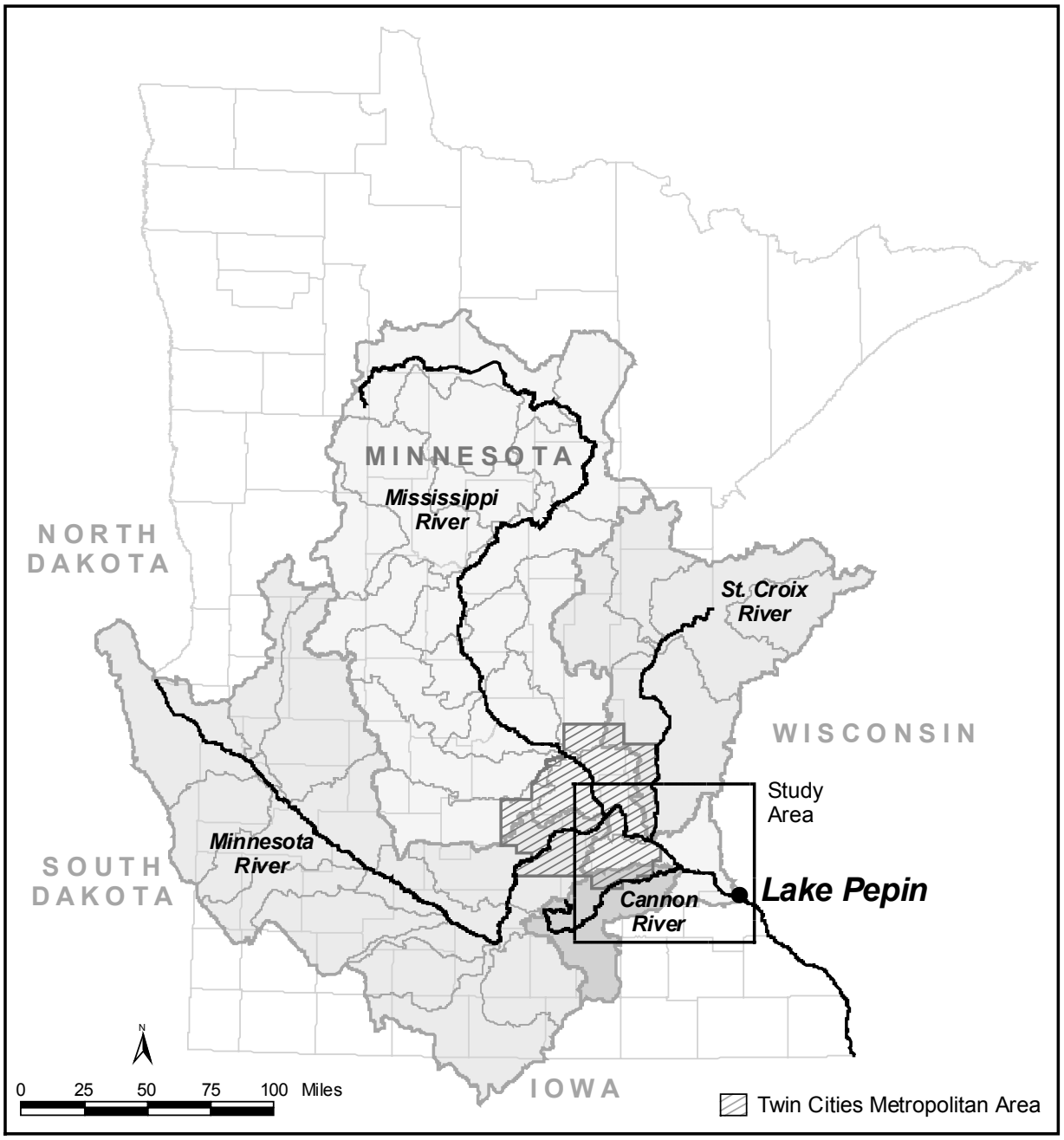


Figure 3. Map of the study area, showing the Mississippi River, from Lock and Dam No. 1 through Lake Pepin, and major features (Craig Skone, MCES).

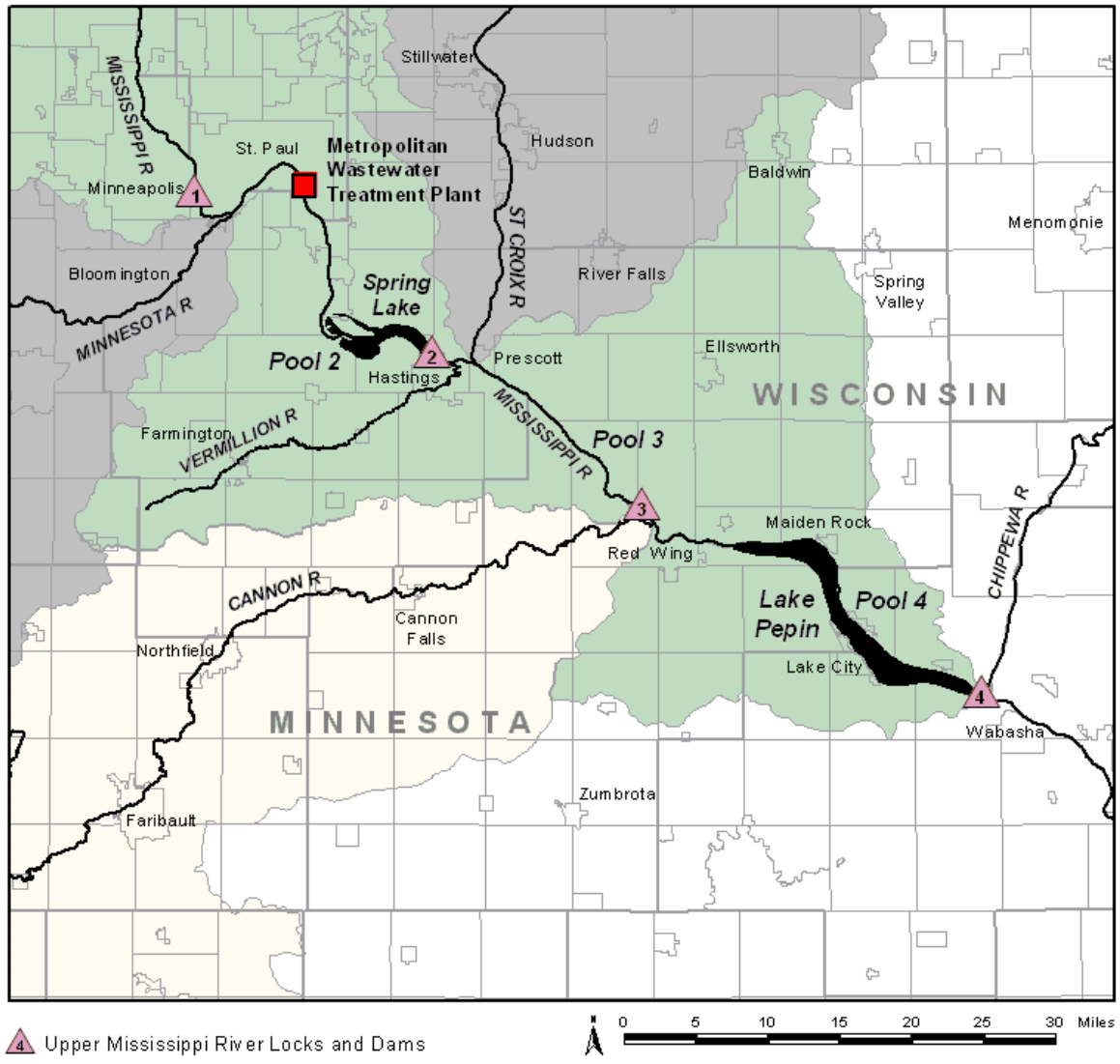


Figure 4. Photograph of algal mats in Lake Pepin during the summer of 1988 (Courtesy of the MDNR).

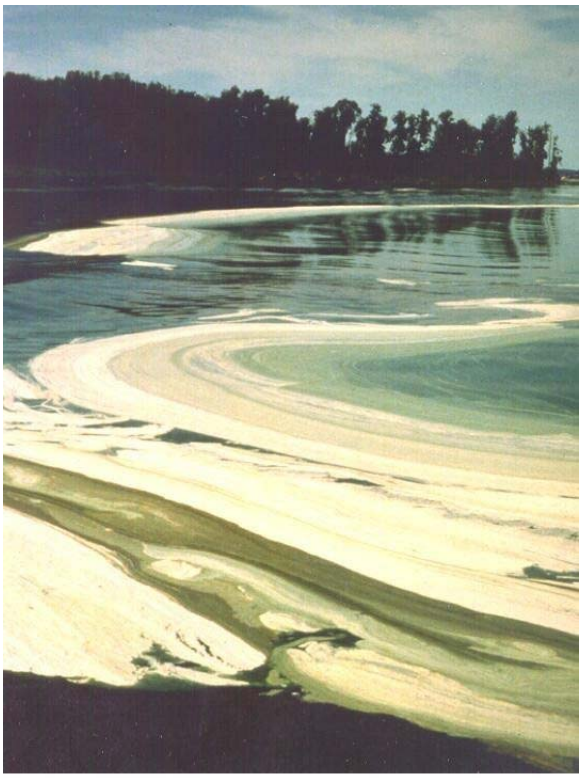


Figure 5. Photograph of a fish kill in Lake Pepin during the summer of 1988 (Courtesy of the MDNR).

The largest point source of phosphorus upstream of Lake Pepin is the Metropolitan Wastewater Treatment Plant (Metro Plant), an advanced secondary facility that discharges treated wastewater to Pool 2 of the Mississippi River near Pig's Eye Lake in St. Paul, Minnesota (Fig. 3). It is the largest wastewater treatment facility (11 m^3/s or 250 mgd) in Minnesota, handling roughly half of the state's wastewater, and it is also the largest facility on the Mississippi River north of St. Louis, Missouri. Lake Pepin lies 80 kilometers (50 miles) downstream of the Metro Plant. The preliminary investigation by the MPCA (1989) demonstrated that, while relative contributions of phosphorus from different point and nonpoint sources vary greatly with river flow, the Metro Plant accounts for the majority of phosphorus loads to Lake Pepin under low flow conditions.

Minnesota State statutes require municipal wastewater facilities to remove phosphorus to 1 mg/L where the discharge is directly to or affects a lake or reservoir (Minnesota Rules 7050.0211, Subpart 1). A second rule applicable to the Mississippi River and other recreational waters states that the aquatic habitat "shall not be degraded in any material manner."

The Metro Plant discharges directly to a river, not a lake, but the question of its effect on Lake Pepin arose in 1989 during negotiations for re-issuance of the facility's discharge permit. Not enough information was available at the time to determine its effect, so the Metro Plant was issued a shortened three-year permit in 1990. The permit placed no limits on effluent phosphorus concentrations but contained requirements to study the phosphorus issue.

The 1990 permit required the Metropolitan Waste Control Commission (MWCC), which owned and operated the Metro Plant, to investigate technologies for removing phosphorus at the Metro Plant and to conduct environmental studies of the effects of phosphorus loads on the water quality of Lake Pepin and Spring Lake. Spring Lake is a small, shallow backwaters area (less than 10 km^2) located 18 kilometers (11 miles) downstream of the Metro Plant in the pooled area above Lock and Dam No. 2 in Hastings, Minnesota (Fig. 3). Both studies were to be completed prior to the drafting of a new permit in 1993, at which time the information could be used to determine an appropriate effluent limitation for phosphorus.

1.2 Lake Pepin Phosphorus Study, 1990–92

The effects of phosphorus loads on the water quality of the Mississippi River from Lock and Dam No. 1 through Lake Pepin were studied from 1990 to 1992 by the MWCC in partnership with a number of agencies and consultants. The study included river and effluent monitoring, historical data analyses, sediment flux measurements, diatom stratigraphy, dilution bioassays, literature reviews, and computer modeling. More than a dozen reports were produced, and the findings were compiled in an executive summary by the MWCC (1993). A Phosphorus Study Cooperators Group was formed in 1990 to track the progress of the studies and share information and ideas. Members included staff from the MWCC, MPCA, Metropolitan Council, Minnesota Department of Natural Resources (MDNR), Minnesota-Wisconsin Boundary Area Commission (MWBAC), U.S. Army Corps of Engineers (USACE), and Wisconsin Department of Natural Resources (WDNR). The Metropolitan Council is a regional planning agency that serves the seven-county metropolitan area of Minneapolis and St. Paul, Minnesota, and provides essential services to the region. MWCC was overseen by the Metropolitan Council and later merged with it.

One important outcome of the Phosphorus Study Cooperators Group was the establishment of a water-quality goal for Lake Pepin (Heiskary, 1993):

> "An average chlorophyll *a* goal of 30 µg/L (corrected for pheophytin) is recommended for Lake Pepin for the summer period (June–September). This goal is to be applied as a whole-lake average for summer river flows ranging from 4,600 to 20,000 cfs (130 to 570 m^3/s) at the U.S. Geological Survey gage at Prescott, Wisconsin."

Pheophytin-corrected chlorophyll *a,* also referred to as viable chlorophyll *a*, is a measure of living algae. Pheophytin *a* is a degradation product that interferes with the measurement of chlorophyll *a* unless a correction is applied.

The water-quality goal for Lake Pepin served as a target for various phosphorus management strategies that were tested with computer models. In setting the goal, the following information on the perceptions of lake users was gathered:

- Studies of regional patterns in lake users' perceptions
- Surveys of residents in the Lake Pepin area on lake uses and water quality
- Subjective ratings of water quality by volunteers monitoring Lake Pepin

In general, lake users in the region regarded algal levels that corresponded to viable chlorophyll *a* concentrations of 30 µg/L or less as acceptable. However, user information specific to Lake Pepin was limited during this initial study.

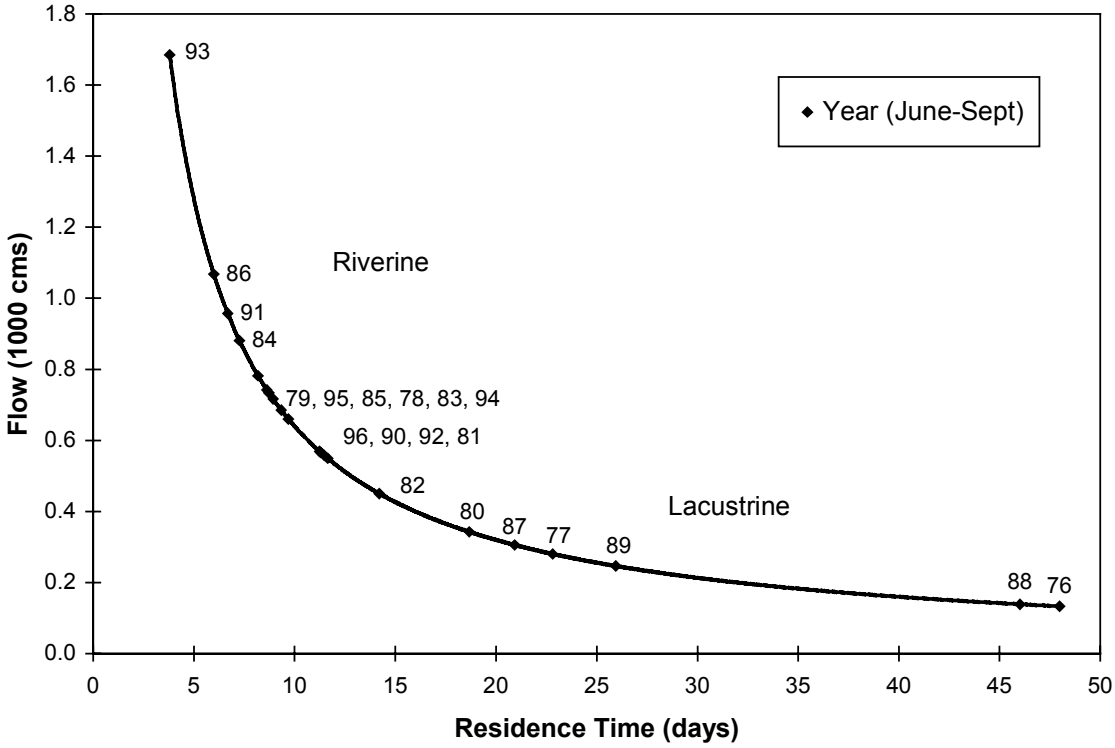
Water-quality and flow information was also considered in setting the goal. Nuisance blue-green algae flourish in Lake Pepin when water temperatures are warm and river flows are low. Chlorophyll *a* concentrations can be high in Lake Pepin when water temperatures are cool and river flows are high, especially in the spring, but the algal community during these periods is usually dominated by diatoms, which do not produce the surface mats, odors, and other problems associated with blue-green algae. At river flows under 20,000 cfs (570 m^3/s), residence time in Lake Pepin increases to over 10 days, making conditions more lacustrine (lake-like) than riverine (Fig. 6). Longer residence times provide the physical stability required by many blue-green algae (Paerl, 1988). Mean summer flows below 4,600 cfs (130 m^3/s) represent extreme conditions that occur less than 1 in 50 years, so this value was used as the lower flow limit. The mean summer flow in 1988 was 4,910 cfs (139 m^3/s).

The executive summary for the 1990–92 phosphorus studies listed the following key findings (MWCC, 1993):

- The Mississippi River contains an abundance of phosphorus.
- The Metro Plant is only one of numerous point and nonpoint sources of phosphorus loads.
- Phosphorus reductions at the Metro Plant alone will result in little short-term reduction of algal blooms in Lake Pepin.
- Additional phosphorus reductions at sources across the watershed are needed to realize significant long-term improvements in water quality.
- A basin-wide management strategy is needed to address both point and nonpoint sources of phosphorus.

Despite these findings, a number of unresolved issues remained. First, low river flows did not occur during the study period, leaving gaps in the understanding of

Figure 6. Mean summer water residence time and flow in Lake Pepin, June through September, 1976–96 (after Heiskary and Vavricka, 1993).



nutrient and algal dynamics under critical conditions. Second, much data were collected on phosphorus loads from various sources, but not much was known about the fate of phosphorus once it reached the river and how phosphorus was transported downstream. For example, sediment was suspected as an important vehicle for transporting phosphorus, but none of the analytical tools could properly address this aspect. Third, the study found that substantial amounts of phosphorus were released at times from the sediment bed in Lake Pepin, but more research was needed to understand this process and its contribution to the overall phosphorus budget of the lake. For example, questions were raised but not answered on how phosphorus deposited in high flow years was connected to phosphorus released in low flow years and how release rates might respond to decreased loads over time.

With these and other uncertainties remaining about the effects of phosphorus, the 1993 discharge permit for the Metro Plant required Metropolitan Council Environmental Services (MCES, formerly MWCC) to continue the environmental studies of phosphorus in the Mississippi River over the next five years (1994–98). The permit also contained a phosphorus effluent limitation (4 mg/L as a monthly average) and required implementation of phosphorus removal in a quarter of the facility's wastewater stream by 1998. A concurrent agreement, in effect for the same five-year period (1994–98), required MCES to invest $8.8 million in programs to reduce phosphorus loads from nonpoint sources in the Twin Cities Metropolitan Area (Metro Area) and commit up to $2 million to environmental studies of phosphorus.

1.3 Lake Pepin Phosphorus Study, 1994–98

The Phosphorus Study Cooperators Group continued to meet during the second phase of the phosphorus study, providing oversight and direction. Staff from the U.S. Environmental Protection Agency (USEPA), U.S. Geological Survey (USGS), and University of Minnesota joined the original members at some meetings. During the first two years, MCES drafted a work plan with a list of potential studies and sponsored workshops for the Cooperators Group on sediment, algae, and modeling. At the workshops, participants helped to identify key questions and determine the monitoring, research, and modeling projects needed to answer them.

In 1995 MCES drafted the document "Mission, Definitions, and Questions to Address" (Appendix A), which was adopted by the Cooperators Group in June 1996 as a guide for the 1994–98 phosphorus study. The mission statement was as follows:

> "To study the effect of phosphorus loadings from the Metro Plant and other sources on the water quality of the Mississippi River, specifically algal blooms in Lake Pepin and Spring Lake, and to project the water-quality benefits to the river of reduced phosphorus loadings from the Metro Plant and other sources."

The mission broadened the scope of the 1994–98 studies by including phosphorus sources other than the Metro Plant. Among the 13 questions to address, top priority was given to better understandings of phosphorus dynamics, the relationship of phosphorus to algae, and the projected benefits of reducing phosphorus. While important to address, lower priorities were assigned to understanding algal dynamics (e.g., what controls the composition of the algal community) and historical changes in water quality in response to human activities.

To achieve the mission and answer questions posed for the 1994–98 studies, MCES arranged and coordinated six major study components, which are described in the following sections. The Science Museum of Minnesota examined sediment cores from Lake Pepin to estimate historical changes in phosphorus and sediment loads and diatom communities (Section 1.3.1). The University of Minnesota studied historical trends in agricultural practices and wastewater discharges in order to relate human activities to changes in phosphorus and sediment loads (Section 1.3.2). MCES assessed a 21-year water-quality database to determine sources and patterns of phosphorus, chlorophyll, and sediment loads to the Mississippi River above Lake Pepin (Section 1.3.3). The U.S. Army Engineer Waterways Experiment Station conducted limnological studies of Lake Pepin to analyze fluxes of nutrients and suspended solids and to examine phytoplankton dynamics (Section 1.3.4). The Minnesota-Wisconsin Boundary Area Commission coordinated a volunteer monitoring program of Lake Pepin and Spring Lake to evaluate water quality from the lake users' perspective (Section 1.3.5). HydroQual, Inc., (HydroQual) developed an advanced eutrophication model to study current water-quality conditions and project future conditions under various phosphorus management strategies (Section 1.3.6). In support of modeling, MCES conducted an extensive monitoring program in 1996 that included provisions for high loading events as well as low river flows.

1.3.1 Historical Changes in Sediment and Phosphorus Loading Rates, 1500s–1996

Science Museum of Minnesota,
St. Croix Watershed Research Station

About 10,000 years ago, near the end of the last glacial period, Lake Pepin was formed as a result of an alluvial dam that was shaped by sand and gravel carried by the swifter Chippewa River in west-central Wisconsin and deposited in the slower Mississippi River above Wabasha, Minnesota (Wright *et al.,* 1998). Its special formation makes it the only natural impoundment on the Mississippi River, the rest having been produced by the construction of locks and dams, mostly in the 1930s. In fact, Lake Pepin is one of the few natural depositional basins on a large river in the world, posing a nearly unique opportunity for unlocking the history of a major river by examining its sediment (Engstrom and Almendinger, 2000). The sediment bed of Lake Pepin contains a chronology of past loading rates and water quality, which reflects the impact of land-use changes over a large drainage area, including much of Minnesota and parts of three adjoining states.

To reconstruct the history of sediment and phosphorus loading rates to the Mississippi River upstream of Lake Pepin, MCES funded a research project by the St. Croix Watershed Research Station of the Science Museum of Minnesota. Researchers collected, dated, and analyzed multiple cores from the sediment bed of Lake Pepin. By describing natural background conditions in Lake Pepin before European settlement, the project provided an important benchmark to compare with the current state of eutrophication and sedimentation in the lake. Also, the gradual infilling of Lake Pepin with sediment deposits was projected using current rates of sediment accumulation, providing a predicted lifespan for the lake. See Engstrom and Almendinger (2000) for a complete description of this research project.

Fieldwork for the coring study started in summer 1995 with a seismic survey of Lake Pepin along 26 shore-to-shore transects. Seismic information, which delineates the deposition of fine-grained sediments, was needed to design an appropriate sampling scheme for deep sediment cores. In September 1995 and June and October 1996, 25 deep sediment cores were collected from Lake Pepin along five shore-to-shore transects perpendicular to flow (Fig. 7). A piston corer with a 7-cm diameter was driven two to

Figure 7. Photograph of researcher collecting deep sediment cores in Lake Pepin (Courtesy of the SMM).

four meters into the sediment bed, with the deepest cores collected in the upstream end of the lake where deposition rates are highest. The entire length of each core was stored for later processing.

Magnetic susceptibility, which determines the concentration of fine-grained ferromagnetic minerals, was measured across the entire length of all 25 cores. By evaluating the magnetic profiles, ten of the 25 cores (two per transect) were selected for detailed stratigraphic analysis and subsectioned into 4-cm increments. The sediment cores were dated and stratigraphically correlated using lead-210, cesium-137, radiocarbon, magnetic susceptibility, pollen, and loss-on-ignition analyses. Each method provided different strengths, time markers, and checks against other methods. The cores yielded information dating back to the 1500s, with each 4-cm section representing approximately 40 years in the 1800s, 20 years from 1890 to 1930, and a decade in the most recent sediments.

Physical and chemical characteristics of the sediment samples were also examined. Organic, carbonate, and inorganic (clastic) content were determined by standard loss-on-ignition techniques, and grain sizes were measured by laser analytical methods. The Soil, Water, and Climate Department of the University of Minnesota was subcontracted to conduct a source apportionment study of Lake Pepin sediment (Nater and Kelley, 1998). The "signatures" of a wide array of heavy minerals in the bottom sediments of the three major river basins (Mississippi, Minnesota, and St. Croix) were constructed and compared against the mineral composition of Lake Pepin sediments. Ten surficial sediment samples were collected and analyzed from the lower reaches of the two tributaries and the Mississippi River near Lock and Dam No. 1. Distinct mineral signatures in sediments from the three rivers allowed apportionment of sediment deposits in Lake Pepin among the three river basins. The elemental compositions of sediment samples from ten Lake Pepin cores were analyzed and matched statistically to their sources using a chemical mass-balance model.

Sediment core samples from Lake Pepin were also subjected to phosphorus and diatom analyses. Samples from 20 of the Lake Pepin sediment cores were analyzed for four forms of phosphorus: total, exchangeable (NH_4Cl-P), Fe/Al-bound (NaOH-P), and carbonate-bound (HCl-P) phosphorus. This information provided clues about phosphorus sources and long-term trends in sediment composition. Diatom microfossils were identified and counted in ten subsamples from one sediment core collected at the downstream end of Lake Pepin. The diatom analysis was used to reconstruct changes in the algal community since European settlement. It also provided a method for reconstructing phosphorus concentrations in the water column using diatom-phosphorus calibration models. The models were based on information about the distribution of diatom species among lakes of known water chemistry, including lakes in southeast England, British Columbia, and Michigan. Mercury concentrations over time were examined in a separate study (Balogh *et al.*, 1999).

Uncertainty. High sedimentation rates and a strong longitudinal gradient of deposits in Lake Pepin made sediment dating and loading rate estimates more difficult than in other systems, but by applying an array of dating tools and collecting multiple cores, this problem was addressed. Results from different dating methods and different cores constrain one another. According to the principal investigators, uncertainties remained, especially for the older strata, but the final results appeared robust. The phosphorus mass balance was made difficult and less certain by the lack of a single diatom-phosphorus model for the diatoms represented in Lake Pepin and by the lack of river flow data prior to 1890. Diatom-inferred phosphorus concentrations matched measured values for the current decade, but the investigators judged past esti-

mates "less secure," especially in the presettlement strata. See Engstrom and Almendinger (2000) for a more thorough discussion of uncertainty in this project.

1.3.2 Human Activities Related to Historical Changes in Loading Rates, 1860–1996

University of Minnesota,
Soil, Water, and Climate Department

As described in the previous section, researchers at the St. Croix Watershed Research Station reconstructed the history of sediment and phosphorus loading rates to Lake Pepin; however, they did not collect historical information on human activities in the watershed that might explain changes in the loading rates. For this work, MCES funded a project by the Soil, Water, and Climate Department of the University of Minnesota. The project's objectives were to compile a database of agricultural practices and wastewater discharges over the past 130 years and to evaluate whether these activities were related to changes in sediment and phosphorus accumulation in Lake Pepin. The project is fully documented in Mulla *et al.* (2000).

Researchers at the university compiled historical data on river flows, human and animal populations, manure and fertilizer applications, cropping systems, soil erosion, and wastewater discharges (Fig. 8). Information at intervals of 10 to 20 years since 1860 was collected for the three major river basins (Mississippi, Minnesota, and St. Croix). Data sources included the USGS, U.S. Census, U.S. Agricultural Census, Land Management Information Center, Natural Resources Conservation Service, MDNR, MCES, and MPCA. Estimates of river flows before 1920 were not available.

Figure 8. Photograph of a soybean field in southern Minnesota (Cathy Larson, MCES).

Where direct information was not available, reasonable estimates were made. Phosphorus applied in manure was estimated from the numbers of cattle, swine, and chickens and the average amount of phosphorus produced per animal. A similar approach was used to calculate historical loads of phosphorus in wastewater by estimating per capita rates from treatment plant data before and after the phosphorus detergent ban in 1976. Applications of phosphorus in commercial fertilizer were reconstructed using recent and historical statistical data on fertilizer sales and tons of phosphorus applied at state and county levels.

Once compiled, the historical data on human activities were statistically correlated with historical accumulation rates for sediment and phosphorus in Lake Pepin and historical phosphorus loading rates to the lake. Linear regression was also applied to test for relationships between the dependent variables (accumulation and loading rates) and multiple independent variables (e.g., row-crop area, wastewater discharges, and river flow). It is important to note that these types of analyses can indicate statistically significant relationships but cannot determine causes.

Uncertainty. Uncertainty in the study results varies with the quality and quantity of historical data or, where data were not available, the estimation method. Most accurate are likely the crop areas, population estimates, and river flows. Phosphorus applications from manure were estimated from animal populations (U.S. Agricultural Census, 1860–1992) and average phosphorus amounts produced per animal, which were obtained from a 1995 report by the Minnesota Department of Agriculture. The estimates assume that phosphorus production per animal has not changed in 130 years. The actual tonnage of phosphorus applied via commercial fertilizers was known only for the Minnesota and Upper Mississippi River Basins in 1986 and 1996. Historical phosphorus applications for the three river basins were estimated using statewide phosphorus applications (and the portion each basin represented in 1986 and 1996) or, prior to 1930, basin-wide fertilizer sales.

Effluent phosphorus concentrations have been monitored at wastewater treatment plants (WWTPs)

in the Metro Area since the 1970s; however, phosphorus monitoring at WWTPs outside the Metro Area was limited before the 1990s, when it became a standard permit requirement. Several steps and assumptions were made in estimating historical phosphorus loads from WWTPs. The principal investigators judged the wastewater load estimates for 1960–1990 to be "reasonably certain," with uncertainty increasing in older estimates.

1.3.3 Sources of Phosphorus, Chlorophyll, and Sediment, 1976–96

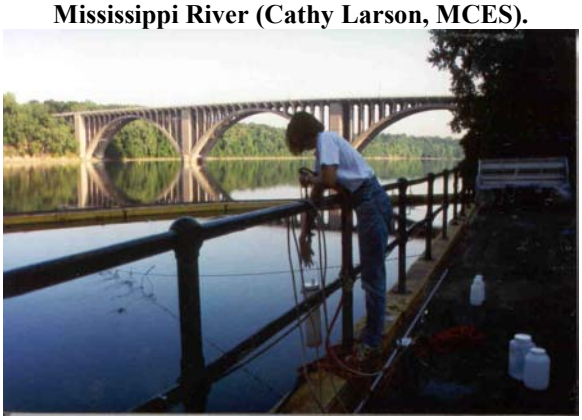
Metropolitan Council Environmental Services, Environmental Planning and Evaluation Dept.

Since the 1920s, MCES and its predecessors have monitored the water quality of the Mississippi and other major rivers in the Metro Area. Currently, surface grab samples are collected two to four times a month at 22 stations on the Mississippi, Minnesota, St. Croix, Vermillion, and Rum Rivers and analyzed for a suite of variables (Fig. 9). Nutrients, solids, and chlorophyll are monitored twice a month at 14 of the 22 stations. Data collected since 1976 are easily retrieved from a computer database. Also, flow and effluent quality of the Metro Plant and other MCES WWTPs have been monitored since the facilities were constructed. Effluent nitrogen and phosphorus concentrations have been routinely monitored since the 1970s. MCES Laboratory Services conduct the chemical analyses of these river and effluent samples.

With this information readily at hand, MCES scientists compiled and compared loads from major sources to the Mississippi River, from Lock and Dam No. 1 through Lock and Dam No. 3, during the two most recent decades. For the period from 1976 to 1996, total phosphorus (TP), soluble reactive phosphorus (SRP), total suspended solids, and chlorophyll *a* were examined at three key locations: 1) Mississippi River at Lock and Dam No. 1; 2) near the mouth of the Minnesota River; and 3) near the mouth of the St. Croix River. Annual, seasonal, and monthly loads and concentrations from the three rivers were calculated using the FLUX program (Walker, 1986) and USGS flow estimates. Annual yields were estimated for the three river basins. Phosphorus loads from point sources in the three river basins were compiled with information from the MPCA, WDNR, and MCES.

Annual, seasonal, and monthly patterns of loads and concentrations from the three river basins were studied and compared. Relationships with flow and between suspended solids and phosphorus were also explored. These analyses were complemented by information from event-based monitoring of six tributaries to the lower Minnesota River. Hydrology, geomorphology, and land use in the three river basins were examined to explain differences in water quality. The relative contributions of phosphorus loads from point and nonpoint sources in the three basins were compiled for select periods representing low, average, and high river flows. See Meyer and Schellhaass (2002) for a complete description of the data, analyses, and results.

Figure 9. Photograph of scientist collecting a water sample at Lock and Dam No. 1 on the Mississippi River (Cathy Larson, MCES).



1.3.4 Phosphorus Fluxes and Phytoplankton Dynamics in Lake Pepin, 1994–96

U.S. Army Engineer Waterways Experiment Station, Eau Galle Aquatic Ecology Laboratory

The MPCA and MDNR have routinely monitored the water quality of Lake Pepin since 1990; however, more intensive monitoring of both the water column and sediment bed in Lake Pepin would be needed to answer questions about nutrient and algal dynamics in this complex aquatic system. In particular, research on nutrient fluxes to and from the sediment bed was a high priority for the 1994–98 studies. MCES requested assistance from the USACE, St. Paul District, under Section 22 of the Water Resources Development Act (Public Law 93–251). With cooperative funding from the USACE, U.S. Army Engineer Waterways Experiment Station (USAE-WES), and MCES, limnological studies of Lake Pepin were conducted over a three-year period (1994–96) by the USAE-WES Eau Galle Aquatic Ecology Laboratory in Spring Valley, Wisconsin. The main objectives were to examine fluxes of nutrients and suspended solids (seston), determine the relative importance of various external and internal sources of phosphorus, and study phytoplankton dynamics in Lake Pepin.

For a complete description of the study methods and results, see James *et al.*, 2000.

For the three-year period from 1994 to 1996, the USAE-WES compiled detailed annual nutrient and seston budgets for the Mississippi River, Lock and Dam No. 1 through Lake Pepin. Water-quality and flow information were collected year-round by the USAE-WES, MCES, USACE, and USGS on the Mississippi River (at Lock and Dam Nos. 1–3), two major tributaries (Minnesota and St. Croix Rivers), three smaller tributaries, the Metro Plant, and four smaller WWTPs. Using the FLUX program (Walker, 1986), annual inputs and outputs of total suspended solids, total phosphorus, soluble reactive phosphorus, and chlorophyll *a* were estimated for Pool 2, Pool 3, the headwaters of Pool 4, and Lake Pepin. Retention and export rates were calculated by comparing inputs and outputs for the four reaches.

Limnological monitoring was conducted on a weekly basis by the USAE-WES at five to seven stations along the vertical axis of Lake Pepin and at two stations in Spring Lake. Samples were collected at the surface and 1-m depth intervals year-round except during periods of ice formation and breakup. Measurements included those required for the budgets as well as temperature, dissolved oxygen, volatile suspended solids, turbidity, total nitrogen, nitrate-nitrite nitrogen, ammonium nitrogen, silicon, and community net and gross primary productivity and respiration. Three-meter depth-integrated samples were collected at four stations in Lake Pepin for phytoplankton enumeration and alkaline phosphatase activity. Alkaline phosphatase activity indicates the level to which phosphorus is limiting algal growth.

Sediment-bed characteristics and nutrient fluxes in Lake Pepin were intensely studied by the USAE-WES. During the ice-covered months of 1995 and 1996, surficial sediment samples were collected at 120 randomly selected stations in Lake Pepin. The samples were analyzed for sediment characteristics and nutrient fractions, including porewater SRP and various forms of phosphorus bound to inorganic matter. On a monthly basis from April to October, 1994–96, triplicate sediment peepers were located at three stations in Lake Pepin to examine *in situ* Fickean diffusional fluxes and vertical chemical gradients at the sediment-water interface via dialysis techniques.

During January through March, 1995 and 1996, six replicate sediment cores were collected from each of 22 randomly selected locations in Lake Pepin for measuring SRP release rates under oxic and anoxic conditions in sediment incubation systems at the Eau Galle laboratory (Fig. 10). In addition, six replicate cores were collected in May, June, and September 1996 and February 1997 at four sites in Lake Pepin and two sites in Spring Lake for a seasonal analysis of nutrient release rates under different redox and temperature conditions. The sediment peepers and sediment incubation systems are described in James and Barko (1991).

Figure 10. Photograph of sediment incubation system at the Eau Galle Aquatic Ecology Laboratory (Courtesy of the USAE-WES).

1.3.5 Volunteer Monitoring of Lake Pepin and Spring Lake, 1994–98

Minnesota-Wisconsin Boundary Area Commission And Volunteers

To evaluate the water-quality goal for Lake Pepin from the lake users' perspective and to engage local residents in the phosphorus study, the Minnesota-Wisconsin Boundary Area Commission coordinated a volunteer monitoring program for Lake Pepin and Spring Lake from 1994 to 1998, with funding provided by MCES. The MWBAC program expanded upon the MPCA's Citizen Lake Monitoring Program. In both programs, volunteers monitored specific locations throughout the summer, where they subjectively rated water quality on two or three scales and measured water transparency with a Secchi disk. In addition, MWBAC volunteers measured water tem-

perature and collected water samples for laboratory analyses in an effort to compare user perceptions of water quality with chemical measurements. Results of the volunteer monitoring program are summarized in this report and described in detail in Force and Macbeth (2001).

During 1994–98, twenty-five volunteers were recruited and trained for the lake-monitoring program by MWBAC staff. Volunteers monitored 13 locations in Lake Pepin and three locations in Spring Lake every other week from mid-May through September, for a total of 47 sampling dates at each location during the five-year period (Fig. 11). On each visit, they rated the lake for its physical condition based on algal levels (from 1 "crystal clear" to 5 "severely high algal levels"), its recreational suitability (from 1 "beautiful, could not be better" to 5 "nearly impossible"), and the level of suspended sediment (low, average, or high). Rating scales for physical condition and recreational suitability were taken directly from the MPCA program. "Sediment-in-Water" was a new scale added to the MWBAC program in recognition of the magnitude and importance of suspended solids in the Mississippi River.

Volunteers measured water temperature just below the surface and obtained transparency measurements with a Secchi disk. A two-liter water sample was collected with a two-meter depth-integrated sampler. Samples were sent to the USAE-WES Eau Galle Aquatic Ecology Laboratory (1994–96) or MCES Laboratory Services (1997–98) for analytical measurements of total phosphorus, total suspended solids, volatile suspended solids, turbidity, and chlorophyll *a*. Data were stored in the USEPA's STORET database and analyzed by MWBAC staff.

Figure 11. Photograph of volunteer monitoring the water quality in Lake Pepin (Courtesy of the MWBAC).

1.3.6 Advanced Eutrophication Model, 1985–96 and 1998–2021

HydroQual, Inc.

In the 1990–92 Lake Pepin Phosphorus Study, two different modeling approaches were applied: the MPCA applied the BATHTUB model (Heiskary *et al.*, 1993), while the MWCC applied the WASP model (EnviroTech, 1993). Both groups studied the critical low flow year of 1988 and two higher flow years (1990 and 1991). Although river flows were higher, 1990 and 1991 offered richer data sets for modeling, due to expanded water-quality monitoring during the 1990–92 studies. Both models provided good initial assessments of nutrient and algal dynamics in the study area and concluded that flow and light were the main factors controlling algal levels under current conditions of high nutrient loads. Both models also indicated that phosphorus reductions at the Metro Plant alone would result in little short-term improvement in water quality, and additional phosphorus reductions across the basin would be needed for substantive long-term improvements.

However, both models were unable to fully represent the fate and transport of phosphorus in the river. Notably, they lacked the ability to track phosphorus sorbed to suspended sediment, which was thought to play an important role in the Minnesota and Mississippi Rivers. Also, phosphorus release from the sediment bed was shown to contribute substantially to the phosphorus budget of Lake Pepin, but rates were externally specified by the modelers rather than internally calculated by the models. These shortcomings plus the choice of modeling individual years (not several consecutive years) made it impossible to determine the relationship between phosphorus loading and deposition in high flow periods and sediment phosphorus release in subsequent low flow periods. This led, in turn, to a high degree of uncertainty in the model predictions.

In August 1994, MCES sponsored a workshop for the Phosphorus Study Cooperators Group to discuss the framework needed to address these outstanding modeling issues. Also invited were national modeling experts from the USEPA, USGS, and USAE-WES. Recommendations compiled from the workshop formed the basic description of a modeling project proposal for the 1994–98 Phosphorus Study. HydroQual, Inc., was contracted by MCES to complete this project and develop an advanced eutrophication model of the Mississippi River from Lock and Dam No. 1 through Lake Pepin. Summary and project reports by HydroQual (2002a and 2002b) discuss

the modeling framework, calibration, and projection results.

The framework developed by HydroQual is a three-dimensional and time variable modeling system composed of three linked components: hydrodynamics, sediment transport, and eutrophication. Each component is an advanced model previously applied to a variety of aquatic systems. For example, the eutrophication model is a descendent of the Chesapeake Bay model (Cerco and Cole, 1994).

The hydrodynamic model calculates velocity and flow distributions, water depths, and mixing processes, and it simulates the formation and breakup of intermittent periods of thermal stratification in Lake Pepin. The sediment transport model simulates the downstream movement of suspended particles as well as the deposition and resuspension of sediment in pooled areas of the river (Fig. 12). The model tracks two classes of solids: cohesive (fine-grained) and noncohesive (coarse-grained). Cohesive solids play an important role in the sorption and transport of phosphorus, while noncohesive solids must be tracked to accurately calculate the net accumulation rates of sediment and phosphorus in depositional areas. The linked hydrodynamic and sediment transport models provide inputs to the eutrophication model.

The eutrophication model is a mathematical representation of the transport and transformation of various forms of phosphorus, nitrogen, and carbon, including dissolved and particulate, organic and inorganic, and labile and refractory forms. Refractory forms decompose more slowly than labile forms. Along with the spatial and temporal distribution of nutrients, the model tracks dissolved oxygen concentrations and the growth and death of three algal groups. Particulate inorganic phosphorus was added in this study to account for phosphorus sorbed to inorganic particles. Sorbed phosphorus and particulate forms of phosphorus, nitrogen, and carbon settle to the sediment bed. A coupled sediment-flux model tracks the deposition of particulate matter to the sediment, the anaerobic decomposition of the organic matter in the sediment bed, and the release of inorganic nutrients into the water column. By accounting for sediment transport, phosphorus sorption, and sediment flux, the modeling framework bridges the connection between phosphorus loading and deposition during high flow periods and sediment phosphorus release during low flow periods.

Figure 12. Photograph of engineer measuring the resuspension properties of Lake Pepin sediments (Cathy Larson, MCES).

Three dimensions were required in the model to capture lateral differences in water quality, such as algal growth in the shallow backwaters of Spring Lake, and vertical differences, such as light penetration and thermal stratification in the deeper waters of Lake Pepin. The advanced eutrophication model was calibrated against data from the 12-year period from 1985 to 1996, which covered a range of flows and phosphorus loading events. This period includes two high flow years (1985 and 1986) before the three-year drought (1987–89), followed by the data-rich 1990s. Once the calibration was completed and the model provided a reasonable representation of river water quality, different phosphorus reduction strategies were tested to predict future water-quality conditions in Lake Pepin and Spring Lake. Two cycles of the 12-year hydrodynamic model were repeated to create a projection model for the years 1998–2021. MCES developed phosphorus reduction scenarios for the Metro Plant and its other facilities, and the MPCA developed phosphorus reduction scenarios for point and nonpoint sources in the three major river basins.

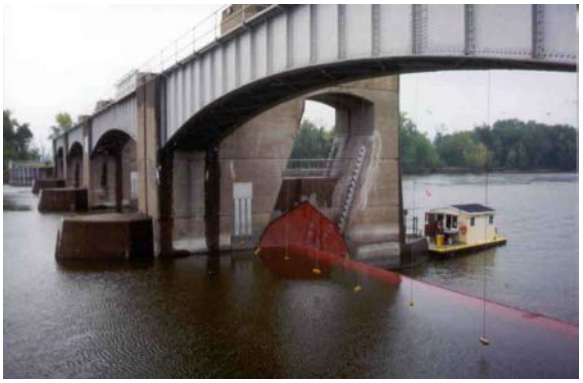
Uncertainty. HydroQual (2002a) conducted a statistical evaluation of the model results, comparing model-computed values with field- and laboratory-measured values. Monthly average concentrations of selected variables were compared at selected locations. The statistical tests included linear regression and median relative error. The median relative errors over the 12-year calibration period (1985–96) were 13.5% for total phosphorus, 20.5% for soluble reactive phosphorus, 26.5% for viable chlorophyll *a*, and 4.9% for dissolved oxygen. The calibration results for 1988 yielded median relative errors of 11.2, 17.4, 37.8, and 8.2%, respectively, for the four variables. These results compare favorably with other respected modeling studies, supporting the use of this tool in projection analyses for the Mississippi River and Lake Pepin.

1.4 Study Area Description

The Mississippi River is the largest river in North America, draining forty percent of the conterminous United States and flowing 3,780 kilometers (2,350 miles) from its headwaters at Lake Itasca in northern Minnesota to the Gulf of Mexico. In addition to its economic and recreational importance, the Mississippi River is a significant ecological and environmental resource (Smith *et al.*, 1994; The McKnight Foundation, 1996).

The Upper Mississippi River extends from its headwaters to the confluence with the Ohio River at Cairo, Illinois. Over a 1380-km (860-mi) reach from St. Anthony Falls in Minneapolis, Minnesota, to the Ohio River confluence, the Upper Mississippi River is an impounded system of 29 locks and dams, constructed in the 1930s for commercial navigation (Fig. 13). The locks and dams and the navigation pools created by these structures are numbered from upstream to downstream, beginning at Lock and Dam No. 1 and Pool 1 in Minneapolis and ending at Lock and Dam No. 29 and Pool 29 near Cairo, Illinois.

Figure 13. Photograph of roller gate at Lock and Dam No. 3 on the Mississippi River (Cathy Larson, MCES).



The Lake Pepin Phosphorus Study, 1994–98, focused on the reach of the Upper Mississippi River from Lock and Dam No. 1 through the outlet of Lake Pepin, or approximately 140 kilometers (85 miles) between Minneapolis and Wabasha, Minnesota (Fig. 3). Lock and Dam Nos. 1–4 divide this reach into three navigational pools (Pools 2–4). Two large tributaries, the Minnesota and St. Croix Rivers, enter the Mississippi River in upper Pool 2 and upper Pool 3, respectively. The St. Croix River and the Mississippi River downstream of the St. Croix confluence form the border between Minnesota and Wisconsin.

The eutrophication of two lakes within this reach, Lake Pepin and Spring Lake, was the major issue addressed by this study. Lake Pepin occupies much of Pool 4, while the smaller Spring Lake lies in the pooled area upstream of Lock and Dam No. 2 (Fig. 3). Major sources of nutrient loads to the study area include the Metro Plant, which discharges in mid-Pool 2 downstream of St. Paul, and the Mississippi, Minnesota, and St. Croix Rivers. Following is a brief description of the study area. For a detailed description of the entire Lake Pepin watershed, see Stark *et al.* (1996).

The topography of the study area was determined in large part by Glacial River Warren, which flowed ten to twelve thousand years ago at the end of the most recent glacial period (Waters, 1977). The river drained Glacial Lake Agassiz and carved the Minnesota River Valley and the Mississippi River Valley below their confluence. High bluffs, a wide and deep channel, floodplain lakes, and backwaters characterize this reach of the Mississippi River. Beginning in the late 1800s, the U.S. Army Corps of Engineers constructed wing dams and closing dams to divert flow back into the main channel to scour and deepen it for navigational traffic. In the 1930s, the Corps built a series of locks and dams to maintain a navigational channel of at least nine feet in depth.

The Mississippi River from Lock and Dam No. 1 through Lake Pepin is an important natural, cultural, economic, and recreational resource for the region. In November 1988, the National Park Service designated the 116-km (72-mi) reach through the Metro Area—from Dayton, Minnesota, to Prescott, Wisconsin—as the Mississippi National River and Recreation Area. Ten years later, in July 1998,

President Clinton announced the selection of the same segment as an American Heritage River.

An inventory of benefits conducted during the first phosphorus study cited several reports that document high levels of recreation in the study area (MPCA, 1993). For example, in August 1990, a special task force reported a total of 22 marinas with 2,883 slips and 30 launch ramps with 1,718 parking spaces in this reach, with many pending permit requests for new or expanded marinas (Mississippi River Marina Cumulative Impacts Task Force, 1990). Boating density was "at or near heavy congestion levels" on most of the main channel. As a more recent measure, the USACE recorded over 50,000 recreational vessels passing through Lock and Dam Nos. 1–4 during 1999, with the greatest traffic through Lock and Dam No. 3, between the St. Croix River and Lake Pepin (Dennis Holme, USACE St. Paul District, personal communication). The most popular boating activities are fishing, cruising, sailing, waterskiing, and swimming.

Locations along the Upper Mississippi River are designated as miles above the Ohio River confluence (e.g., UM815.6 is located on the Upper Mississippi River 815.6 river miles upstream of the Ohio River confluence). Table 1 contains a list of major features in the study area and their locations.

Table 1. Approximate locations of major features in the study area, provided as mile points on the Upper Mississippi River.

Feature	River Mile
Lock and Dam No. 1	UM847.7
Minnesota River Confluence	UM844.0
Metro Plant Outfall	UM835.1
Spring Lake	UM824–820
Lock and Dam No. 2	UM815.6
St. Croix River Confluence	UM811.5
Lock and Dam No. 3	UM796.9
Cannon River Confluence	UM795.7
Vermillion River Confluence	UM795.7
Lake Pepin	UM785–765
Lock and Dam No. 4	UM753.8

Lake Pepin, the primary focus of the Phosphorus Study, is a large and relatively deep natural impoundment in Pool 4 of the Upper Mississippi River. The lake is located 80 kilometers (50 river miles) downstream of St. Paul, between Red Wing and Wabasha, Minnesota (Fig. 3). Sand deposited by the higher gradient Chippewa River in Wisconsin created a large delta in the slower Mississippi River, impounding upstream waters and creating Lake Pepin after the glaciers retreated. Today, Lake Pepin is used extensively for recreational activities, such as boating, swimming, water-skiing, and fishing, and is also an important commercial, historical, and aesthetic resource for the region.

Table 2 lists the morphometric characteristics of Lake Pepin. It is a relatively long and narrow lake nestled between bluffs on the Minnesota and Wisconsin shores. Like other impoundments, Lake Pepin is shallower at its upstream end and increases in depth in a downstream direction. Mean annual flow of the Mississippi River upstream of Lake Pepin at Prescott, Wisconsin is 500 m^3/s (17,700 cfs; Mitton *et al.*, 1996). Water residence time varies with flow, typically ranging from 6 to 47 days.

Table 2. Morphometric characteristics of Lake Pepin (Heiskary and Vavricka, 1993).

Surface Area	102.7 km^2
Mean Depth	5.4 m
Maximum Depth	17 m
Width	1.7–3.3 km
Maximum Fetch	19 km
Length	33.5 km
Volume	552.8 hm^3
Watershed Area	121,966 km^2
Residence Time	19 days (mean); 6–47 days (typical range)

The watershed area of Lake Pepin is approximately 122,000 km^2, encompassing more than half of the land area of Minnesota and portions of Wisconsin, Iowa, and South Dakota (Fig. 2). The Lake Pepin watershed can be further subdivided into the basin areas of three major rivers, as follows (Hank DeHaan, USGS Upper Midwest Environmental Sciences Center, personal communication):

Mississippi River Basin (Through Lock and Dam No. 1) 51,000 km^2
Minnesota River Basin 44,000 km^2
St. Croix River Basin 20,000 km^2

Mean annual flows at key gaging stations on the rivers during water years 1935–96 were as follows:

Mississippi River near Anoka, Minnesota
240 m^3/s (8,480 cfs)
Minnesota River near Jordan, Minnesota
120 m^3/s (4,240 cfs)
St. Croix River at St. Croix Falls, Wisconsin
140 m^3/s (4,940 cfs)

The three major river basins account for approximately 96% of the flow and 95% of the drainage area measured at Lock and Dam No. 3 (Heiskary and Vavricka, 1993).

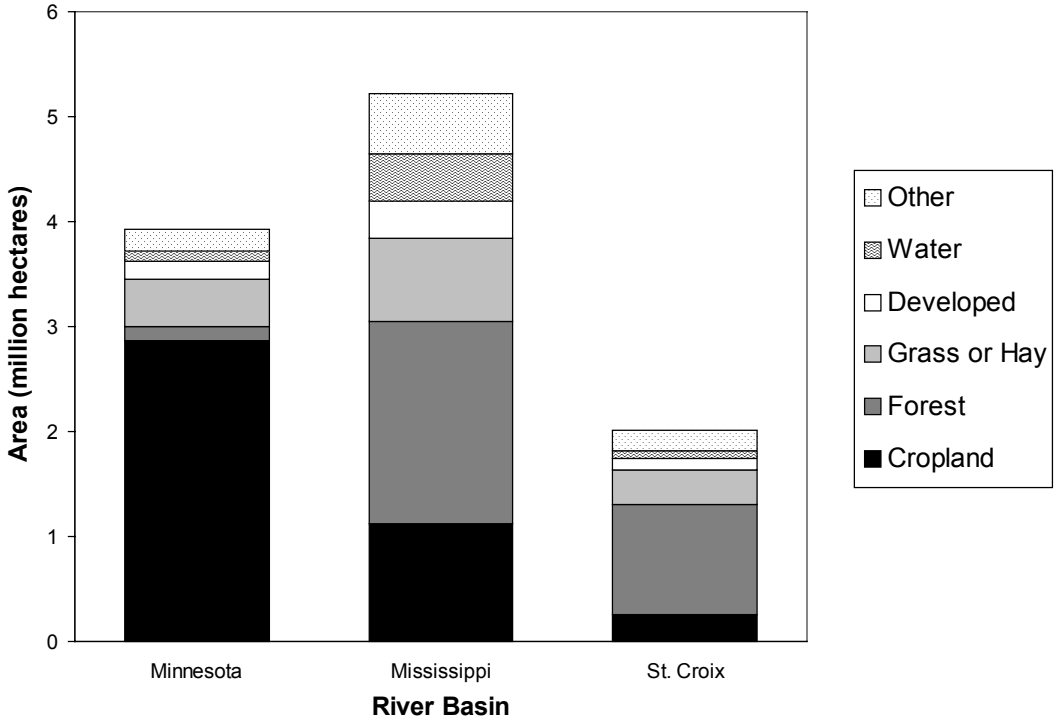
The Minnesota River drains the southwestern portion of Minnesota and minor portions of Iowa and South Dakota (Fig. 2; Meyer and Schellhaass, 2002). Soils in the basin are generally fine textured, fertile, and highly productive. At the time of the 1997 National Resources Inventory, the Minnesota River Basin was covered in 73% cultivated cropland, which included row crops, drilled crops, and hay or pasture in rotation (Fig. 14). The great majority (~90%) of original wetlands in the basin have been tiled and drained for agricultural uses.

The Mississippi River drains north central Minnesota, and the St. Croix River, a National Wild and Scenic River, drains northeastern Minnesota and part of northwestern Wisconsin (Fig. 2; Meyer and Schellhaass, 2002). The soils of both basins are naturally well drained and predominantly coarse textured. The Mississippi River Basin upstream of Prescott, Wisconsin, has a mix of land and water cover, with forest (37%), cultivated cropland (21%), and grass or hay (15%) leading the list in 1997 (Fig. 14; "Grass or Hay" includes permanent pasture or hay land, horticultural land, and land in the Conservation Reserve Program). Croplands in this basin are located mainly on fine-textured soil in the southern part of the basin. Forests (52%) and permanent pasture or hay land (17%) dominated the St. Croix River Basin in 1997 (Fig. 14). Mean annual precipitation increases from west to east across the three basins, from 56 cm/yr to 81 cm/yr. Runoff also increases from west to east, from less than 5 cm/yr to as high as 35 cm/yr.

The Cannon and Vermillion Rivers are two smaller tributaries that together drain 4420 km^2 of primarily agricultural lands in southeastern Minnesota (Fig. 3). The two rivers join before merging with the Mississippi River 1.6 km (1.0 mi) downstream of Lock and Dam No. 3.

Spring Lake, a secondary focus of the Phosphorus Study, is a shallow floodplain lake on the west side of the pooled area behind Lock and Dam No. 2 (Fig. 3). The lake is located 18 kilometers (11 miles) downstream of St. Paul, near Hastings, Minnesota.

Figure 14. Major land uses and water cover in the Mississippi River Basin upstream of Prescott, Wisconsin, and in the Minnesota and St. Croix River Basins in 1997 (Source: Susan Ploetz, 1997 National Resources Inventory, U.S. Department of Agriculture).



Before European settlement, the area was a floodplain forest and marsh separated from the main channel by a series of natural levee islands (USACE, 1991a; Schilling, 1984). In the mid-1800s, the lake was formed when a mill and dam were constructed on a creek draining the marsh. Since construction of Lock and Dam No. 2 at Hastings in 1931, water levels in the lake have been stable, and the bordering islands have increased in size with dredged material from channel maintenance. Stump fields from the former floodplain forest are still evident in the lake. The median depth of Spring Lake is 1.3 meters, and the maximum depth is 4.6 meters. The surface area is roughly six square kilometers. Mean annual flow of the Mississippi River upstream of Spring Lake at St. Paul, Minnesota is 320 m^3/s (11,300 cfs; Mitton *et al.*, 1996). A regional park is located on the south side of the lake in Dakota County, Minnesota.

The Twin Cities Metropolitan Area surrounds the confluence of the Mississippi and Minnesota Rivers and is bordered on the east by the lower St. Croix River. The seven-county Metro Area occupies 7,700 km^2, of which 35% is developed for urban land uses (Metropolitan Council, 1995). The area had an estimated population in 1996 of almost 2.5 million people (Metropolitan Council, 1996a).

The Metro Plant is the largest wastewater treatment facility in Minnesota, with a design capacity of 251 mgd (11 m^3/s; Fig. 15). The facility treats 80 percent of the wastewater in the Metro Area and roughly half of the state's wastewater. It is the largest facility on the Mississippi River north of St. Louis, Missouri. The Metro Plant is owned by the Metropolitan Council and operated by its Environmental Services Division. The facility serves 1.8 million people, 63 communities, and 800 industries. The level of treatment is advanced secondary with activated sludge aeration, nitrification, chlorination, and dechlorination. In 1996, biological phosphorus removal was implemented in a quarter of the waste stream. Currently, the Metro Plant has an annual average effluent flow of 9.6 m^3/s (220 mgd) and discharges treated wastewater to the middle of Pool 2 of the Mississippi River. The Metro Plant is the largest point source of phosphorus upstream of Lake Pepin.

Figure 15. Aerial photograph of the Metropolitan Wastewater Treatment Plant in St. Paul, Minnesota (Courtesy of MCES).

2 RESULTS AND DISCUSSION

Results from the six major components of the Lake Pepin Phosphorus Study, 1994–98, are provided in the following sections. Drawing from results of research projects by the Science Museum of Minnesota and University of Minnesota, Section 2.1 describes past conditions of water quality in Lake Pepin: what algal communities were like before European settlement and how phosphorus and sediment loading rates have changed over time in response to human activities. Section 2.2 integrates the results of studies by the USAE-WES, MWBAC, MCES, and HydroQual and describes current water-quality conditions in the Mississippi River, from Lock and Dam No. 1 through Lake Pepin. Specifically, the current status of phosphorus, phytoplankton, and suspended solids are discussed. Finally, Section 2.3 provides the results of model projections by HydroQual of future water-quality conditions in Lake Pepin and Spring Lake under different phosphorus management strategies.

2.1 Past Conditions

The following sections describe water-quality conditions in Lake Pepin before European settlement and how conditions have changed over the past 200 years due to human activities. Section 2.1.1 discusses the history of sediment deposits in Lake Pepin, and Section 2.1.2 discusses changes in phosphorus levels and diatom communities in the lake.

At the beginning of the Lake Pepin Phosphorus Study, the Cooperators Group posed these questions about past conditions in the lake:

- How has the water quality of Lake Pepin changed over time in response to human activities?

- Specifically, how have phosphorus and sediment loads, phosphorus concentrations, and algal communities changed?

In setting water-quality goals for Lake Pepin, it is valuable to have a benchmark to compare with current conditions. Water quality under pristine conditions of the past could provide this benchmark and describe what ultimately might be achieved in Lake Pepin if all human impacts could be mitigated.

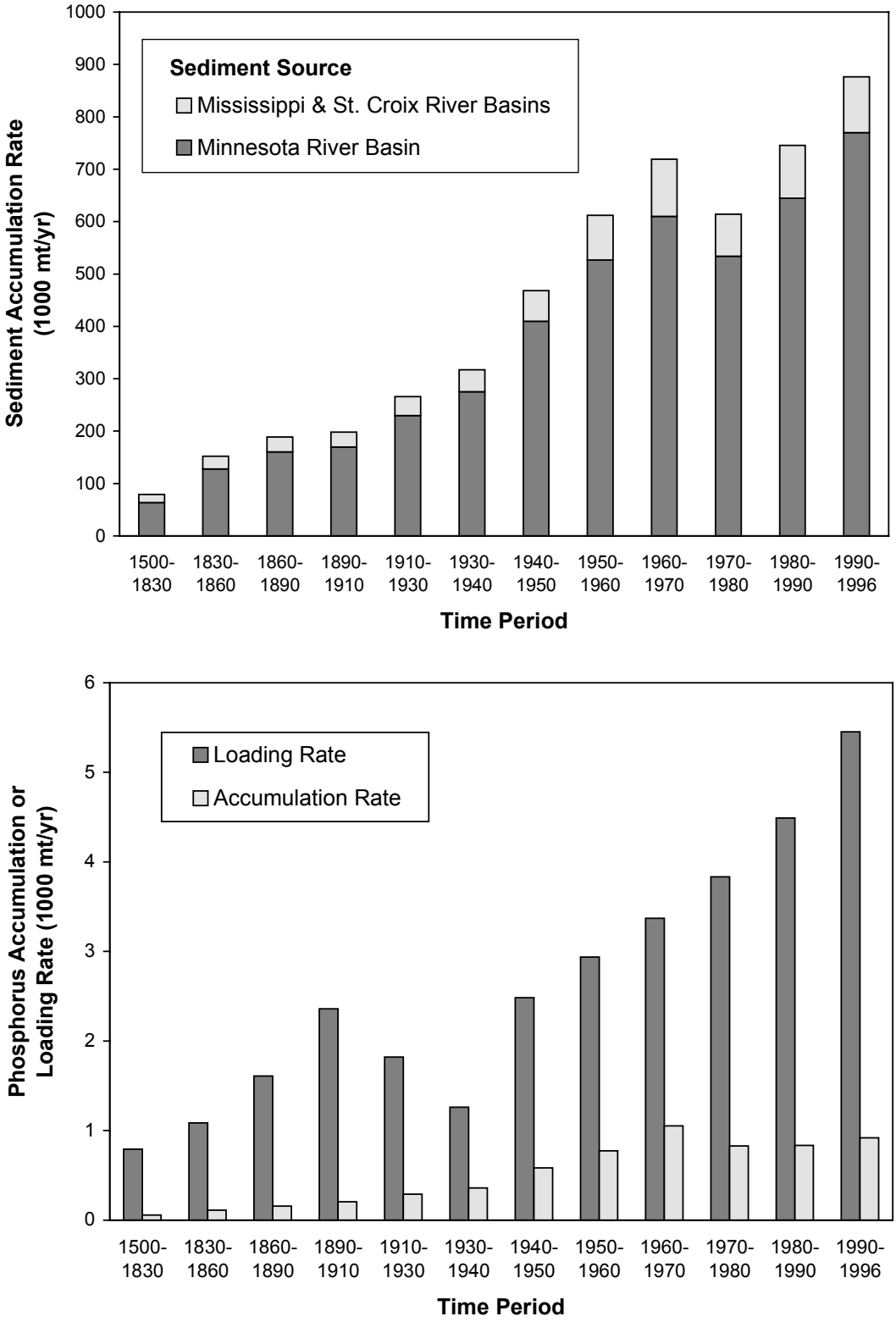
Researchers at the St. Croix Watershed Research Station of the Science Museum of Minnesota dated and analyzed 25 sediment cores collected from Lake Pepin in 1995 and 1996 (described further in Section 1.3.1). From this information, they reconstructed a history of sediment and phosphorus loads to the Mississippi River above Lake Pepin and a history of sediment deposition, phosphorus concentrations, and diatom communities in Lake Pepin. As an adjunct to this project, researchers in the Department of Soil, Water, and Climate at the University of Minnesota compiled historical data on agricultural practices and wastewater discharges in the three major river basins (described further in Section 1.3.2). They examined the relationship of human activities to sediment and phosphorus loading rates in the Lake Pepin watershed. Sections 2.1.1 and 2.1.2 integrate the results of these two research projects. Unless otherwise noted, information contained in these sections was derived from the final research reports for the two projects (Engstrom and Almendinger, 2000; Mulla *et al.*, 2000).

2.1.1 Sediment

Present-day rates of sediment accumulation in Lake Pepin are ten times greater than rates before European settlement. Engstrom and Almendinger (2000) estimated that sediment accumulation rates in Lake Pepin increased from 79,000 metric tons per year (mt/yr) before 1830 to 876,000 mt/yr during 1990–1996 (Fig. 16). The USAE-WES, MCES, and HydroQual calculated suspended solids loads of approximately one million mt/yr to Lake Pepin during 1994–96 (James *et al.,* 2000; Meyer and Schellhaass, 2002; and HydroQual, 2002a). A large portion of the suspended solids entering the lake settles and accumulates in the sediment bed. At an annual average retention rate of 74% (James *et al.,* 2000), a loading rate of one million mt/yr translates to a sediment accumulation rate of 740,000 mt/yr during 1994–96. Note that the years 1990–1996 experienced relatively high precipitation, a high portion of flow from the Minnesota River, and the 1993 flood. The flood year may explain, in part, the higher sediment accumulation rate for the 1990s in the Science Museum study, compared to the other studies.

Sediment accumulation rates doubled around the time of European settlement in the 1830s, increased gradually during the first few decades of the 20th century, and then rose sharply between 1940 and 1960 (Fig. 16; Engstrom and Almendinger, 2000). A clear decline in the 1970s was followed by a return to peak rates during the last two decades. At current rates, over 1.5 cm of sediment is deposited unevenly across the lake bed each year. Deposition rates have a strong longitudinal gradient in Lake Pepin, with the

Figure 16. Sediment accumulation rates, showing sediment contributions by major river basins, and phosphorus accumulation and loading rates in Lake Pepin, 1500–2000 (after Engstrom and Almendinger, 2000).



highest rates at the upstream end, then decreasing rates in a downstream direction.

The amount of area in row-crop production (Fig. 17) is likely the most important factor contributing to historical changes in soil losses in the Lake Pepin watershed (Mulla *et al.*, 2000). These soil losses are strongly controlled by soil erosion in the Minnesota River Basin. Soils in this watershed are fine textured and more susceptible to wind and water erosion. As far back as measured (to the 1500s), the Minnesota River Basin contributed over 70% of the sediment deposited in Lake Pepin (Fig. 16; Nater and Kelley, 1998). This portion has grown to over 80%, as prairies were converted to small grain and pasture and later to row crops. The Minnesota River Basin contributed an estimated 85% of the sediments deposited in Lake Pepin in the 1990s. The factors most strongly correlated with sediment loss in the Minnesota River Basin were changes in row-crop area ($r = 0.95$), population ($r = 0.92$), and river flow (since 1920; $r = 0.86$) (Mulla *et al.*, 2000). A linear regression model involving row-crop area explained 84% of the variation in sediment loss from this basin.

In the Lake Pepin watershed, wheat production peaked at the turn of the century, while pasturelands have declined since the 1930s, when they were first recorded (Mulla *et al.*, 2000). Row-crop production has increased steadily in the three basins since 1860 (Fig. 17) and now dominates the landscape of the Minnesota River Basin (Fig. 14). The largest increase occurred between 1940 and 1954, when row-crop area nearly doubled from 970 thousand to 1.8 million hectares. In 1992 there were three million hectares of row crops in the three basins, with the majority in the Minnesota River Basin.

2.1.2 Phosphorus and Diatoms

Solids settling to the bottom of Lake Pepin contain a certain amount of phosphorus sorbed to inorganic soil particles, such as clay, and phosphorus in organic matter, such as dead algae. In sediment samples dated to presettlement times, Engstrom and Almendinger (2000) reported phosphorus concentrations of 0.6–0.8 mg/g dry wt. Over the past 200 years, phosphorus concentrations in the sediment bed of Lake Pepin have doubled, ranging from 0.8 to 1.5 mg/g dry wt in the most recent deposits (1990–96), after a peak of 1.6–1.8 mg/g dry wt between 1950 and 1970. Concentrations declined after 1970 likely due to dilution by coarser, phosphorus-poor sediment, as evidenced by increased sediment grain size and carbonate content during recent decades. James *et al.* (2000) measured phosphorus concentrations in surficial sediment samples collected during 1994–96 and found an average concentration of 1.2 mg/g dry wt. In both studies, the most common forms of sediment phosphorus were iron- and aluminum-bound phosphorus.

With sediment phosphorus concentrations doubling and sediment accumulation rates increasing 10-fold from the 1830s to the 1990s, phosphorus was accumulating at increasing rates in Lake Pepin sediments. Engstrom and Almendinger (2000) found a 15-fold increase in phosphorus accumulation rates over the past 200 years, from 60 mt/yr before 1830 to 900 mt/yr in recent years (Fig. 16). A peak rate of 1050 mt/yr occurred during the 1960s.

However, phosphorus in the sediment is only part of the story: much of the phosphorus in Lake Pepin is soluble and remains in the water column until flushed out the lake. James *et al.* (2000) estimated an annual retention rate of 13% for total phosphorus in Lake Pepin during 1994–96, compared to 74% for suspended solids. In order to estimate phosphorus loads over time, the Science Museum needed a way to estimate phosphorus concentrations in the water column as well as the sediment bed of Lake Pepin. To accomplish this, the numbers and types of diatoms in sediment core samples were analyzed, and from this information, phosphorus concentrations in the water column could be reconstructed.

Algal communities in Lake Pepin, as represented by diatoms, have changed from clear-water benthic taxa and mesotrophic planktonic taxa in presettlement times to exclusively planktonic assemblages characteristic of highly eutrophic conditions today (Fig. 18; Engstrom and Almendinger, 2000). Around 1860, benthic and planktonic diatoms each represented about half of the diatom community. Since 1940, over 90% of the diatoms have been planktonic species. Factors explaining this change are increased phosphorus levels and possibly decreased light availability due to shading by phytoplankton or turbidity from suspended solids.

Two reconstructions of historical phosphorus concentrations in the water column of Lake Pepin were produced from the diatom data, using different reference sets for diatom species and phosphorus optima (Fig. 18). The first estimate better represents more recent conditions of high phosphorus concentrations, while the second estimate is probably a more accurate reconstruction of presettlement conditions (see Engstrom and Almendinger, 2000, for more

Figure 17. Agricultural phosphorus applications and row-crop area (top panel) and human population and wastewater phosphorus loads (bottom panel) in the Minnesota, Mississippi, and St. Croix River Basins upstream of Lake Pepin, 1860-1990 (after Mulla *et al*., 2000). Does not include St. Croix wastewater loads.

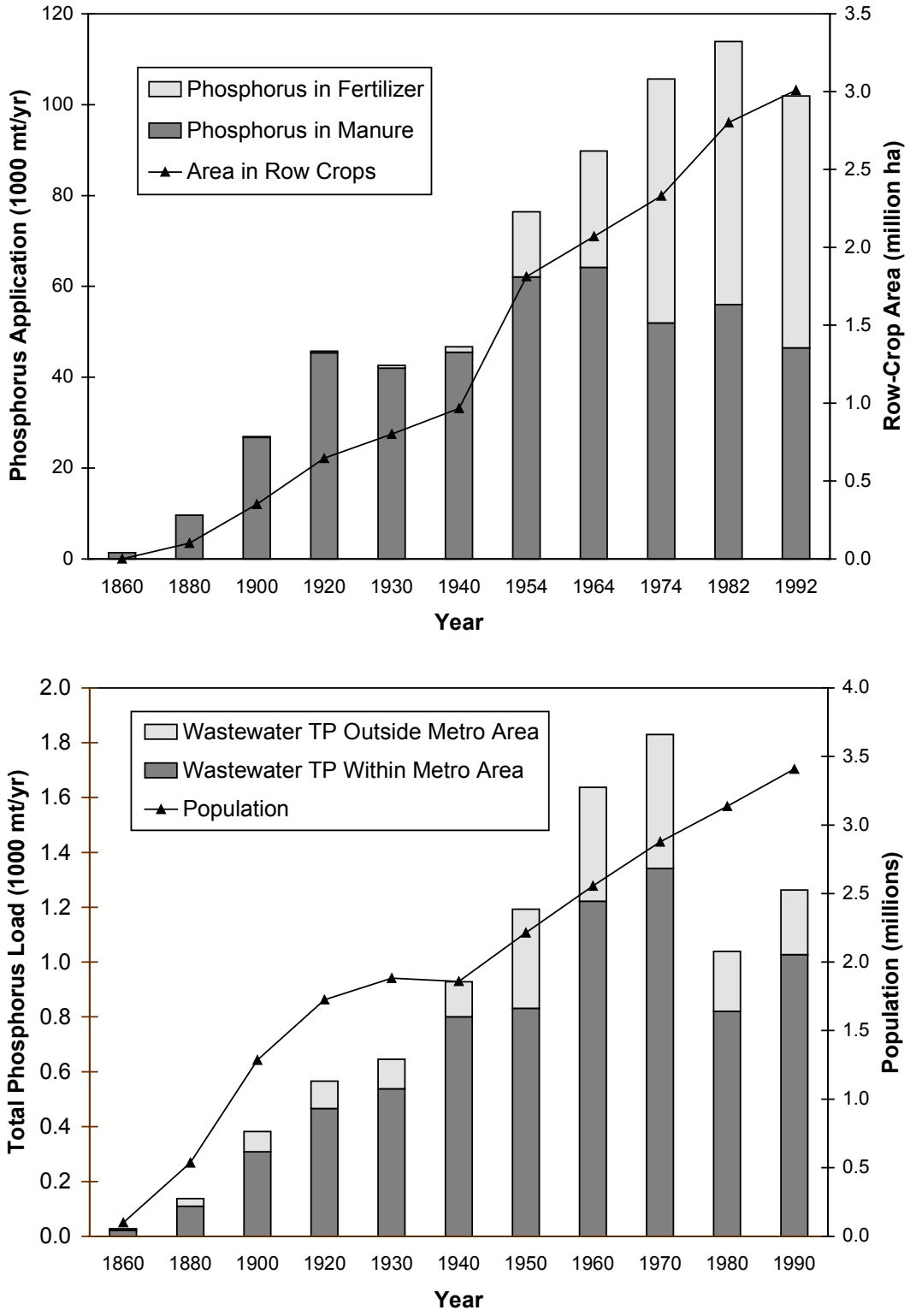
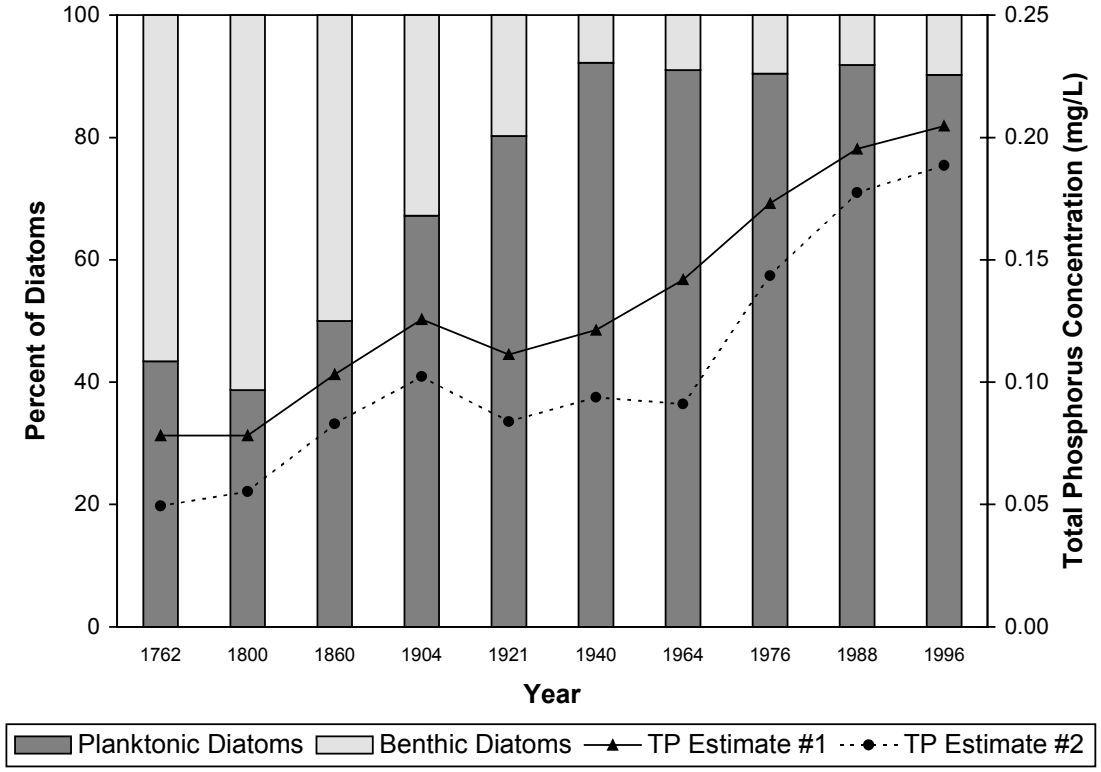


Figure 18. Percentages of planktonic and benthic diatoms and concentrations of diatom-inferred phosphorus in Lake Pepin, 1762–1996 (after Engstrom and Almendinger, 2000). Two estimates of total phosphorus concentrations represent alternative reconstructions based on species optima from different data sets.



information). Based on these reconstructions, phosphorus concentrations in the water column of Lake Pepin have increased four-fold since European settlement, from a summer average of 0.05 to 0.20 mg/L.

Engstrom and Almendinger (2000) estimated historical phosphorus loading rates to Lake Pepin by first calculating phosphorus exports from the lake (using diatom-inferred phosphorus concentrations and estimated river flows) and then adding phosphorus deposits in the sediment. Since European settlement, phosphorus loads to Lake Pepin have increased seven-fold to 5450 mt/yr during 1990–96, compared to 800 mt/yr before 1830 (Fig. 16). The USAE-WES, MCES, and HydroQual estimated mean phosphorus loads of 3800–4500 mt/yr to Lake Pepin during 1994–96 (James *et al.,* 2000; Meyer and Schellhaass, 2002; and HydroQual, 2002a). Part of the difference in load estimates for 1994–96 and 1990–96 may be explained by the flood year of 1993. Both HydroQual and MCES estimated a phosphorus load of approximately 6000 metric tons to Lake Pepin in 1993.

Driven by population growth and modulated by river flow, agricultural applications of fertilizer and wastewater discharges (Fig. 17) are likely the most important anthropogenic factors controlling historical changes in phosphorus loads to Lake Pepin (Mulla *et al.*, 2000). Total phosphorus loads to Lake Pepin were significantly correlated to historical changes in population (r = 0.96), row-crop area (r = 0.94), river flow (since 1920; r = 0.94), and phosphorus fertilizer applications (r = 0.92). A linear regression model involving fertilizer applications and river flows explained 94% of the variation in phosphorus loads. Row-crop production may have enhanced the movement of phosphorus from fields to streams. Phosphorus accumulation in the sediment of Lake Pepin was related to row-crop area (r = 0.85), river flow (since 1920; r = 0.84), and phosphorus discharges from Metro Area WWTPs (r = 0.82). A linear regression model involving row-crop area and WWTP phosphorus discharges explained 85% of the variation in phosphorus accumulation rates.

In 1940 commercial fertilizer applications of phosphorus (as P) on agricultural lands in the three

basins was slightly greater than a thousand metric tons per year (Fig. 17; Mulla *et al.*, 2000). Applications increased to 14,000 mt in 1954, 26,000 mt in 1964, and 55,000 mt in 1992. Including phosphorus in the manure of three million hogs and one million cattle, the agricultural application of phosphorus in the Lake Pepin watershed is currently around 100 thousand mt/yr.

Phosphorus loads from wastewater discharges increased with population growth until the 1970s (Fig. 17). Human population has increased over 30 times, from 100 thousand in 1860 to over three million in 1990. The 1976 statewide ban on phosphates in detergents reduced phosphorus loads contributed by WWTPs by approximately 40% between 1970 and 1980. However, phosphorus loads to Lake Pepin did not decrease significantly after 1976 (Fig. 16), despite decreases in WWTP loads and little change in fertilizer applications. It is suspected that increased river flows in the 1980s and 1990s, especially from the Minnesota River Basin, offset decreases in WWTP phosphorus loads with increased loads from nonpoint sources. Phosphorus loads from WWTPs in the three basins were approximately 2100 mt/yr in 1994–96 (Meyer and Schellhaass, 2002).

In summary, the most dramatic changes in sediment, phosphorus, and algae in Lake Pepin have occurred since 1940 as a result of population growth and poor management of land and water resources across the watershed.

2.2 Current Conditions

The following sections examine current water-quality conditions in the Mississippi River from Lock and Dam No. 1 through Lake Pepin. Phosphorus, phytoplankton, and suspended solids are described in Sections 2.2.1, 2.2.2, and 2.2.3, respectively. Current concentrations, spatial and temporal patterns, loading sources, and dynamics are discussed. Finally, Section 2.2.4 describes lake users' perceptions of current water quality in Spring Lake and Lake Pepin.

Due to different sources of information, discussions of current concentrations will first focus on the river (between Lock and Dam Nos. 1 and 3) and then the lakes (Spring Lake and Lake Pepin). For reaches within the Metro Area, MCES is the primary source of water-quality data for the Mississippi River and its tributaries, the Minnesota and St. Croix Rivers. Meyer and Schellhaass (2002) analyzed MCES data from 1976 to 1996 in their report on loading sources, which is further described in Section 1.3.3. During 1994–96, the Eau Galle Aquatic Ecology Laboratory of the USAE-WES collected the most comprehensive data set to date on nutrients, phytoplankton, and sediment in Lake Pepin and Spring Lake, which is documented in James *et al.* (2000) and further described in Section 1.3.4.

This report relies most heavily on the USAE-WES results for Spring Lake and Lake Pepin; however, several agencies have monitored the water quality of these two lakes in recent years. As a partner in the Lake Pepin Phosphorus Study, the MWBAC coordinated a volunteer monitoring program for both lakes from 1994 to 1998 to study lake users' perceptions of water quality (further described in Section 1.3.5). In 1990 the St. Paul District of the USACE studied the water quality of Spring Lake and other backwater lakes in Pool 2 (USACE, 1991b). The MWCC (now MCES) monitored Lake Pepin for several years in the 1970s and early 1980s but set the southern boundary of its Mississippi River monitoring program at Lock and Dam No. 3 from 1982 to 1995. Since 1996 MCES has analyzed samples from Lake Pepin in support of the advanced eutrophication model. The MPCA monitored Lake Pepin at times during the 1970s and 1980s; however, since 1990, the agency has committed to long-term monitoring of the lake during May-October. And, as part of an interagency Long Term Resource Monitoring Program for the Upper Mississippi River, the MDNR has monitored the water quality, vegetation, and biology of Lake Pepin and other locations in Pools 4 and 5 since 1990.

This section will also examine the complex issues of phosphorus fate and transport, factors controlling algal growth and community composition, and sediment trapping and accumulation. These discussions will rely heavily on the findings by James *et al.* (2000) and HydroQual (2002a and 2002b). James *et al.* (2000) conducted research on phosphorus, phytoplankton, and sediment dynamics in Lake Pepin and constructed detailed mass balances for Pool 2, Pool 3, Pool 4 headwaters, and Lake Pepin (further described in Section 1.3.4). To study the fate and transport of phosphorus, the role of sediment in phosphorus transport, and the relationship of phosphorus to algal growth, HydroQual (2002a and 2002b) developed an advanced eutrophication model of the Mississippi River, from Lock and Dam No. 1 through Lake Pepin (further described in Section 1.3.6). The model was built using data collected by the USAE-WES, MCES, and other agencies during 1985–96.

2.2.1 Phosphorus

The main objective of the 1994–98 Lake Pepin Phosphorus Study was to develop a better understanding of phosphorus dynamics in the Mississippi River and Lake Pepin. Among the key questions to address were the following:

- What are the relative contributions by different loading sources to the phosphorus balance in Lake Pepin?
- What are the rates of phosphorus flux from the sediment beds of Lake Pepin and Spring Lake under different conditions? What are the mechanisms of phosphorus release?
- What is the fate of phosphorus discharged to the Mississippi River upstream of Lake Pepin? How much is transported downstream to Lake Pepin? How much is deposited in Lake Pepin sediment and later released back to the water?

To help answer these questions, investigators looked at phosphorus information from a variety of sources. MCES examined phosphorus concentrations and loads in the Minnesota, Mississippi, and St. Croix Rivers during the period from 1976 to 1996. USAE-WES researchers and MWBAC volunteers monitored phosphorus levels in Spring Lake and Lake Pepin during 1994–96 and 1994–98, respectively. The USAE-WES also measured phosphorus release rates from the lake beds and constructed detailed balances of phosphorus inputs and outputs in the Pools and Lake Pepin to estimate net retention or export. Using a computer model of the Mississippi River and Lake Pepin, HydroQual studied the fate and transport of phosphorus. Concurrent with the Lake Pepin Phosphorus Study, the USGS National Water-Quality Assessment Program examined nitrogen and phosphorus in streams, streambed sediment, and groundwater in the Upper Mississippi River Basin through the outlet of Lake Pepin (Kroening and Andrews, 1997).

The following sections summarize the results of these studies, beginning with descriptions of current phosphorus concentrations in the river (Section 2.2.1.1) and lakes (Section 2.2.1.2). These descriptions will be followed by estimates of external and internal phosphorus loads to the study area (Sections 2.2.1.3 and 2.2.1.4, respectively). Finally, Section 2.2.1.5 discusses findings about the fate and transport of phosphorus in the Mississippi River from Lock and Dam No. 1 through Lake Pepin.

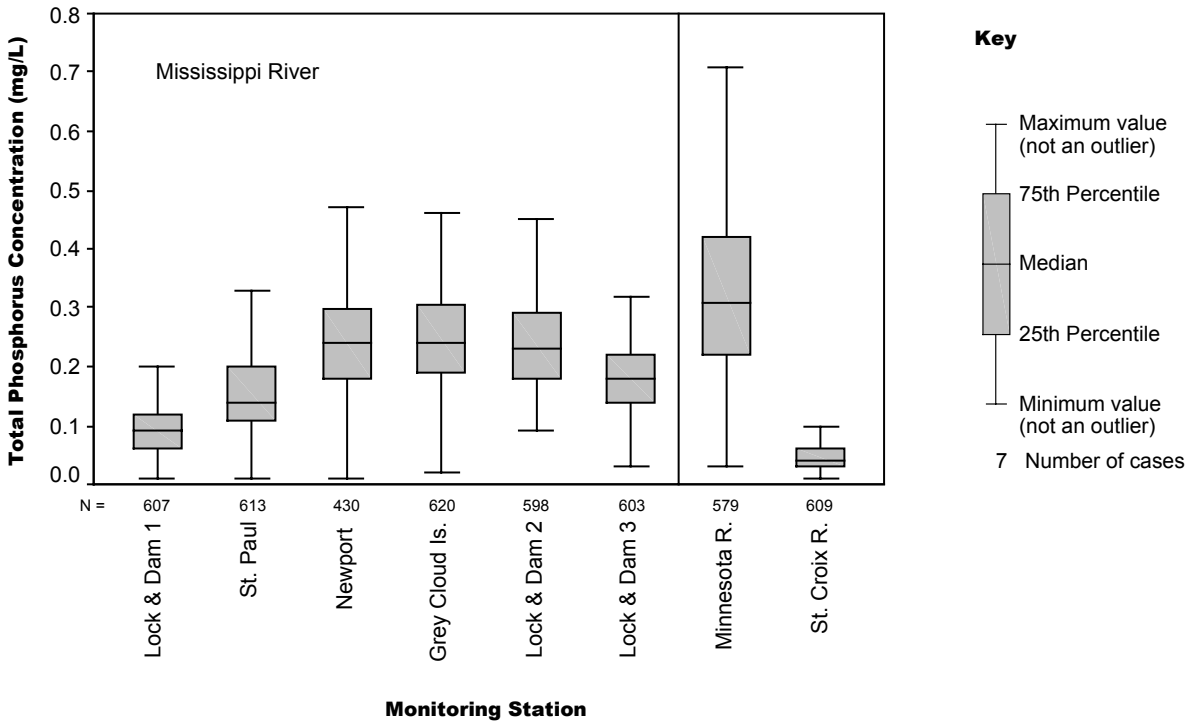
2.2.1.1 Phosphorus Concentrations in the Mississippi River, Lock and Dam Nos. 1–3

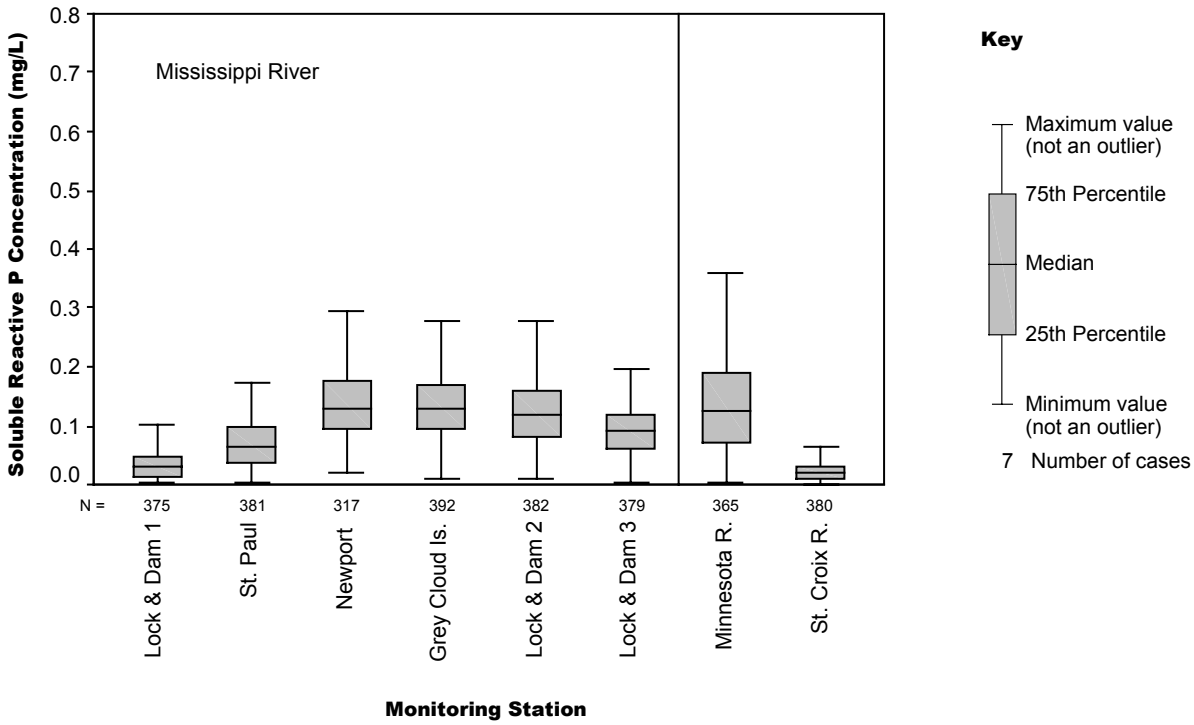
Over the 21-year period from 1976 to 1996, median total phosphorus concentrations monitored by MCES at Lock and Dam Nos. 1, 2, and 3 were 0.09, 0.23, and 0.18 mg/L, respectively (Fig. 19). Median concentrations of the two major tributaries, near their mouths, were 0.31 mg/L in the Minnesota River, which enters eight kilometers (five miles) downstream of Lock and Dam No. 1, and 0.04 mg/L in the St. Croix River, which enters six kilometers (four miles) downstream of Lock and Dam No. 2. The Metro Plant discharges to Pool 2 between St. Paul and Newport, Minnesota, and the mean effluent TP concentration over the same period was 2.7 mg/L.

Long-term median TP concentrations were more than twice as high at Lock and Dam No. 2 than at Lock and Dam No. 1, due principally to inputs from the Minnesota River and Metro Plant. In contrast, the addition of more dilute waters from the St. Croix River lowered the long-term median TP concentration in the Mississippi River by approximately 20 percent between Lock and Dam Nos. 2 and 3. In a trophic classification scheme for rivers based on chlorophyll *a* and nutrients, Dodds *et al.* (1998) proposed a boundary between mesotrophic and eutrophic states at a TP concentration of 0.075 mg/L. Under this scheme, phosphorus levels near the mouth of the Minnesota River and in Pools 2 and 3 of the Mississippi River are indicative of highly eutrophic conditions.

Within the Metro Area, phosphorus concentrations in the Minnesota and Mississippi Rivers also fail to meet current water-quality goals. Under USEPA direction, regional nutrient criteria for rivers are being developed, with state nutrient standards to follow (USEPA, 1998). Prior to this effort, the USEPA recommended a phosphorus goal of 0.10 mg/L for most rivers and 0.05 mg/L for rivers entering a lake or reservoir (USEPA, 1986). MPCA phosphorus criteria for lakes vary by use and ecoregion from <0.015 mg/L for drinking water supplies in the Northern Lakes and Forests Ecoregion to <0.090 mg/L for partial support of primary contact recreation in the Western Corn Belt Plains Ecoregion (Heiskary and Wilson, 1989). These goals for phosphorus are intended to protect rivers and lakes against degraded water quality, especially excessive algae and low oxygen levels, and impaired uses, such as swimming and fishing. In 1996 the Metropolitan Council adopted a goal of no adverse impact on water quality,

Figure 19. Boxplots of total and soluble reactive phosphorus concentrations at selected sites on the Mississippi River, Lock and Dam Nos. 1–3, and near the mouths of the Minnesota and St. Croix Rivers, January through December, 1976–96 (Data source: MCES). SRP was not monitored in 1976.





so that by the year 2015, the quality of water leaving the Metro Area will be as good as where it enters (Metropolitan Council, 1996b). During 1976–96, phosphorus concentrations consistently increased in the Mississippi River between Anoka and Hastings, Minnesota, which represent northern and southern boundaries of the Metro Area.

Eutrophication studies generally focus on the amount of soluble reactive phosphorus (SRP) in lakes and rivers, because SRP is the form of phosphorus most readily available for uptake by algae. In 1977 MCES started routinely measuring SRP in samples from all major river-monitoring stations. SRP was monitored less frequently (~1/month) than TP (~2/month) until the phosphorus studies in the 1990s, when both forms were monitored at the same frequency (2–4/month).

Over the 20-year period from 1977 to 1996, median SRP concentrations at Lock and Dam Nos. 1, 2, and 3 were 0.029, 0.120, and 0.090 mg/L, respectively (Fig. 19). As with total phosphorus, the two major tributaries displayed markedly different concentrations of SRP near their mouths: 0.126 mg/L in the Minnesota River and 0.020 mg/L in the St. Croix River. SRP has not been routinely monitored in Metro Plant effluent; however, based on special studies during 1990–92 and 1996, SRP was estimated to represent approximately 90% of effluent total phosphorus. This translates to an estimated mean SRP concentration of 2.4 mg/L during 1976–96. Spatial patterns of long-term median SRP concentrations in Pools 2 and 3 paralleled those of total phosphorus, with sharp increases downstream of the Minnesota River and Metro Plant and a distinct decrease downstream of the St. Croix River. On average, SRP concentrations quadrupled between Lock and Dam Nos. 1 and 2 and then decreased by 25% between Lock and Dam Nos. 2 and 3.

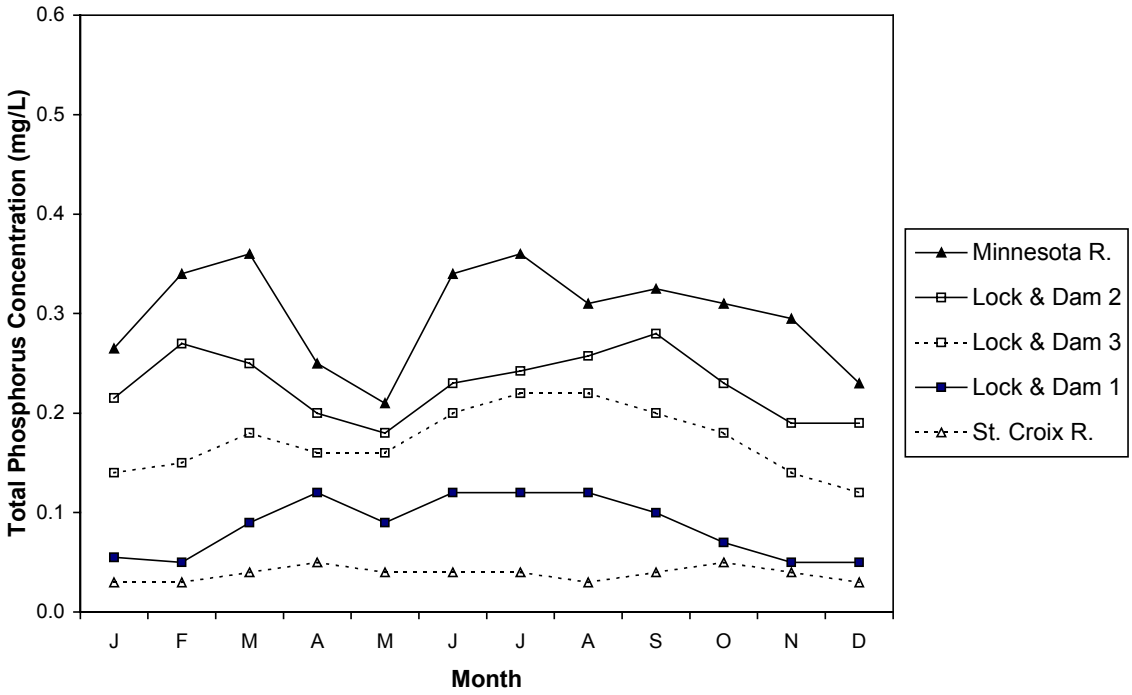
During 1977–96, the long-term median percent of TP as SRP rose from 37% at Lock and Dam No. 1 to 52% at Lock and Dam Nos. 2 and 3. All three major loading sources (Minnesota River, Metro Plant, and St. Croix River) had higher median percentages of TP as SRP (45, 90, and 50 percent, respectively) than the Mississippi River at Lock and Dam No. 1. However, the greatest increase in the long-term median percent of TP as SRP in the Mississippi River occurred below the Metro Plant (from 42% at St. Paul to 54% at Newport, Minnesota).

During the summer months (June–September), long-term median TP concentrations at Lock and Dam Nos. 1–3 were 0.03 mg/L higher than long-term annual median concentrations at these sites, and SRP concentrations were approximately 0.01 mg/L higher in the summer. Seasonal patterns are more clearly seen in month-to-month variations in median TP concentrations in the Mississippi River and its tributaries (Fig. 20). In particular, a distinct bimodal pattern appears in monthly median TP concentrations in the Minnesota River near its mouth and downstream at Lock and Dam Nos. 2 and 3, with peaks in the summer and late winter and valleys in the spring (April–May) and early winter (December–January). The springtime dip is even more distinct in SRP concentrations (Fig. 20).

Kroening and Andrews (1997) discovered a similar seasonal pattern in phosphorus concentrations and suggested some possible explanations. High summer concentrations may be due to runoff-transported fertilizers, while high winter concentrations may be due to decreased dilution of wastewater effluents during low flows. Low spring concentrations may be caused by increased dilution from snowmelt and spring rain events. In addition, the three rivers typically experience diatom blooms with warming temperatures in the spring, which likely explain the May minimum in SRP concentrations. Meyer and Schellhaass (2002) documented differences in seasonal phosphorus inputs from point and nonpoint sources, with point-source inputs being relatively stable from month to month, and nonpoint-source inputs being highly variable and dependent on rainfall events. They concluded that, in all three rivers, point sources are the most important contributors of phosphorus during the winter months and periods of low flow in the summer, and nonpoint sources are the most important contributors in the summer months of most years.

This dependency on river flow and the difference in phosphorus inputs between point and nonpoint sources also help to explain year-to-year variations in TP and SRP concentrations (Fig. 21). In the Minnesota River near its mouth and in the Mississippi River at Lock and Dam No. 2, for example, annual median TP concentrations peaked in the low flow years of 1976, 1988, and 1989 and were lower in the high flow years of 1986 and 1992–96. As river flows decreased, there was less water available to dilute high phosphorus concentrations from wastewater effluents. Under low flow conditions in 1988, median TP concentrations at Lock and Dam Nos. 1, 2, and 3 were 0.09, 0.28, and 0.20 mg/L, respectively. Concentrations in lower Pool 2 were substantially higher in 1988 than long-term median concentrations due to

Figure 20. Median monthly concentrations of total and soluble reactive phosphorus in the Mississippi River at Lock and Dam Nos. 1, 2, and 3 and near the mouths of the Minnesota and St. Croix Rivers, January through December, 1976–96 (Data source: MCES). SRP was not monitored in 1976.



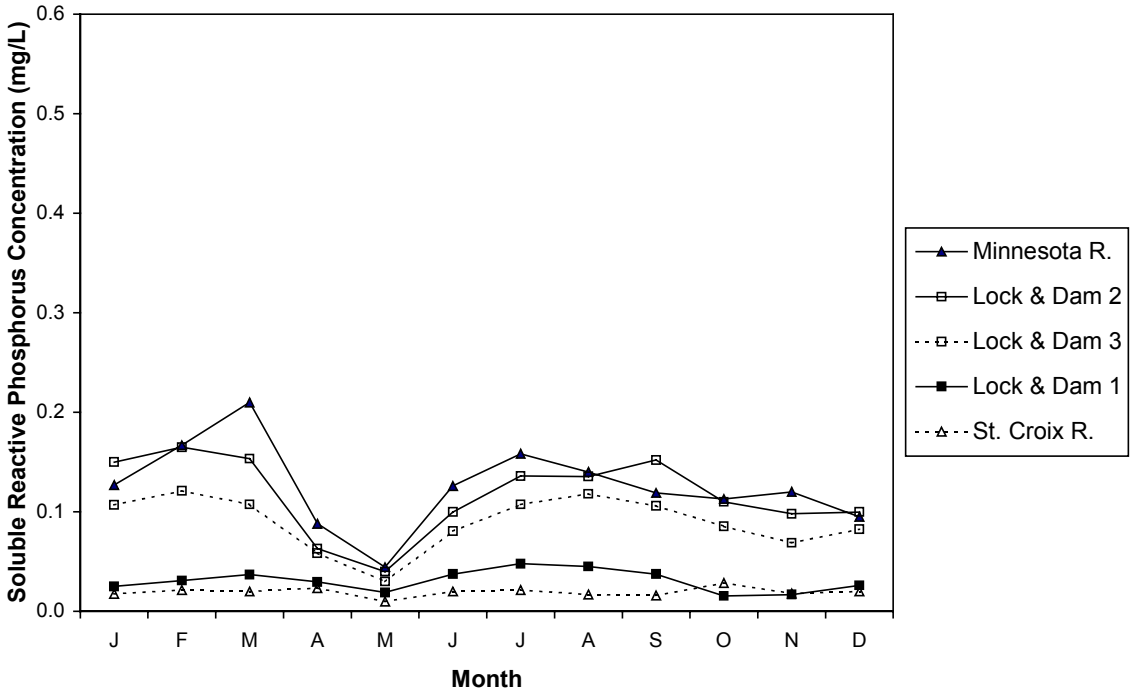
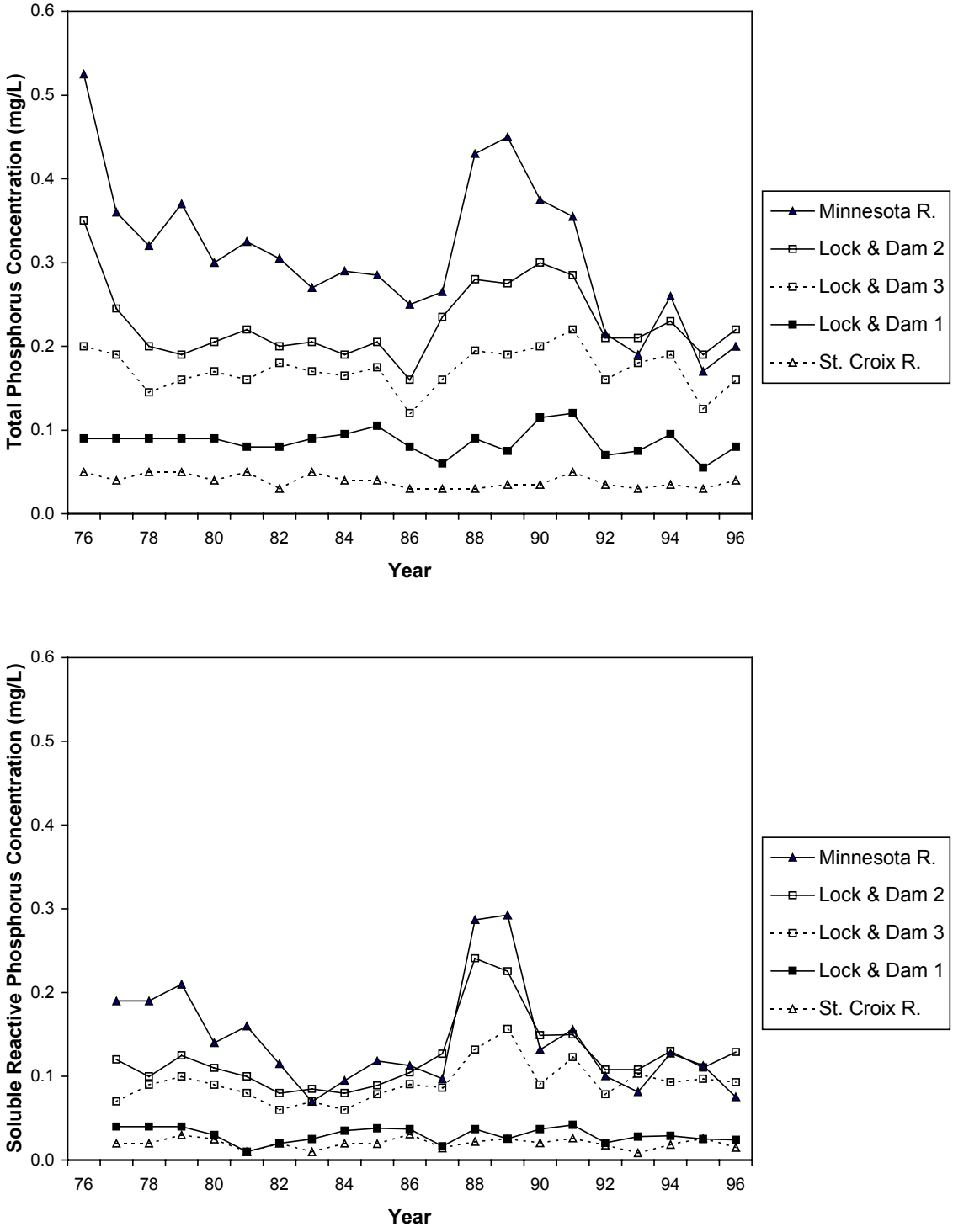


Figure 21. Median annual concentrations of total and soluble reactive phosphorus in the Mississippi River at Lock and Dam Nos. 1, 2, and 3 and near the mouths of the Minnesota and St. Croix Rivers, January through December, 1976–96 (Data source: MCES). SRP was not monitored in 1976.



a higher proportion of Metro Plant effluent flow relative to Mississippi River flow. In 1988 mean flows at the Metro Plant and Lock and Dam No. 2 were 9.4 and 145 m^3/s (214 mgd and 5120 cfs), respectively, or 6.5% Metro Plant effluent at Lock and Dam No. 2. In 1988 the median percent of TP as SRP climbed above 70% in lower Pool 2, with median SRP concentrations of 0.037, 0.241, and 0.132 mg/L at Lock and Dam Nos. 1, 2, and 3, respectively. At Lock and Dam No. 2, the median SRP concentration in 1988 was double the long-term median of 0.120 mg/L.

Within the study area, the most commonly measured forms of phosphorus have historically been total phosphorus, soluble reactive phosphorus, and to a lesser degree, particulate phosphorus. As discussed above, a high portion of the phosphorus in Pools 2 and 3 of the Mississippi River has been in the soluble reactive form—the form most readily available for algal uptake. During the phosphorus studies in the 1990s, MCES and other agencies began measuring molybdate-reactive phosphorus in both filtered and unfiltered samples. The difference (total - dissolved) roughly represents the portion of phosphorus sorbed to inorganic suspended solids (labeled particulate inorganic phosphorus), which was suspected as an important factor in phosphorus transport. The role of particulate inorganic phosphorus in the Mississippi River and Lake Pepin is discussed in Section 2.2.1.5. MCES also added dissolved phosphorus to its monitoring program in 1990. These five measured fractions of phosphorus (total, particulate, dissolved, soluble reactive, and total reactive) formed the basis for the modeling analysis by HydroQual.

2.2.1.2 Phosphorus Concentrations in Spring Lake and Lake Pepin

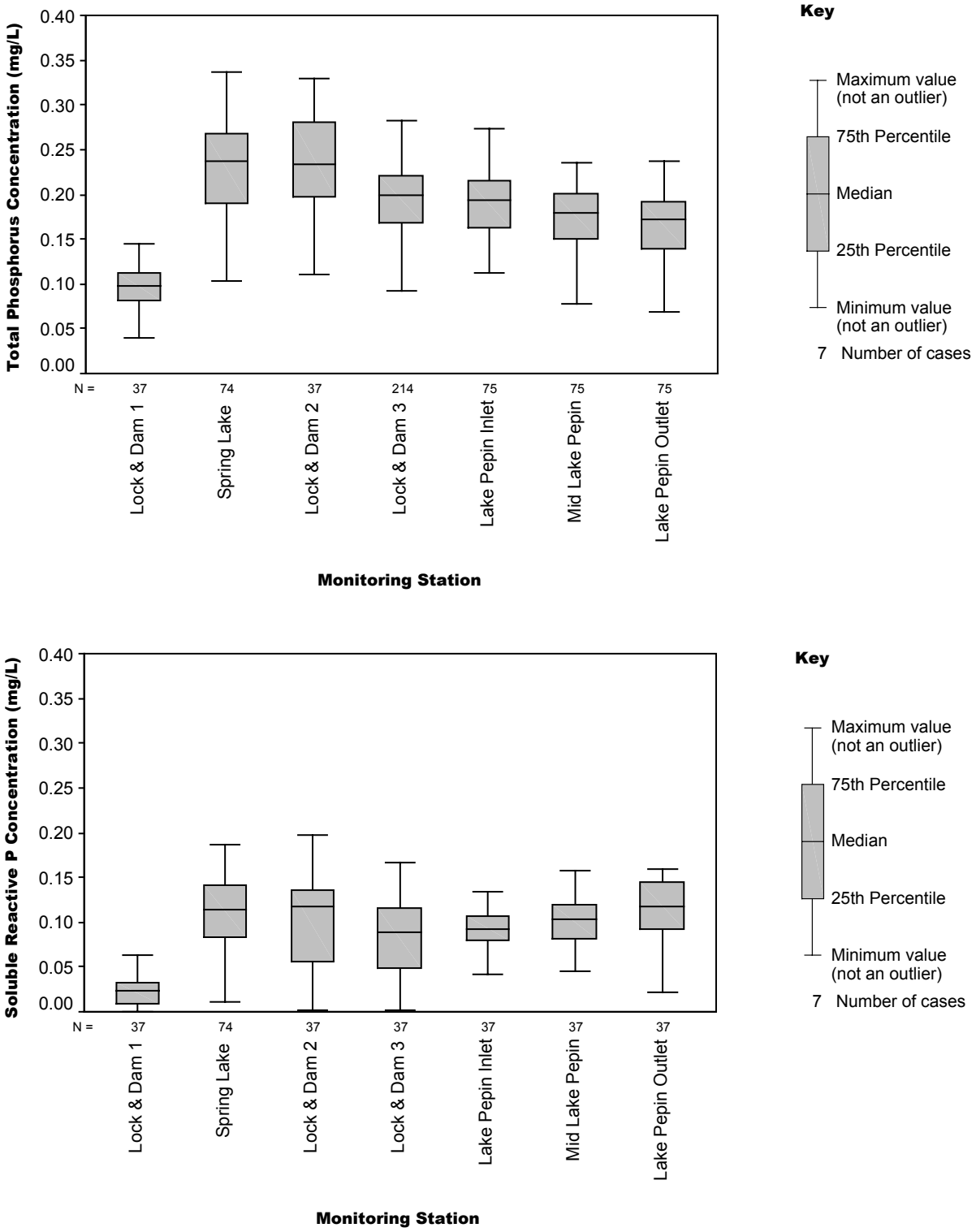
During 1994, 1995, and 1996, the USAE-WES surveyed the water quality of the Mississippi River, Lock and Dam Nos. 1–4, with special emphasis on Spring Lake and Lake Pepin (James *et al.*, 2000). Long-term monitoring programs of the USGS (flow) and MCES (water quality) provide data to compare the three-year period to a longer period of record. MCES started monitoring SRP in 1977, so the 20 years between 1977 and 1996 were chosen for the comparison. Downstream of the St. Croix River and upstream of Lake Pepin, the USGS maintains a gaging station on the Mississippi River at Prescott, Wisconsin (UM811.4), and MCES collects water-quality samples nearby at Lock and Dam No. 3 (UM796.9). There are no major tributaries or point sources between Prescott and Lock and Dam No. 3. The mean flow at Prescott during 1994–96 was 100 m^3/s (3600 cfs) higher than during 1977–96. At Lock and Dam No. 3, the median TP concentration for 1994–96 was somewhat lower than the median for 1977–96 (0.16 and 0.18 mg/L, respectively), while the median SRP concentration was somewhat higher (0.096 and 0.090 mg/L, respectively). Flow and water quality upstream of Lake Pepin during 1994–96 could be characterized as "normal."

Figure 22 provides a summary of TP and SRP concentrations in USAE-WES surface samples from Spring Lake, Lake Pepin, and Lock and Dam Nos. 1, 2 and 3 for May through October, 1994–96. The majority of USAE-WES lake samples were collected during these months, when most lake recreation occurs. As in the MCES data, phosphorus concentrations sharply increased between Lock and Dam Nos. 1 and 2, due primarily to loads from the Minnesota River and Metro Plant, and decreased between Lock and Dam Nos. 2 and 3, due primarily to dilution by the St. Croix River. Over the three-year period, median phosphorus concentrations in Spring Lake (TP, 0.238 mg/L; SRP, 0.115 mg/L) were nearly identical to those at Lock and Dam No. 2 (TP, 0.234 mg/L; SRP 0.117 mg/L). In summer 1990, the St. Paul District of the USACE also found the water quality of Spring Lake similar to a nearby site in the main channel of lower Pool 2 (USACE, 1991b). However, Stefan and Demetracopoulos (1979) demonstrated that, under low flow conditions, the mixing of lower Pool 2 and Spring Lake is dependent on wind speed and direction.

During May–October, 1994–96, total phosphorus concentrations were higher in Spring Lake than in Lake Pepin, where TP concentrations generally decreased in a downstream direction (Fig. 22). The median TP concentration fell from 0.193 mg/L at Lake Pepin's inlet (UM787.0) to 0.172 mg/L at its outlet (UM764.5). The median SRP concentration at the inlet to Lake Pepin (0.092 mg/L) was also lower than in Spring Lake (0.115 mg/L); however, SRP concentrations in Lake Pepin increased in a downstream direction (Fig. 22). At the outlet of Lake Pepin, the median SRP concentration (0.117 mg/L) was identical to the median at Lock and Dam No. 2 and very similar to the median in Spring Lake.

MWBAC volunteer data agreed very closely with USAE-WES data. During May–September, 1994–96, the volunteer data yielded a mean TP concentration of 0.224 mg/L for Spring Lake and 0.164 mg/L for Lake Pepin when flows were greater than 20,000 cfs (570 m^3/s; Macbeth and Gostovich, 1998). Mean concentrations in the two lakes were 0.271

Figure 22. Boxplots of total and soluble reactive phosphorus concentrations in the Mississippi River at Lock and Dam Nos. 1, 2, and 3 and at selected sites in Spring Lake and Lake Pepin, May through October, 1994–96 (Data source: USAE-WES).



and 0.207 mg/L, respectively, at lower flows. Within the targeted low flow range (under 20,000 cfs), TP concentrations were significantly higher and more variable in Spring Lake than in Lake Pepin and, likewise, significantly higher and more variable in upper Lake Pepin than in lower Lake Pepin. The five-year summary (1994–98) of the volunteer monitoring program contained similar results (Force and Macbeth, 2001).

Summer TP concentrations averaging over 200 µg/L in Spring Lake and over 150 µg/L in Lake Pepin during 1994–96 indicate highly enriched conditions with a high potential for algal blooms, if other conditions for algal growth are met. At a conference on lakes, Carlson (1999) suggested that TP concentrations above 100 µg/L, chlorophyll *a* concentrations above 55 µg/L, and Secchi-disk transparency readings less than 0.5 m may indicate a hypereutrophic lake. As stated by Carlson, hypereutrophy is usually regarded as extreme eutrophy, where the algae are limited by light due to self-shading.

James *et al.* (2000) documented and discussed the contrasting spatial patterns of TP and SRP concentrations along the length of Lake Pepin. Decreasing TP concentrations from the inlet to the outlet of Lake Pepin suggested an overall loss of phosphorus to the sediment bed, as particulate matter settles out of the water column. Increasing SRP concentrations suggested the occurrence of internal loading or transformations from particulate to soluble phases within the lake. The longitudinal gradient of SRP concentrations was especially pronounced in summer (see top panel in Fig. 23). Brief periods of stratification were observed in the summer months of 1994–96. During rare periods of anoxia, gradients of slightly higher SRP concentrations were observed near the sediment surface (see bottom panel in Fig. 23), which offered further evidence of internal loading. The USAE-WES measured sediment phosphorus release in Lake Pepin and estimated internal loading rates for the entire lake. Their findings are presented in Section 2.2.1.4.

SRP concentrations in the inflow and outflow of Lake Pepin exhibited a complex seasonal pattern during the three-year period of 1994–96 (Fig. 24; James *et al.*, 2000). With peak spring flows, SRP concentrations declined to a minimum in both the inflow and outflow, possibly due to dilution or spring diatom blooms. A similar spring minimum was seen in the MCES data for the mouth of the Minnesota River and the Mississippi River at Lock and Dam Nos. 2 and 3 (Section 2.2.1.1 and Fig. 20).

Winter SRP concentrations were greater in the inflow than the outflow of Lake Pepin, suggesting the retention of SRP. In contrast, summer SRP concentrations were greater in the outflow than the inflow, suggesting the export of SRP. This seasonal pattern was repeated in the SRP:TP ratio. During peak spring flows, SRP was a minor portion of TP (< 10%) and there was little change longitudinally in the ratio. In winter, SRP formed a large portion of TP (up to 80%). In summer, the SRP:TP ratio increased from 40–60% at upstream stations to 60–80% at downstream stations.

For the first phosphorus study, Heiskary and Vavricka (1993) compiled and analyzed data collected by the MWCC, MPCA, and MDNR during 1976–91 in a report on Lake Pepin water quality. Inflow TP concentrations exceeded outflow concentrations in 9 of 15 summers, while outflow SRP concentrations exceeded inflow concentrations in 13 of 14 summers. Mean inflow and outflow TP concentrations for these summers were 0.225 and 0.215 mg/L, respectively, and mean inflow and outflow SRP concentrations were 0.100 mg/L and 0.149 mg/L. Water residence time in Lake Pepin was shown to influence water-quality characteristics. The mean water residence times for the summers of 1976–91 ranged from 6 days in 1986 to 47 days in 1976 (Fig. 6). As one example of water-quality differences, TP concentrations were significantly higher in the low flow year of 1988 than in the higher flow years of 1990 and 1991.

2.2.1.3 Loading Sources of Phosphorus

Phosphorus loads from the Minnesota, Mississippi, and St. Croix Rivers and a myriad of point and nonpoint sources converge upstream of Lake Pepin at Lock and Dam No. 3 near Red Wing, Minnesota. Meyer and Schellhaass (2002) found strong linear relationships between annual river flows and annual phosphorus loads in the Mississippi, Minnesota, and St. Croix Rivers. In the Mississippi River at Lock and Dam No. 3, flows and phosphorus loads varied greatly year-to-year and month-to-month during 1976–96 (Figs. 25 and 26). Estimated annual TP loads at this location ranged from 1500 metric tons in the drought year of 1988 to 6300 metric tons in the flood year of 1993 (Fig. 25). During the 1987–89 drought, mean annual flows were below 425 m^3/s (15,000 cfs) and annual TP loads were less than 2000 metric tons. In contrast, during the four years preceding the drought (1983–86), mean annual flows were above 700 m^3/s (25,000 cfs) and annual TP loads were greater than 4000 metric tons.

Figure 23. Longitudinal and vertical variations in soluble reactive phosphorus concentrations in Lake Pepin on July 5, 1994 and September 10, 1996 (from James et al., 2000).

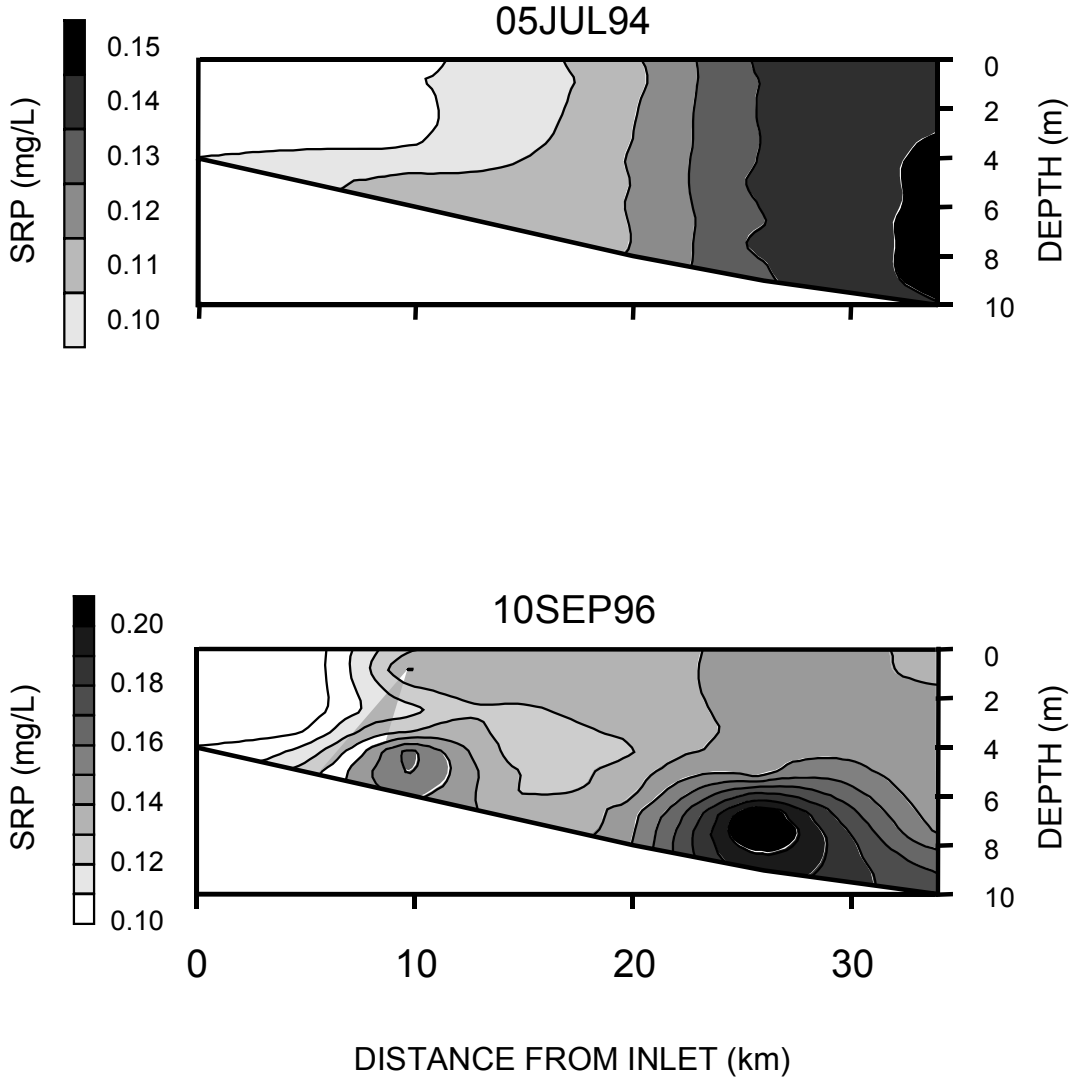
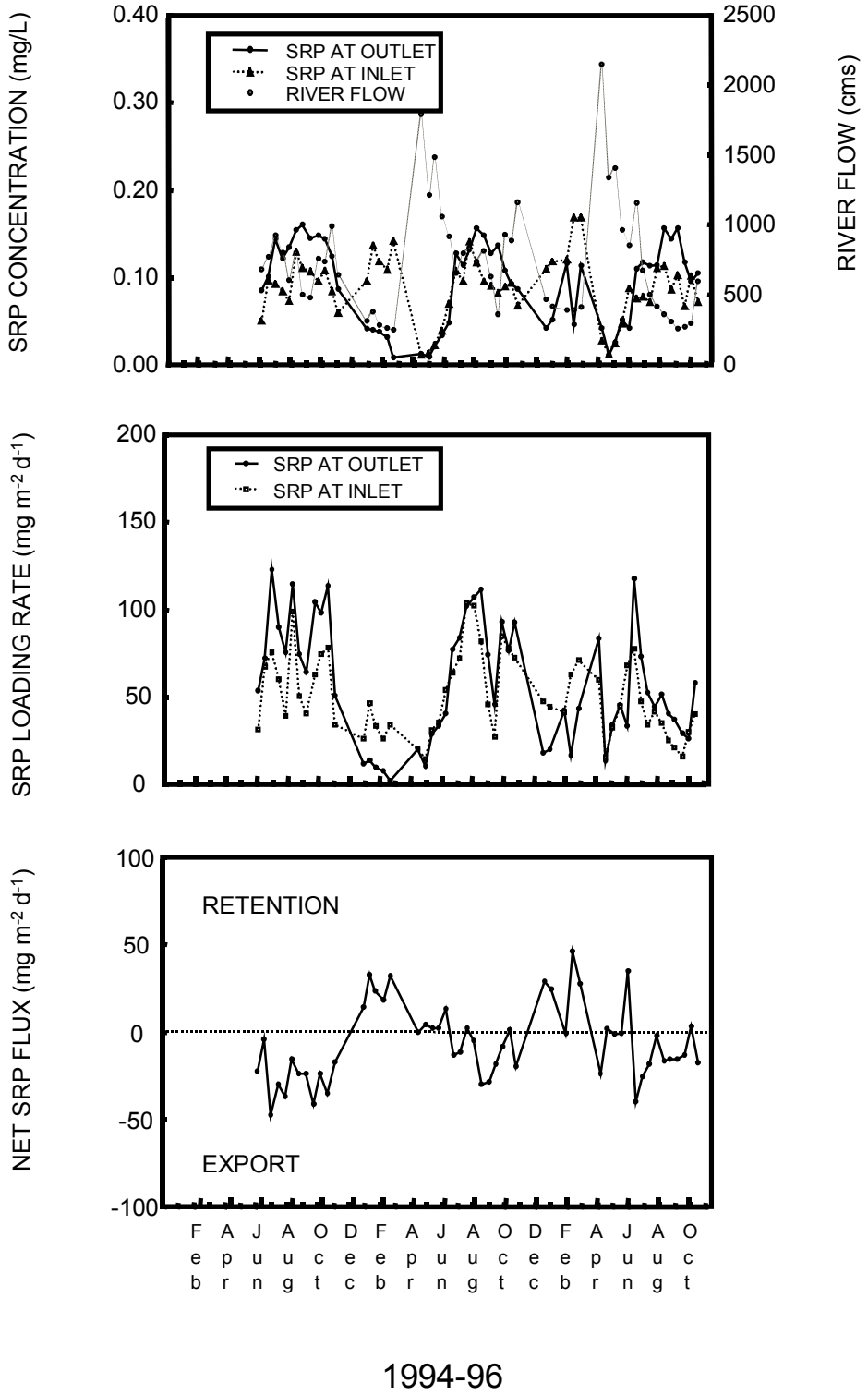


Figure 24. Seasonal variations in river flow and SRP concentrations and loading rates at the inlet and outlet of Lake Pepin and net SRP flux rates in Lake Pepin, 1994-96 (from James *et al.*, 2000).



Over the same 21-year period, mean monthly TP loads at Lock and Dam No. 3 peaked in April at 540 metric tons (Fig. 26). Mean monthly flows were also highest in April (1,260 m^3/s or 44,600 cfs at Prescott, Wisconsin). Both flows and TP loads decreased in May (1,020 m^3/s and 400 mt, respectively). However, as flows continued to decline in June and July, mean monthly TP loads rose to a second peak of approximately 450 metric tons. This bimodal pattern of monthly TP loads at Lock and Dam No. 3 most closely matched the pattern for the Minnesota River, where monthly TP loads peaked in April and again in June. Meyer and Schellhaass (2002) explained that the greatest rainfall amounts and erosivity indices occur in June, July, and August, leading to the greatest potential for soil erosion in these three months. However, as crops mature in late summer, corn and soybean canopies fill the gaps between crop rows, reducing the impact of rain. At the same time, evapotranspiration rates increase, reducing runoff. These factors may have led to greatly reduced TP loads at Lock and Dam No. 3 in August.

In compiling phosphorus loads and yields from MCES data for 1976–96, Meyer and Schellhaass (2002) found substantial differences among the three major river basins. Loads were estimated at the mouths of the Minnesota and St. Croix Rivers and at Lock and Dam No. 1 on the Mississippi River. Over the 21-year period, the Minnesota River produced much higher phosphorus loads than the other two rivers. The Minnesota, Mississippi, and St. Croix Rivers produced mean annual TP loads of 1570, 890, and 260 mt/yr, respectively, and mean annual SRP loads of 610, 320, and 110 mt/yr, respectively. Mean annual flows over the same period were 178 m^3/s (6270 cfs) in the Minnesota River, 262 m^3/s (9250 cfs) in the Mississippi River at Lock and Dam No. 1, and 157 m^3/s (5530 cfs) in the St. Croix River, yielding a flow ratio of approximately 7:10:6 among the three rivers (Minnesota : Mississippi : St. Croix) compared to a TP load ratio of 18:10:3. Phosphorus yields from the three basins were 0.37, 0.18, and 0.16 kg/ha/yr, respectively, for the Minnesota, Mississippi, and St. Croix River Basins. Possibly due to its fine-textured and more highly erodible soils, combined with a predominance of row-crop agriculture, the Minnesota River Basin yielded twice the amount of phosphorus per area as the other two basins. See Meyer and Schellhaass (2002) for a further discussion of different loading patterns from the three major rivers.

Both point and nonpoint sources contribute phosphorus loads to the Minnesota, Mississippi, and St. Croix Rivers. Phosphorus loads from nonpoint sources vary greatly from year to year, depending on the amount of annual precipitation and runoff, while point source loads are comparatively stable. Knowing this, Meyer and Schellhaass (2002) addressed the question of relative contributions from point and nonpoint sources in the major river basins by compiling TP loads over three flow regimes: low (1988), normal (1994–96), and high (1993). Figure 27 summarizes the results. During periods of low river flows, point sources contributed the majority of phosphorus loads to the Mississippi River upstream of Lake Pepin (e.g., 89% in 1988). River flows are low in the winter and during extended dry periods in the summer; at these times, runoff from urban and rural areas is substantially reduced, lowering inputs from nonpoint sources. However, at high river flows, nonpoint sources dominated TP loads to the study area (e.g., 75% in 1993). At normal flows, TP loads were roughly split between point and nonpoint sources (e.g., 55% and 45%, respectively, during 1994–96).

Note that river flows in the 1980s and 1990s, especially flows in the Minnesota River, were higher than historical flows. The mean flow of the Minnesota River at Jordan, Minnesota, was 125 m^3/s (4,430 cfs) during 1935–99 and 189 m^3/s (6,690 cfs) during 1980–99. If applied to earlier periods or the future, loading information from the 1980s and 1990s may tend to overestimate contributions from nonpoint sources, especially those in the Minnesota River Basin, and underestimate relative contributions by point sources.

The combined phosphorus load from the three major river basins and the Metro Plant was two to three times higher during years of normal-high flow than in low flow years (Fig. 27). For example, the combined TP load was roughly 2000 metric tons in 1988, 6000 metric tons in 1993, and 4000 mt/yr during 1994–96 (Meyer and Schellhaass, 2002). Average annual TP loads from the Metro Plant were very similar during these three periods (890 mt in 1988, 890 mt in 1993, and 1100 mt/yr during 1994–96). In years with higher river flows, increased TP loads were the result of increased loads from nonpoint sources. Both the portion and magnitude of TP loads contributed by nonpoint sources increased as rainfall, runoff, and river flows increased.

During five recent years representing low, normal, and high river flows (1988, 1994–96, and 1993, respectively), the Minnesota River accounted for 50–85% of the TP load from nonpoint sources, and the Metro Plant accounted for 50–60% of the TP load

Figure 25. Mean annual total phosphorus loads in the Mississippi River at Lock and Dam No. 3 and in the Metro Plant effluent, with mean annual flows of the Mississippi River at Prescott, Wisconsin, January through December, 1976–96 (Data sources: MCES and USGS).

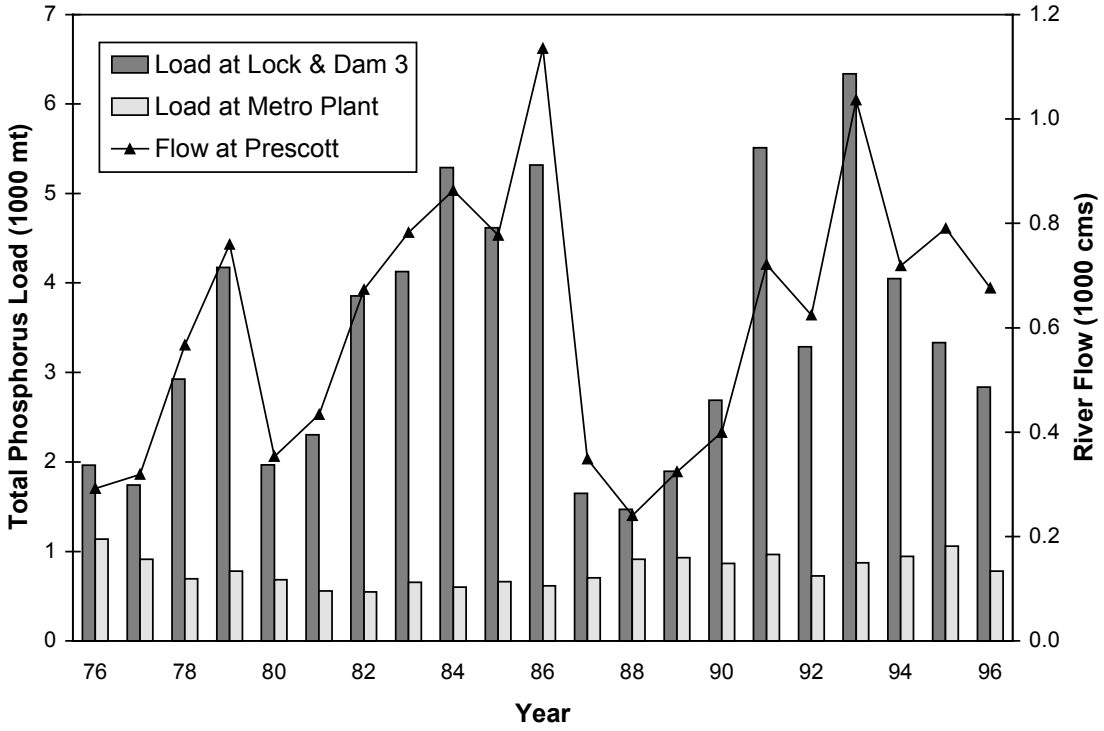


Figure 26. Mean monthly total phosphorus loads in the Mississippi River at Lock and Dam No. 3, with mean monthly flows of the Mississippi River at Prescott, Wisconsin, 1976–96 (Data sources: MCES and USGS).

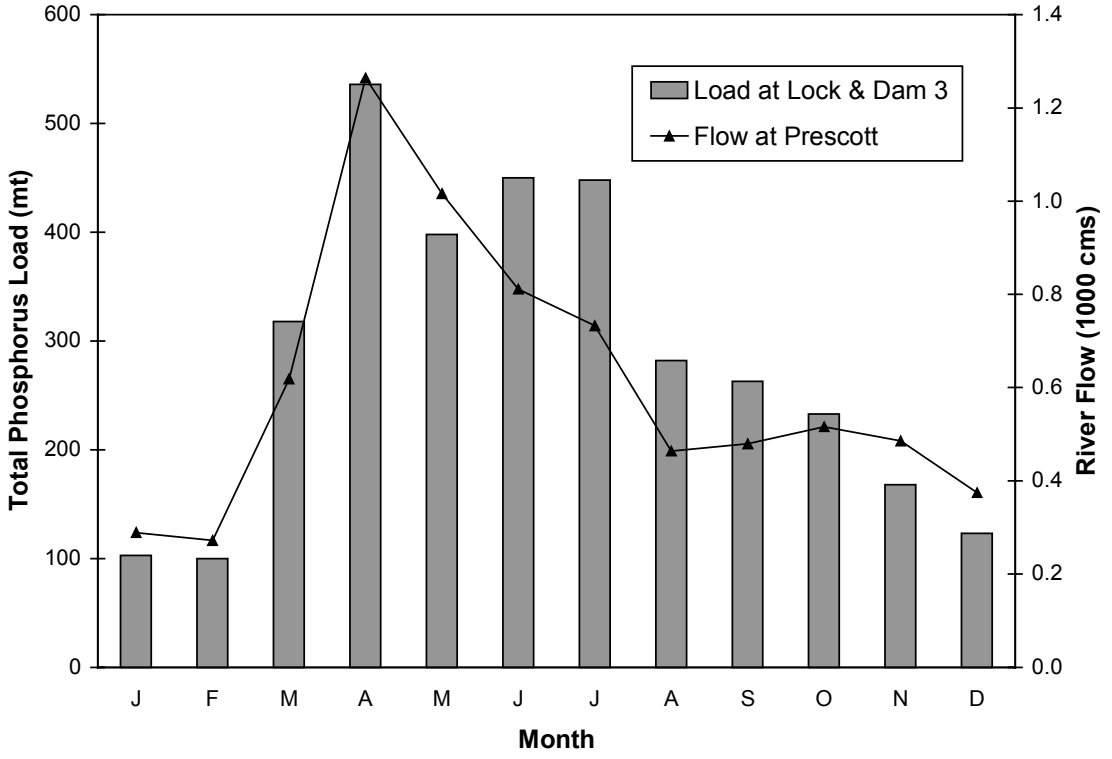
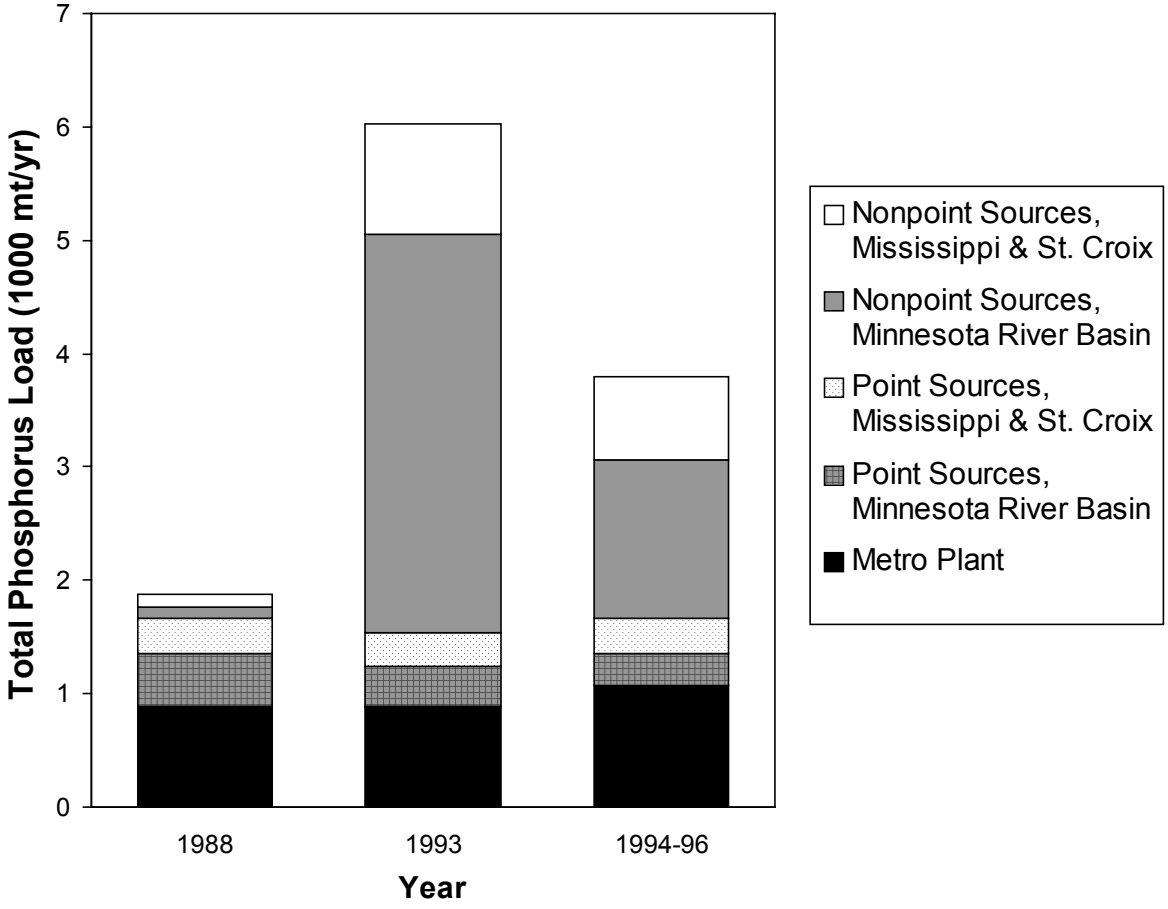


Figure 27. Mean annual total phosphorus loads from the Metro Plant and other point and nonpoint sources in the Minnesota, Mississippi (to Lock and Dam No. 1), and St. Croix River Basins during periods of low (1988), high (1993), and normal (1994–96) river flows (after Meyer and Schellhaass, 2002).



from point sources (Fig. 27; Meyer and Schellhaass, 2002). During the 21-year period from 1976 to 1996, the Metro Plant contributed 23% (790 mt/yr) of the estimated TP load to the Mississippi River upstream of Lake Pepin (3400 mt/yr), and the Minnesota River—point and nonpoint sources combined—contributed 45% (1540 mt/yr).

Phosphorus from point sources contains a much higher percentage (generally >85%) of soluble reactive phosphorus, the form most readily available for algal uptake (Meyer and Schellhaass, 2002). The Metro Plant alone contributed an estimated 40% of the SRP load to the Mississippi River upstream of Lake Pepin during the 20-year period from 1977 to 1996, or an average of 700 metric tons per year (assuming 90% TP as SRP in the effluent). The Metro Plant's SRP contribution climbed to over 60% during the low flow years of 1987 and 1988. During the normal flow years of 1994–1996, the median percent of TP as SRP was 35–44% in the three major rivers (Mississippi River at Lock and Dam No. 1 and the Minnesota and St. Croix Rivers near their mouths). Again, water quality in the three rivers reflects inputs from both point and nonpoint sources.

Swenson (1998) estimated that phosphorus loads in runoff from residential, commercial, and industrial areas in the Twin Cities Metropolitan Area ranged from 103 to 238 mt/yr. Estimates were based on current land-use data for the Metro Area and phosphorus loading rates for different land-use types from three previous studies. In comparison, the total phosphorus load from nonpoint sources in the three major river basins, including portions of the Metro Area, was estimated to be 2130 mt/yr in 1994–96 (Fig. 27; Meyer and Schellhaass, 2002). In 1996 approximately 884 mt of phosphorus (as P) in commercial fertilizers were sold for non-agricultural use in Minnesota (Swenson, 1998). In comparison, approximately 50,000 mt of phosphorus (as P) in commercial fertilizers were applied to agricultural lands in 1992 in the three major river basins (Mulla *et al.,* 2000).

2.2.1.4 *Internal Phosphorus Loading in Spring Lake and Lake Pepin*

The exchange of phosphorus between the sediment bed and overlying water is a major component of the phosphorus cycle in natural waters (Wetzel, 1975). It is regulated by mechanisms associated with mineral-water equilibria, sorption processes, redox interactions, and biological activities. In most lakes, the net movement of phosphorus is from the water into the sediment, with the sediment acting as a phosphorus sink. In particular, under oxic conditions, the sediment is an efficient trap for phosphate, which is adsorbed on and complexed with iron oxides and other compounds. However, under low oxygen levels, as often found in eutrophic systems, phosphate is desorbed and released from sediment particles, becomes mobile in sediment porewater, and may migrate to the water column. "Internal" phosphorus loading occurs when the sediment bed of a lake acts a source of soluble reactive phosphorus to the water column.

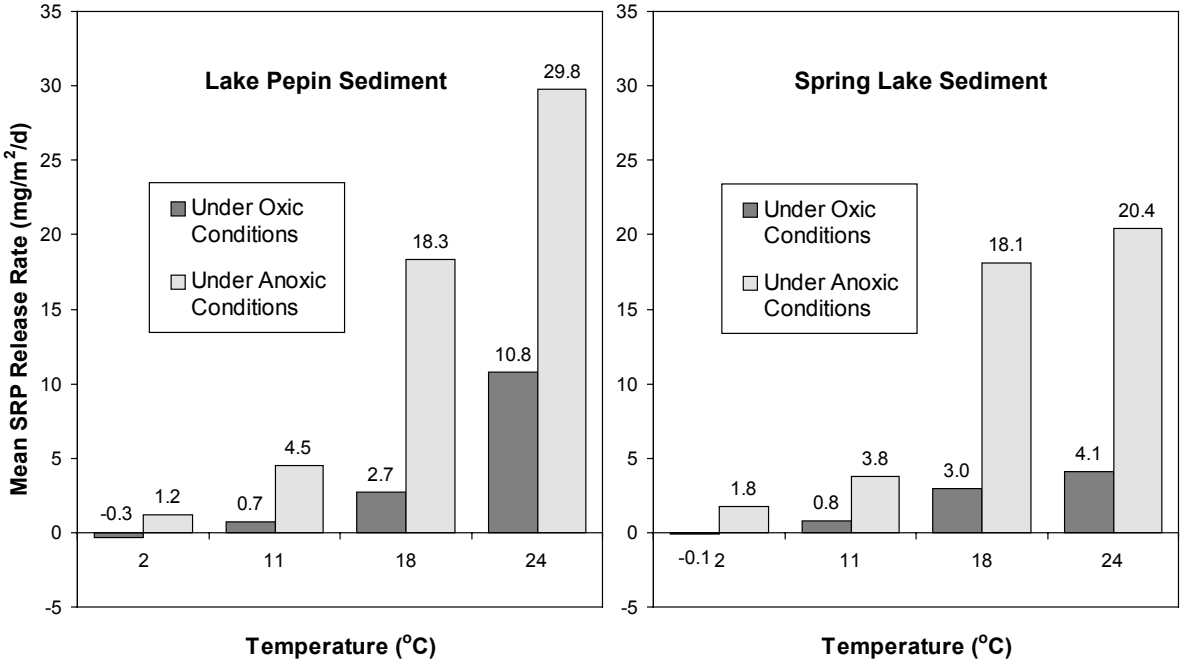
In their initial assessment of severe algal blooms in Lake Pepin during the summer of 1988, the MPCA (1989) discovered large discrepancies between phosphorus concentrations measured in lake-water samples and concentrations estimated by a model using loads from known sources. Model-estimated concentrations were much lower than observed concentrations. Internal loading was given as a likely explanation for the difference. This early finding was reinforced by additional research during the Lake Pepin Phosphorus Study, 1990–92. In a review of historical water-quality data (1976–91) for Lake Pepin, Heiskary and Vavricka (1993) found that, in 13 summers out of 14, SRP concentrations were greater at the lake outlet than at the inlet. Direct discharges and tributaries to the lake were comparatively small, and their loads did not explain the increase in concentrations.

James *et al.* (1993) conducted the first laboratory measurements of SRP release rates from Lake Pepin sediments, which yielded rates of approximately 15 mg/m^2/day under anoxic conditions and a surprising 4 mg/m^2/day under oxic conditions. In order to match observed SRP concentrations and account for internal loads in Lake Pepin during the summer of 1988, SRP release rates were set to 15–20 mg/m^2/day in the BATHTUB model (Heiskary *et al.*, 1993) and 15–85 mg/m^2/day in the WASP model (EnviroTech, 1993). When it came to applying the models to future conditions, there was much discussion at the end of the 1990–92 studies on how SRP release rates would change in response to reductions in external phosphorus loads to Lake Pepin. At the time, neither model supported direct simulations of phosphorus sorption in the water column, phosphorus transformations in the sediment bed, or phosphorus fluxes between the sediment bed and water column; however, these capabilities were being developed in other projects, such as the Chesapeake Bay model (Cerco and Cole, 1994).

Clearly, the rates and dynamics of phosphate flux from the sediment bed in Lake Pepin were critical areas to research during the 1994–98 phosphorus studies. For this purpose, the USAE-WES conducted additional research in the laboratory and field, and HydroQual developed a modeling system to track the movement of phosphorus across the sediment-water interface. Using sediment peepers in the field and sediment incubation systems in the laboratory during 1994–96, the USAE-WES measured SRP release rates from the sediment of Spring Lake and Lake Pepin under different redox and temperature conditions (James *et al.*, 1997). Applying sediment and water-quality data from the USAE-WES, MCES, and other agencies, HydroQual (2002a, 2002b) developed an advanced eutrophication model, which included a sediment-bed submodel, to simulate the dynamics of SRP release in Spring Lake and Lake Pepin during the 12-year period from 1985 to 1996.

James *et al.* (1997 and 2000) summarize the findings of the USAE-WES project. SRP release rates measured from the sediment bed of Lake Pepin were high and within the range of rates measured in eutrophic lakes. *In-situ* rates measured with sediment peepers at three locations in Lake Pepin during April–October, 1994–1996, ranged from 0.2 to 11.6 mg/m^2/day. Thermal stratification and hypoxic conditions near the sediment bed occurred infrequently during these three years of normal flows. In the laboratory, Lake Pepin sediments released substantial amounts of SRP under oxic as well as anoxic conditions; however, anoxic rates at 20°C (mean = 14.5 mg/m^2/day) were roughly five times greater than oxic rates at 20°C (mean = 2.9 mg/m^2/day). In the sediment incubation systems, average oxic rates ranged from 0 mg/m^2/day at 2°C to 11 mg/m^2/day at 24°C, while average anoxic rates ranged from 1 to 30 mg/m^2/day over the same temperature range (Fig. 28). At 2°C, 11°C, and 18°C, SRP release rates measured in the lab from sediment cores collected in Spring Lake were similar to oxic and anoxic rates measured from Lake Pepin cores (Fig. 28). Rates measured from Spring Lake sediment at summer temperatures of 24°C were lower.

Figure 28. Mean SRP release rates from sediment samples collected in Lake Pepin and Spring Lake in 1995–96, measured in the laboratory under different redox and temperature conditions (after James *et al.*, 2000).



James *et al.* (2000) found that seasonal differences, such as temperature, and dissolved oxygen concentrations at the sediment-water interface were the primary factors controlling SRP release rates in Spring Lake and Lake Pepin. Rates varied greatly by both temperature and oxygen levels and, as a consequence, can change with the weather, river flow, and location. While shown to be a factor in other studies, the pH in Lake Pepin was generally less than the level at which SRP release is enhanced. *In-situ* SRP release rates in Lake Pepin varied primarily as a function of temperature during the normal flow years of 1994–96. Sediment SRP release during the low flow summer of 1988 was likely much higher than during 1994–96. Hypoxia likely occurred more frequently and over wider areas of Lake Pepin in 1988, as evidenced by limited measurements of low DO concentrations and reports of localized fish kills.

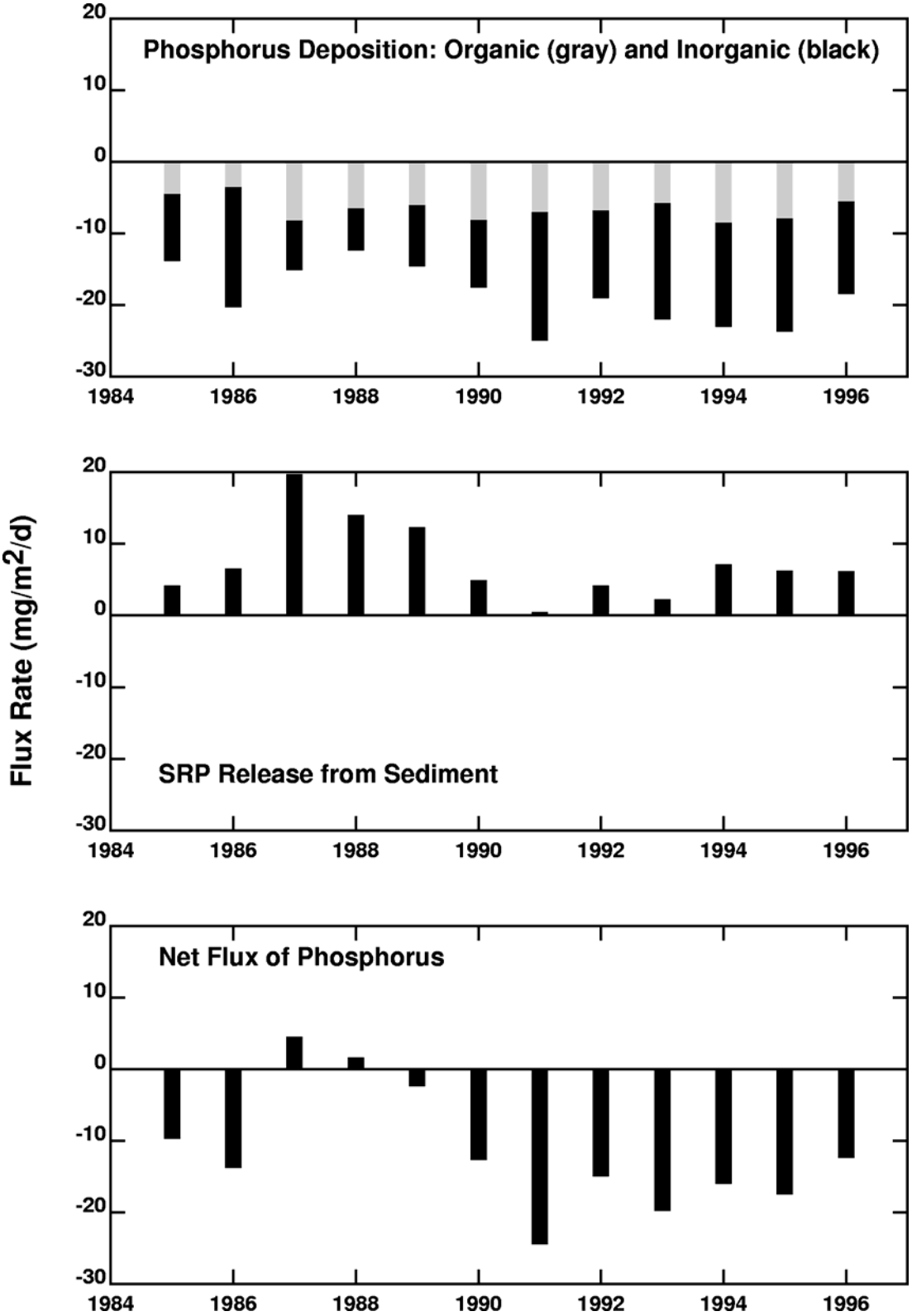
Using the advanced eutrophication model, HydroQual (2002a) estimated that the average SRP release rate across Lake Pepin was 7.3 mg/m^2/day during 1985–96. Annual average rates varied from less than 1 mg/m^2/day in 1991 to nearly 20 mg/m^2/day in 1987 (Fig. 29). SRP release rates were highest under low flow conditions, as seen in 1987–89, when thermal stratification and hypoxia occurred more frequently. During June–September 1988, the average SRP release rate was estimated at 40.4 mg/m^2/day in Lake Pepin**.** On average over the 12-year period, SRP release rates increased somewhat in a downstream direction from approximately 6 mg/m^2/day at the upper end of Lake Pepin to 8 mg/m^2/day at the lower end.

The average whole-lake SRP release rate estimated by HydroQual for the summers of 1994–96 (15.3 mg/m^2/day; James Szydlik, HydroQual, personal communication) was roughly double the rate estimated by the USAE-WES (7.5 mg/m^2/day; James *et al.*, 2000). However, results from both studies support the same general conclusions:

- SRP release rates in Lake Pepin are high and characteristic of eutrophic conditions. Seasonal differences (including temperature) and DO concentrations are the primary factors controlling SRP release rates in Lake Pepin.
- SRP release rates in Lake Pepin greatly increase under higher temperatures and anoxic conditions, which occur most frequently in summer.
- Internal SRP loading constitutes a substantial portion of the total phosphorus budget in Lake Pepin (discussed further in Section 2.2.1.5).

The differences in internal SRP loading rates for Lake Pepin, as estimated by the USAE-WES and HydroQual, are discussed below.

Figure 29. Annual phosphorus flux rates between the sediment and water column in Lake Pepin, 1985-96 (from HydroQual, 2002a).



Differences in Internal SRP Loading Estimates

USAE-WES and HydroQual estimates of the average rates of external and internal SRP loads to Lake Pepin during the summers of 1994–96 are compared in Table 3. While the two estimates of external SRP loading rates were very similar (59.6 and 56.6 $mg/m^2/day$), the internal SRP loading rate estimated by HydroQual (15.3 $mg/m^2/day$) was roughly double the USAE-WES rate (7.5 $mg/m^2/day$). [Note: The removal of June from the HydroQual estimates would not substantially change the loading rates.]

Table 3. Comparison of estimates by the USAE-WES and HydroQual of external and internal SRP loading rates to Lake Pepin during the summers of 1994–96 (James *et al.*, 2000; James Szydlik, HydroQual, personal communication).

	SRP Loading Rate	
Loading Type	USAE-WES[1]	HydroQual[2]
External ($mg/m^2/day$)	59.6	56.6
Internal ($mg/m^2/day$)	7.5	15.3
Internal To Total (%)	11.2%	21.3%

[1] July–Sept, 1994–96 [2] June–Sept, 1994–96

The difference in SRP release rates estimated by the two study partners should not raise a warning flag; the two teams used entirely different approaches, each with their own degree of uncertainty. Also, while the estimates differed, both studies support the major conclusions about internal SRP loading in Lake Pepin: oxic and anoxic rates are high, internal loading is significant, and temperature and oxygen levels are the main controlling factors. Methods used by each group to estimate whole-lake average rates of SRP release are described below.

USAE-WES Method for Estimating Whole-Lake SRP Release Rates

SRP release rates for Lake Pepin were estimated by the USAE-WES as a function of DO concentrations and temperature (James *et al.*, 2000). Two regression equations were developed with temperature as the independent variable and SRP release rate as the dependent variable: one equation for anoxic conditions and one for oxic conditions. Anoxic conditions were defined as DO concentrations below 0.5 mg/L. The regression equations were derived from laboratory measurements of SRP release rates under oxic and anoxic conditions at four temperatures (2, 11, 18, and 24 °C), representing the four seasons. The equations were applied to actual temperature and DO measurements obtained at six Lake Pepin sites during July–September, 1994–96. These measurements were taken weekly at one-meter depth intervals from the water surface to 0.5 m above the sediment bed. The calculated SRP release rates were then weighted with respect to sediment area at each depth interval to estimate the whole-lake internal SRP loading rate.

Uncertainty. As estimated by the USAE-WES, internal SRP loads could account for only 30–56% of the net SRP export from Lake Pepin, computed as the difference between FLUX-calculated loads at the inlet and outlet of Lake Pepin during July–Sept, 1994–96. James *et al.* (2000) suggested desorption in the water column as a possible source for the unexplained net SRP export. It is also possible that DO measurements at 0.5 m above the sediment bed could, at times, underestimate DO concentrations at the sediment-water interface, which are difficult to measure from a boat (John Sullivan, WDNR, personal communication). Current velocities generally decrease above the sediment bed, which would favor a climate producing lower DO concentrations.

HydroQual Method for Estimating Whole-Lake SRP Release Rates

HydroQual compiled SRP release rates for Lake Pepin from the results of a sediment submodel coupled to the advanced eutrophication model of 1985–96 (HydroQual, 2002a and 2002b). The initial state of the sediment bed in 1985 was described using 1990s data from USAE-WES studies of Lake Pepin sediment. In the water-quality model, particulate organic matter that settles is transferred to the sediment submodel, where decomposition is simulated in upper aerobic layer and lower anaerobic layers. Decomposition results in various dissolved products (e.g., particulate organic phosphorus is converted to SRP). The submodel tracks the movement of particulate and dissolved constituents in the sediment layers and between the sediment and water column. Depending on conditions, SRP and other decomposition products may be released from the sediment bed into the water column. Alternatively, they may be buried via sedimentation.

Sediment SRP release rates in the model are strongly affected by temperature and DO concentrations in the overlying water column. Temperature is a factor in the equation for the coefficient that quantifies mixing between the sediment and water. The

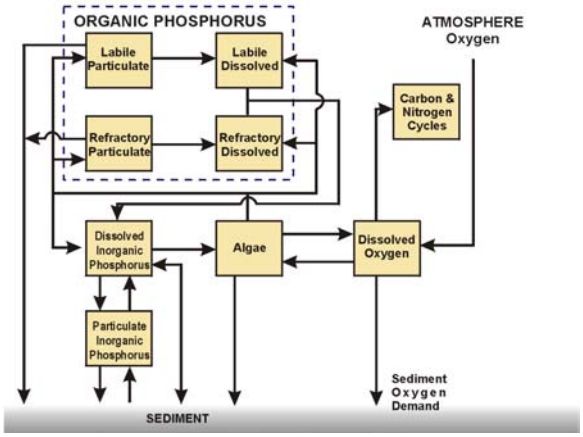
coefficient is expressed in terms of sediment oxygen demand and oxygen concentration in the overlying water, with sediment oxygen demand closely tied to temperature. DO concentrations in the overlying water are a factor in the equations that describe sorption of phosphates to sediment particles (presumably iron oxyhydroxides). At high DO concentrations, phosphates adsorb to particles and remain locked in the sediment bed. As DO concentrations decrease below a critical concentration, phosphates increasingly desorb from particles and may diffuse to the overlying water.

Uncertainty. The critical DO concentration for phosphorus desorption was set high in this application (Edward Garland, HydroQual, personal communication). In other modeling studies, the critical DO concentration was typically set at 2.0 mg/L, in line with the results of limnological studies. In the Lake Pepin model, this parameter was set at 4.0 mg/L to simulate the high SRP concentrations measured in Lake Pepin in summer 1988. This approach was a result of project constraints. To keep within the budget and construct a model for a Pentium processor, the number of vertical layers in the model was limited, which in turn limited the model's ability to simulate stratification and accurately represent DO concentrations near the sediment bed. With finer vertical resolution, it is likely the critical DO concentration for phosphorus sorption could have been set lower. The depth of the active (anaerobic) layer in the sediment submodel is also user-specified and was set at 10 cm (HydroQual, 2002b). The USAE-WES study showed the greatest change in porewater SRP concentrations between 0 and 4 cm (James *et al.*, 1998). The depth of the active layer affects how quickly the model responds to changes. Altering this depth would probably not change the seasonally averaged estimates of SRP release rates.

2.2.1.5 Fate and Transport of Phosphorus

Phosphorus is a very dynamic element in the Mississippi River and other aquatic systems. The modeling framework for the study area, for example, includes seven forms of phosphorus that are constantly undergoing transformations through different processes (Fig. 30; HydroQual, 2002a). Dissolved inorganic phosphorus is used by algae for growth and converted to organic and inorganic forms via respiration and predation. Inorganic phosphorus can also adsorb to suspended particles, and a desorption-sorption exchange exists between dissolved and particulate phases. Organic phosphorus is mineralized to inorganic phosphorus via decomposition. Labile forms decompose in several weeks to a month or two, while refractory forms require several months to a year. Particulate phosphorus, both inorganic and organic, may remain suspended in the water or settle to the sediment bed, and settled particles may be buried or resuspended. In the sediment bed, organic phosphorus decomposes and, under certain conditions, inorganic phosphorus can be released back into the water column (see Section 2.2.1.4). Phosphorus entering the Mississippi River and its tributaries may change forms many times before exiting Lake Pepin, especially when river flows are low (and residence times are high) and temperatures are high (and biological activities are high).

Figure 30. Schematic of phosphorus dynamics in a freshwater lake or river (HydroQual).



To understand the fate of phosphorus discharged to the Mississippi River, the USAE-WES, MCES, and HydroQual compiled phosphorus balances for Pool 2, Pool 3, upper Pool 4, and/or Lake Pepin over different periods of time. Long-term results from the advanced eutrophication model (1985–96) showed only a small fraction of phosphorus retained in the Mississippi River from Lock and Dam No. 1 through Lake Pepin (HydroQual, 2002a). Most phosphorus was flushed through the system and transported downstream of Lake Pepin rather than retained as sediment or biomass. This was partly due to the high portion of soluble phosphorus (see Section 2.2.1.1).

Model results generally agreed with phosphorus balances prepared by the USAE-WES and MCES. The USAE-WES compiled budgets for the three-year period from 1994 to 1996, a period generally characterized by normal flows. Over the three-year period, only 9–13% of the TP loads to Pool 2, upper Pool 4, and Lake Pepin were retained: 12% or 490 mt/yr in

Pool 2, 9% or 370 mt/yr in upper Pool 4, and 13% or 510 mt/yr in Lake Pepin (Fig. 31; James *et al.,* 2000). Over the same three-year period, however, SRP outputs exceeded inputs in Pool 3 and Lake Pepin by 13% on an average annual basis (but varied greatly year-to-year in Lake Pepin) and by 20–30% during July–September (24% in Pool 3 and 30% in Lake Pepin). This contributed to a net export of TP in Pool 3 over the three years (8% or 320 mt/yr). Internal loading accounts for much of the SRP exported from Lake Pepin (Section 2.2.1.4), but SRP export from Pool 3 remains unexplained (resuspension, bank erosion, additional loading sources, and need for better loading estimates were suggested). By contrast, SRP was retained in Pool 2 and the headwaters of Pool 4 during 1994–96, both on an average annual basis (15% and 16%, respectively) and in the summer (24% and 7%, respectively). The mechanism for SRP retention is likely algal uptake or sorption to particles. Over the longer period of 1976–96, Pool 2 retained an estimated 9% or 310 mt/yr of its TP load (Michael Meyer, MCES, personal communication).

HydroQual (2002a) examined total and soluble phosphorus loads to Lake Pepin from 1985 to 1996, especially fluxes between the sediment bed and water column. HydroQual estimates of phosphorus loads to Lake Pepin agreed closely with MCES and USAE-WES estimates (see MCES loading estimates in Fig. 25). During 1985–96, model-calculated TP loads at the inlet to Lake Pepin averaged approximately 4000 mt/yr. The annual average SRP load (2100 mt/yr) was roughly half this amount. Mean long-term TP and SRP loading rates in the summer months (June–September) were 20–25% higher than the annual rates. During the 12-year period, the annual TP load was highest in 1993 (nearly 6000 mt) and lowest in 1988 (under 2000 mt). In all years, the net exchange between the sediment bed and water column of Lake Pepin represented a relatively small fraction (<16%) of the mass of phosphorus flowing into Lake Pepin. The model calculated a net flux of total phosphorus into the sediment bed of Lake Pepin in 10 of 12 years with an overall average deposition rate of 420 mt/yr (Fig. 29), representing 10.5% of the annual average TP load at the lake's inlet.

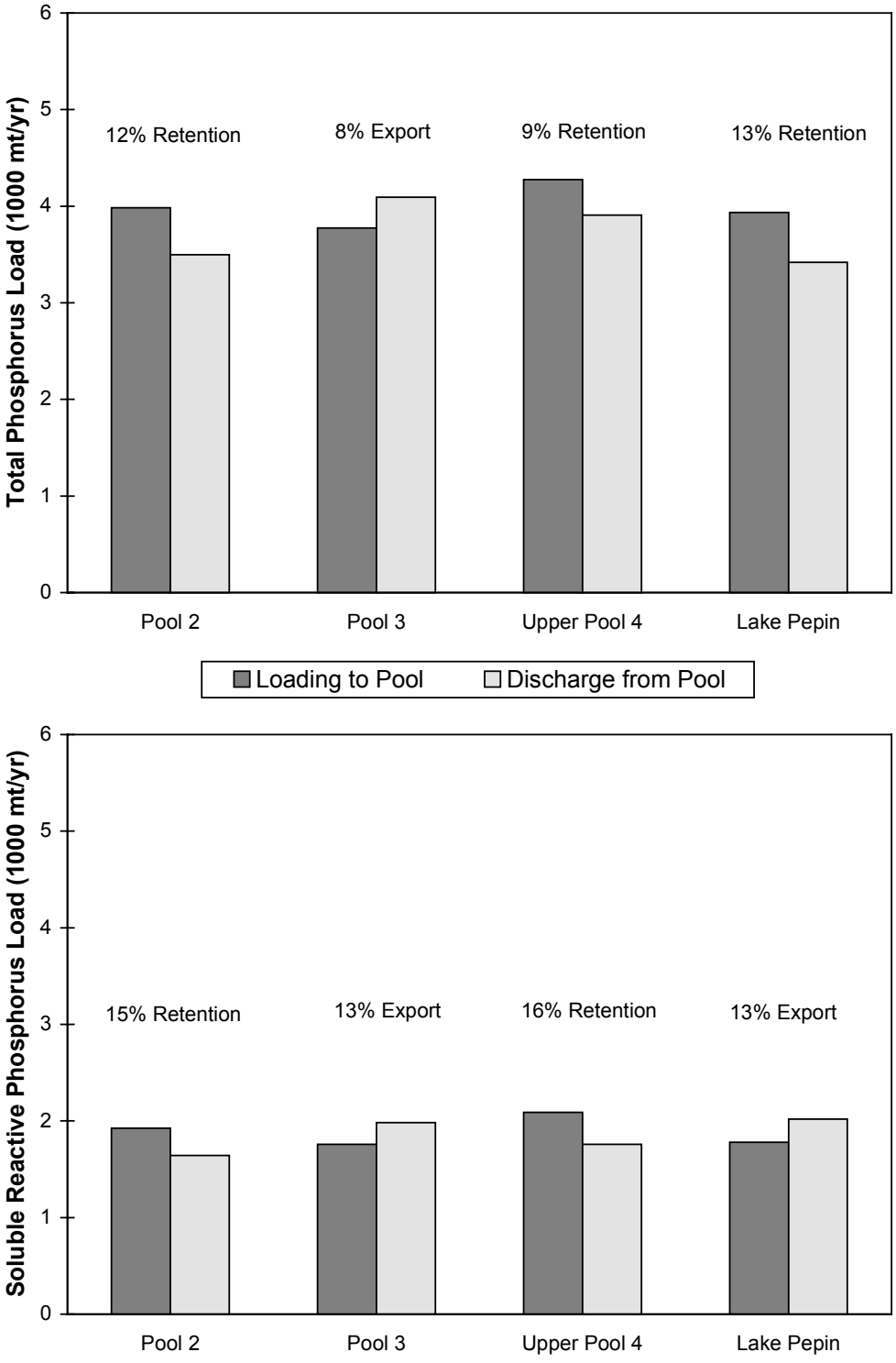
While roughly half of the phosphorus entering Lake Pepin was in the soluble reactive form, particulate forms represented a sizable portion of the phosphorus load and played an important role in the lake (HydroQual, 2002a). Transformations continuously occur within the lake between soluble and particulate, and inorganic and organic forms of phosphorus. Inorganic phosphorus sorbed to particles and organic phosphorus in living algae and detritus may settle to the sediment bed. Elevated concentrations of inorganic phosphorus in Pools 2–4 of the Mississippi River, on the order of hundreds of µg/L, allowed particulate inorganic phosphorus to account for a large portion of the total phosphorus flux to the sediment.

As stated above, only a small fraction of the phosphorus entering Lake Pepin was retained; however, given the magnitude of the load, this fraction amounted to high rates of phosphorus accumulation in the sediment. Phosphorus accumulation rates in Lake Pepin averaged 420 mt/yr (11.5 $mg/m^2/d$) during 1985–96 and 610 mt/yr (16.8 $mg/m^2/d$) in the wet 1990s (Fig. 29; HydroQual, 2002a). James *et al.* (2000) estimated a phosphorus accumulation rate of 468–540 mt/yr in Lake Pepin during 1994–96, while Engstrom and Almendinger (2000) estimated a rate of 920 mt/yr for 1990–96.

Figure 29 shows annual average rates for phosphorus deposition (top panel), SRP release (middle panel), and net phosphorus flux (bottom panel) to and from the sediment in Lake Pepin, as calculated by the advanced eutrophication model for 1985–96 (HydroQual, 2002a). The net phosphorus accumulation rate was at or above 20 $mg/m^2/d$ in the high flow years of 1991 and 1993. By contrast, there was a net flux of phosphorus out of the sediment during the low flow years of 1987 and 1988 (4.5 and 1.6 $mg/m^2/d$, respectively). Deposition of inorganic phosphorus exceeded organic phosphorus in all years except 1987 and 1988. In these two years, increased algal levels and reduced suspended solids caused organic forms to comprise a more significant component of phosphorus deposition. Deposition rates for inorganic phosphorus were greatest in high flow years, such as 1986, 1991, and 1993.

High rates of phosphorus deposition in Lake Pepin have led to high levels of phosphorus in the sediment and sediment porewater. The average concentration of phosphorus in Lake Pepin sediment was 1.219 mg/g dry wt in 1994–96 (James *et al.*, 2000). Sediment phosphorus concentrations were lower in the upper end of the lake, due to dilution by high sediment accumulation rates. Concentrations increased in a downstream direction. Inorganic phosphorus represented the greatest portion (75%) of total sediment phosphorus, and ironbound phosphorus (BD-extractable P) was the largest percentage (44%) of inorganic phosphorus. Ironbound phosphorus was correlated with porewater phosphorus, porewater iron, and total sediment iron, suggesting possible interactions between phosphorus and iron fractions.

Figure 31. Mean annual total and soluble reactive phosphorus loading rates to and from Pool 2, Pool 3, and upper Pool 4 of the Mississippi River and Lake Pepin, 1994–96 (James *et al.*, 2000).



The average concentration of SRP in sediment porewater across Lake Pepin was 1.083 mg/L in 1994–96 (James *et al.*, 2000). Pronounced gradients in SRP concentration existed between the sediment and overlying water at all stations during May–October in the three years. In the overlying water, SRP concentrations were highest (0.01–1.00 mg/L) near the sediment surface and decreased with distance above the sediment. In the upper 4 cm of sediment, porewater SRP concentrations increased markedly with increasing depth. At sediment depths greater than 4 cm, porewater SRP concentrations were usually uniform and often greater than 10 mg/L. Soluble iron profiles near the sediment-water interface were very similar to SRP profiles.

High sediment phosphorus concentrations have led, in turn, to a high potential for SRP release from the sediment and significant internal SRP loads in Lake Pepin. Measurements of SRP release rates in Lake Pepin and whole-lake estimates of internal loads are discussed in detail in Section 2.2.1.4. Over the 12-year period of 1985–96, the model calculated an average SRP release rate of 270 mt/yr or 7.3 mg/m^2/d during January–December, increasing to 18.5 mg/m^2/d during June–September (HydroQual, 2002a). In all 12 years, the sediment bed was a net source of SRP and a net sink of particulate phosphorus (Fig. 29). In the low flow year of 1988, SRP release rates soared to 14.0 mg/m^2/d on an annual basis and 40.4 mg/m^2/d in the summer, leading to a net annual flux of total phosphorus from the sediment (57 mt). The preceding year, 1987, was generally dry except for one superstorm in the Metro Area. The annual SRP release rate in 1987 (19.7 mg/m^2/d) was 41% greater than in 1988, and the net annual TP flux from the sediment bed (160 mt) was almost three times greater. During the low flow years, intermittent periods of vertical stratification likely produced hypoxic conditions in the bottom waters of the lake, resulting in substantial SRP releases from the sediment.

From the model results (James Szydlik, HydroQual, Inc., personal communication), the annual average internal SRP loading rate to Lake Pepin during 1985–96 was 260 mt/yr, and internal SRP loads represented 10% of the total SRP load (external plus internal) to Lake Pepin. In comparison, the mean annual SRP load from the Metro Plant to Pool 2 was an estimated 790 mt/yr over the same period. During the low flow years of 1987–89, the percentage of internal to total SRP loads in Lake Pepin climbed to 34% as an annual average and 68% as a summer average. During the summer of 1988, the sediment bed of Lake Pepin was releasing an estimated 4.0 metric tons per day of SRP to the water column, while the Metro Plant was discharging an estimated 2.4 mt/d of SRP to Pool 2. Phosphorus in the sediment bed of Lake Pepin comes from various point and nonpoint sources in the watershed, including the Metro Plant, but the portions contributed by specific sources are not known due to the complex dynamics of phosphorus.

[Note: Section 2.2.1.5 uses estimates for whole-lake internal loading rates from HydroQual (2002a), which were roughly double the estimates from James *et al.* (2000). For a discussion of the different loading estimates, see the end of Section 2.2.1.4.]

2.2.2 Phytoplankton

The main impetus for the Lake Pepin Phosphorus Study was the occurrence of severe nuisance algal blooms in Lake Pepin during the summer of 1988. As such, another important objective of the 1994–98 study was to develop a better understanding of the relationship between phosphorus and algal dynamics. Some of the key questions posed at the beginning of the study are listed below:

- What are the dynamics of different algal groups in the study area and what controls the composition of the algal community?
- Specifically, how does algal composition and biomass in Spring Lake and Lake Pepin change with nutrient concentrations and river flow?
- And, ultimately, what factors currently and may potentially control the development of nuisance blue-green algal blooms in Spring Lake and Lake Pepin?

The USAE-WES, MCES, MWBAC, and HydroQual projects examined various aspects of algal dynamics. MCES evaluated historical concentrations and loading rates of chlorophyll *a* in the Minnesota, Mississippi, and St. Croix Rivers over the 21-year period from 1976 to 1996. During 1994–98, MWBAC volunteers subjectively rated algal levels in Spring Lake and Lake Pepin and collected samples for chlorophyll *a* measurements. From 1994 to 1996, the USAE-WES conducted extensive limnological studies of Lake Pepin, including measurements of chlorophyll *a*, nutrients, light, phytoplankton species (identification, counts, and biomass), productivity, respiration, and alkaline phosphatase activity. Under current condi-

tions, floating forms of algae (phytoplankton) dominate over attached forms (periphyton), hence the focus on phytoplankton in the Lake Pepin Phosphorus Study. The USAE-WES also constructed budgets for chlorophyll *a* loads and discharges from the navigation pools and Lake Pepin. In the advanced eutrophication model of the Mississippi River, Lock and Dam No. 1 through Lake Pepin, HydroQual tracked the growth and death of three major groups of phytoplankton (spring diatoms, summer blue-green algae, and other summer algae) and chlorophyll *a* concentrations over a 12-year period, 1985–96.

Study findings about phytoplankton and chlorophyll *a* are presented in the following sections. Chlorophyll *a* is a green pigment found in plants, used as a surrogate to measure algal levels. Current concentrations of chlorophyll *a* in the Mississippi River, Spring Lake, and Lake Pepin are described in Sections 2.2.2.1 (river) and 2.2.2.2 (lakes). Sources, production, and losses of chlorophyll and phytoplankton are discussed in Section 2.2.2.3, and factors controlling algal growth and community composition are discussed in Section 2.2.2.4.

The USAE-WES and MCES applied different spectrophotometric laboratory methods to measure chlorophyll *a*. The USAE-WES measured pheophytin-corrected chlorophyll *a* using the modified monochromatic method. Pheophytin-corrected chlorophyll *a* is commonly referred to as "viable" chlorophyll *a*, or that associated with living algae. MCES measured "total" chlorophyll *a* using the trichromatic method and "percent viable" using the modified monochromatic method. By multiplying these two values, MCES then estimated "viable" chlorophyll *a*, which roughly approximates pheophytin-corrected chlorophyll *a* as determined by the modified monochromatic method. MCES has since added pheophytin-corrected chlorophyll *a* to the list of variables routinely measured and recorded.

2.2.2.1 Chlorophyll Concentrations in the Mississippi River, Lock and Dam Nos. 1–3

MCES data for the period of 1976–96 indicated that mean concentrations of viable chlorophyll *a* were fairly uniform across six locations in Pools 2 and 3 of the Mississippi River. At Lock and Dam Nos. 1, 2, and 3 and at three sites in Pool 2, long-term mean concentrations were 24–32 µg/L on an annual basis and 29–38 µg/L during June–September (Figs. 32 and 33). Lake users in Minnesota generally rate conditions as "nuisance algal blooms" when viable chlorophyll *a* concentrations exceed 20 µg/L and as "severe nuisance algal blooms" when concentrations exceed 30 µg/L (Heiskary and Walker, 1988). Nineteen kilometers (12 miles) upstream of Lake Pepin at Lock and Dam No. 3, the mean summer concentration of viable chlorophyll *a* was 29 µg/L for the 21-year period, compared to the water-quality goal of 30 µg/l for Lake Pepin (discussed in Section 1.2).

Viable chlorophyll *a* concentrations generally increased in the pooled area upstream of Lock and Dam No. 2, with long-term mean concentrations above 30 µg/L on both annual and summer bases (Figs. 32 and 33). Long-term mean concentrations then decreased by approximately 15% below the St. Croix River, which displayed low viable chlorophyll *a* levels (8 µg/L annual, 11µg/L summer). Viable chlorophyll *a* concentrations were very high at the mouth of the Minnesota River, with a long-term mean concentration of 45 µg/L both annually and in the summer. However, chlorophyll levels in the Mississippi River did not change appreciably below the Minnesota River; in fact, mean summer concentrations actually decreased between Lock and Dam No 1 and St. Paul. The variability of concentrations was greatest at Lock and Dam No. 2 and the mouth of the Minnesota River, with standard deviations of 33 and 56 µg/L, respectively.

Meyer and Schellhaass (2002) examined the patterns and trends of total chlorophyll *a* concentrations in the Mississippi, Minnesota, and St. Croix Rivers during 1976–96. While mean flow-weighted concentrations were high (53 µg/L annual, 61 µg/l summer) at the mouth of the Minnesota River, they were even higher (60 µg/l annual, 80 µg/l summer) upstream at Jordan, Minnesota, where the river enters the Metro Area. Algae may settle in the deeper, channelized section of the lower 35 kilometers (22 miles) of the Minnesota River, or chlorophyll concentrations may be diluted by inflows from tributaries and point sources. During the winters of 1976–96, total chlorophyll *a* concentrations in the Minnesota River remained high (around 50 µg/l at river miles 3.5 and 39.4) and within the eutrophic range. MCES field crews have, at times, reported a green glow from the river when collecting samples through holes cut in the ice.

In a study of 116 temperate streams, Van Nieuwenhuyse and Jones (1996) found the highest mean summer chlorophyll *a* concentration in the Minnesota River at Jordan, Minnesota. Regression analysis of their compiled data set showed a strong relationship between mean summer chlorophyll *a* and total phosphorus concentrations.

Figure 32. Error bars of viable chlorophyll *a* concentrations at selected sites on the Mississippi River, Lock and Dam Nos. 1–3, and near the mouths of the Minnesota and St. Croix Rivers, January through December, 1976–96 (Data source: MCES).

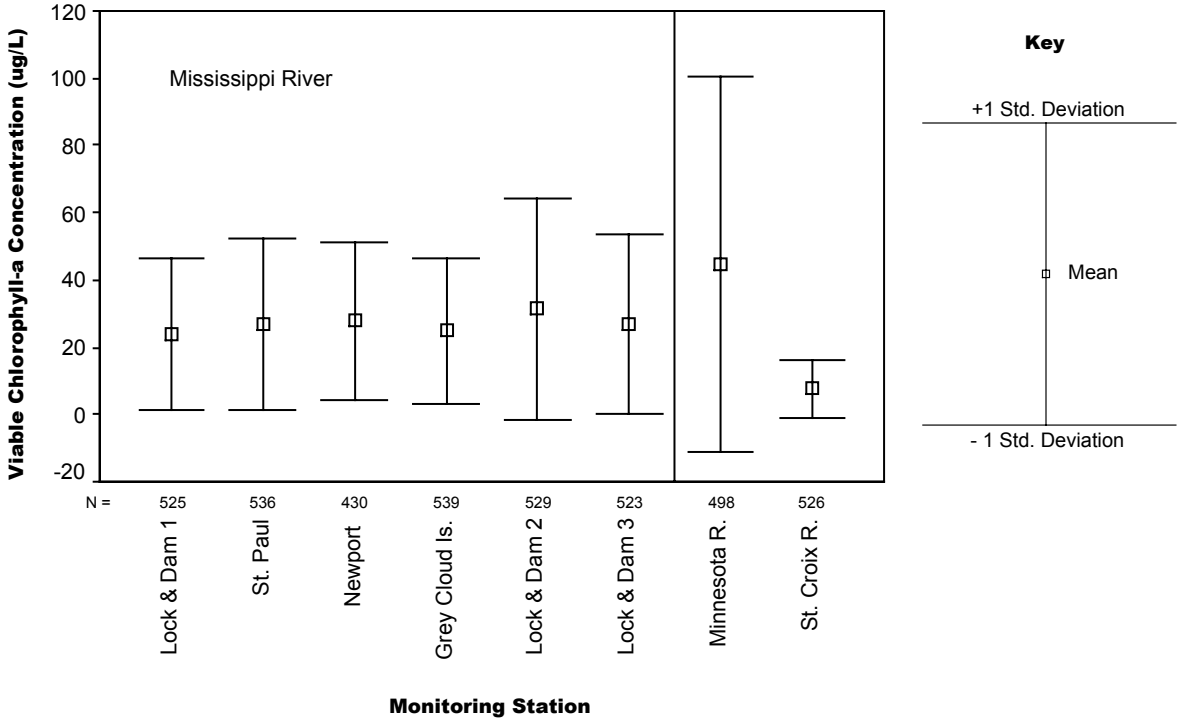
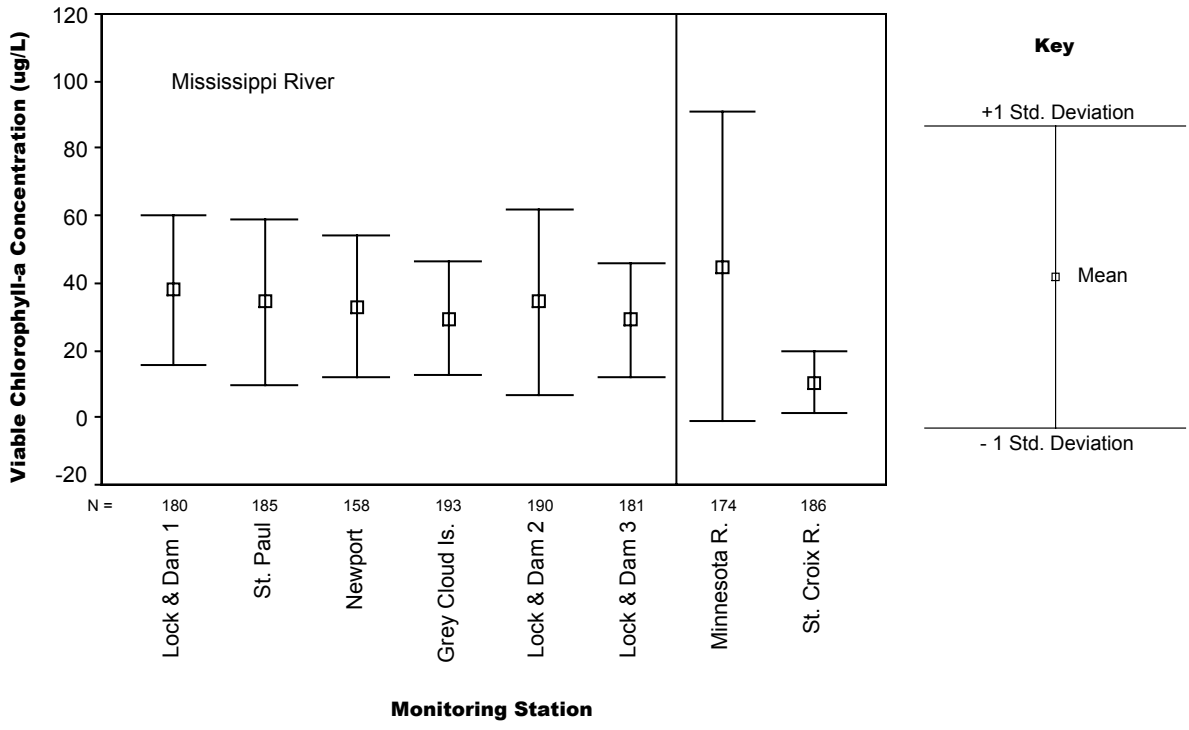


Figure 33. Error bars of viable chlorophyll *a* concentrations at selected sites on the Mississippi River, Lock and Dam Nos. 1–3, and near the mouths of the Minnesota and St. Croix Rivers, June through September, 1976–96 (Data source: MCES).



Over the 21-year period (1976–96), the three rivers had distinctly different seasonal patterns of both total and viable chlorophyll *a* concentrations (Fig. 34; Meyer and Schellhaass, 2002). Chlorophyll levels generally peaked in May and October in the Minnesota River and in May and August in the St. Croix River. Chlorophyll concentrations in the Mississippi River at Lock and Dam No. 1 rose sharply in April and again in August but did not fall sharply in early summer as in the other two rivers. Seasonal patterns at Lock and Dam Nos. 2 and 3 most closely followed those in the Minnesota River with a spring peak in April–May, a sharp decline in June, and a second peak in October. Diatoms are usually associated with cooler temperatures and may account for a sizable portion of the spring and fall chlorophyll peaks. Concentrations of total suspended solids in the Minnesota River were highest in June and July, averaging over 150 mg/L, which reduced the available light and may have limited phytoplankton growth. This effect could have carried downstream to Lock and Dam Nos. 2 and 3.

During low flow years, a strong trend existed in the Mississippi, Minnesota, and St. Croix Rivers toward higher chlorophyll *a* concentrations (Meyer and Schellhaass, 2002). As seen in Figure 35, mean summer concentrations of viable chlorophyll *a* were highest (>48 µg/l) at Lock and Dam Nos. 2 and 3 during the low flow years of 1976 and 1988. Residence times increase as flows decrease, affording more time for algae to grow. Also, light conditions may improve as the rivers carry fewer suspended solids from runoff. Temporal patterns of viable chlorophyll *a* concentrations in the Mississippi River are perhaps best displayed, along with flow, phosphorus, and dissolved oxygen, in HydroQual's (2002a) plots of measured and computed concentrations at Lock and Dam No. 2 for the period from 1985 to 1996 (Fig. 36).

2.2.2.2 Chlorophyll Concentrations in Spring Lake and Lake Pepin

USAE-WES researchers monitored chlorophyll *a* concentrations in Spring Lake and Lake Pepin during 1994–96 (James *et al.*, 2000), and MWBAC volunteers collected samples for chlorophyll *a* and other tests in the two lakes during 1994–98 (Force and Macbeth, 2001). The USAE-WES Eau Galle Aquatic Ecology Laboratory conducted the analytical tests for both studies during 1994–96; MCES analyzed samples from the MWBAC program during 1997-98. To provide a point of reference to the previous section on historical chlorophyll concentrations in the Mississippi River, mean concentrations were compared at Lock and Dam No. 3 for the two periods using the MCES database. Viable chlorophyll *a* concentrations during the three-year period from 1994 to 1996 were 9 µg/L lower than during the 21-year period from 1976 to 1996, probably due to higher flows during the mid-1990s.

Figure 37 plots the means and standard deviations of viable chlorophyll *a* concentrations collected in surface samples by the USAE-WES from the Mississippi River at Lock and Dam Nos. 1–3, Spring Lake, and Lake Pepin during May–October, 1994–96. The majority of USAE-WES lake samples were collected during these months, when most lake recreation occurs. Mean concentrations were fairly uniform at the three Locks and Dams, averaging 22–24 µg/L. The same similarity in chlorophyll *a* concentrations at the three locks was observed in the long-term record (1976–96) from MCES (Figs. 32 and 33). The mean viable chlorophyll *a* concentration in Spring Lake during May–October, 1994–96, was similar to the mean at Lock and Dam No. 2 (23–24 µg/L), but concentrations were somewhat less variable (Fig. 37). Greater differences might be observed between Spring Lake and the main channel of the Mississippi River under low flow conditions. For example, in the dry months of August and September 1996, mean concentrations of viable chlorophyll *a* were 26 µg/L in Spring Lake and 17 µg/L at Lock and Dam No. 2. During May–October, 1994–96, mean viable chlorophyll *a* concentrations were lower in Lake Pepin than in Spring Lake and decreased longitudinally from 17.3 µg/L at the inlet to 9.4 µg/L at the outlet (Fig. 37).

At flows less than 20,000 cfs (570 m^3/s), the MWBAC volunteer monitoring program found no significant differences in viable chlorophyll *a* concentrations between Spring Lake and Lake Pepin, with concentrations in both lakes averaging around 20 µg/L during May–September, 1994–96 (Macbeth and Gostovich, 1998). However, greater variations in Lake Pepin concentrations were noted. Over the same period but at all flows, the USAE-WES recorded mean concentrations of 24.4 µg/L in Spring Lake and 11.9 µg/L in Lake Pepin with a wider range of concentrations (0.5–128.8 µg/L) in Lake Pepin (James *et al.*, 1998).

As in the USAE-WES study, Force and Macbeth (2001) found decreasing concentrations of chlorophyll *a* from the upper to lower end of Lake Pepin during the summers of 1994–97. During May–September 1998, however, mean summer chlorophyll *a*

Figure 34. Mean monthly viable chlorophyll *a* concentrations in the Mississippi River at Lock and Dam Nos. 1, 2, and 3 and near the mouths of the Minnesota and St. Croix Rivers, 1976–96 (Data source: MCES).

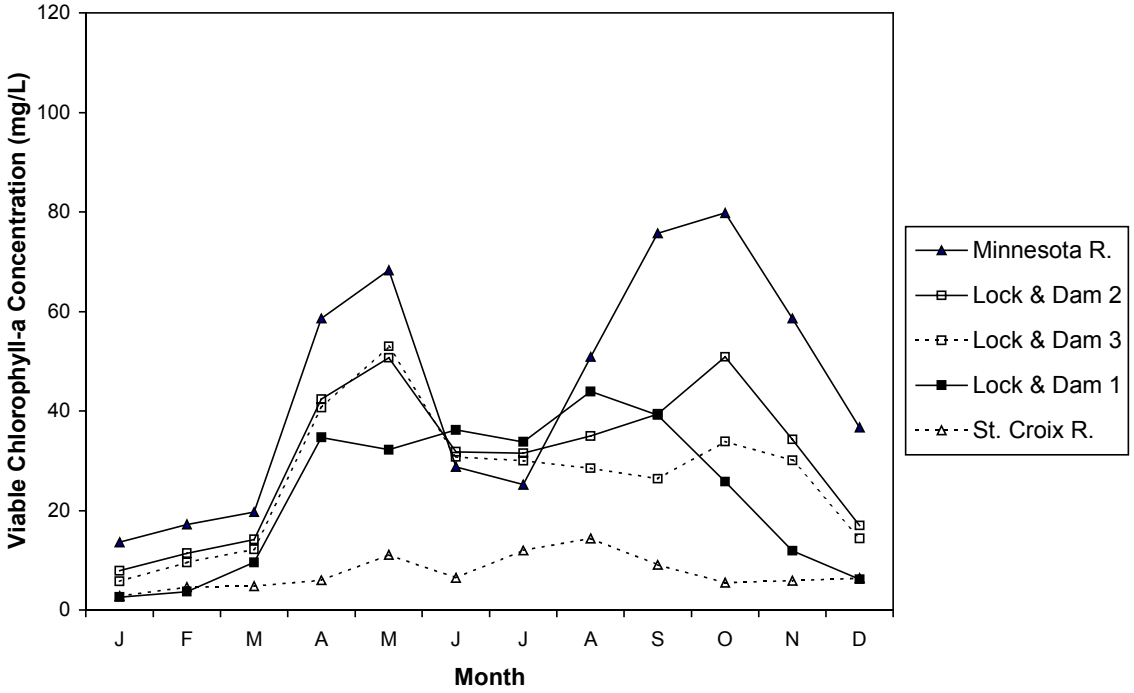


Figure 35. Mean summer viable chlorophyll *a* concentrations in the Mississippi River at Lock and Dam Nos. 1, 2, and 3 and near the mouths of the Minnesota and St. Croix Rivers, June through September, 1976–96 (Data source: MCES).

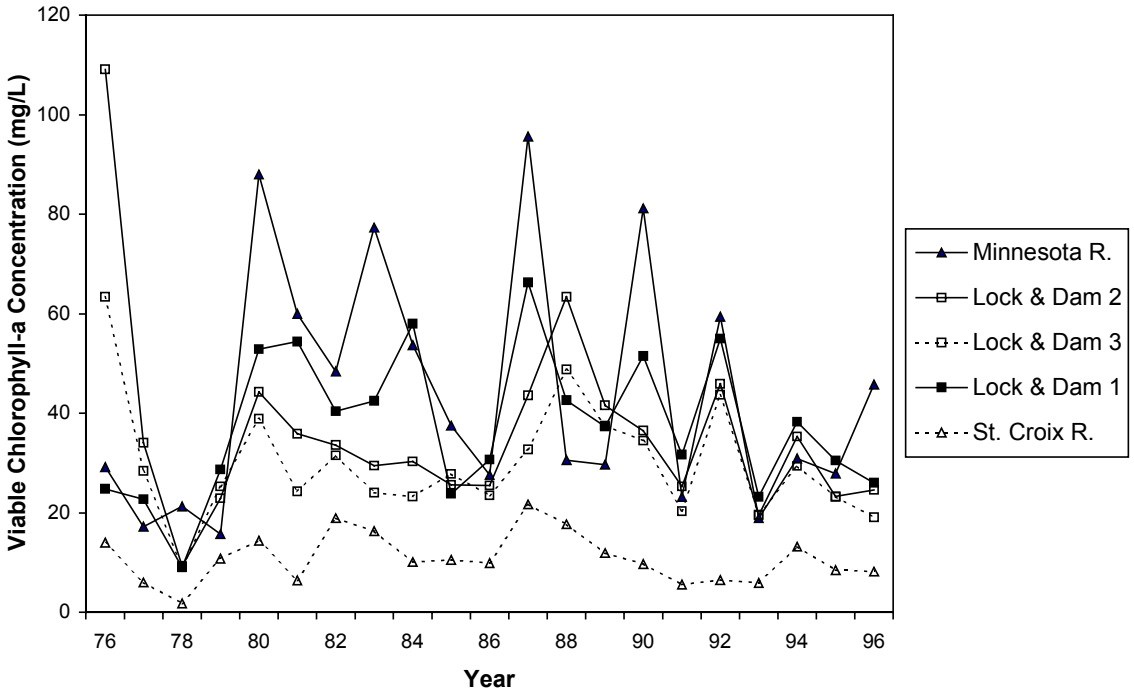


Figure 36. Temporal distributions of mean monthly flows and concentrations of soluble reactive phosphorus, viable chlorophyll *a*, and dissolved oxygen in the Mississippi River at Lock and Dam No. 2, 1985–96 (from HydroQual, 2002a). Lines represent monthly means computed by the model. Points represent monthly mean concentrations and bars represent monthly ranges of data collected by MCES.

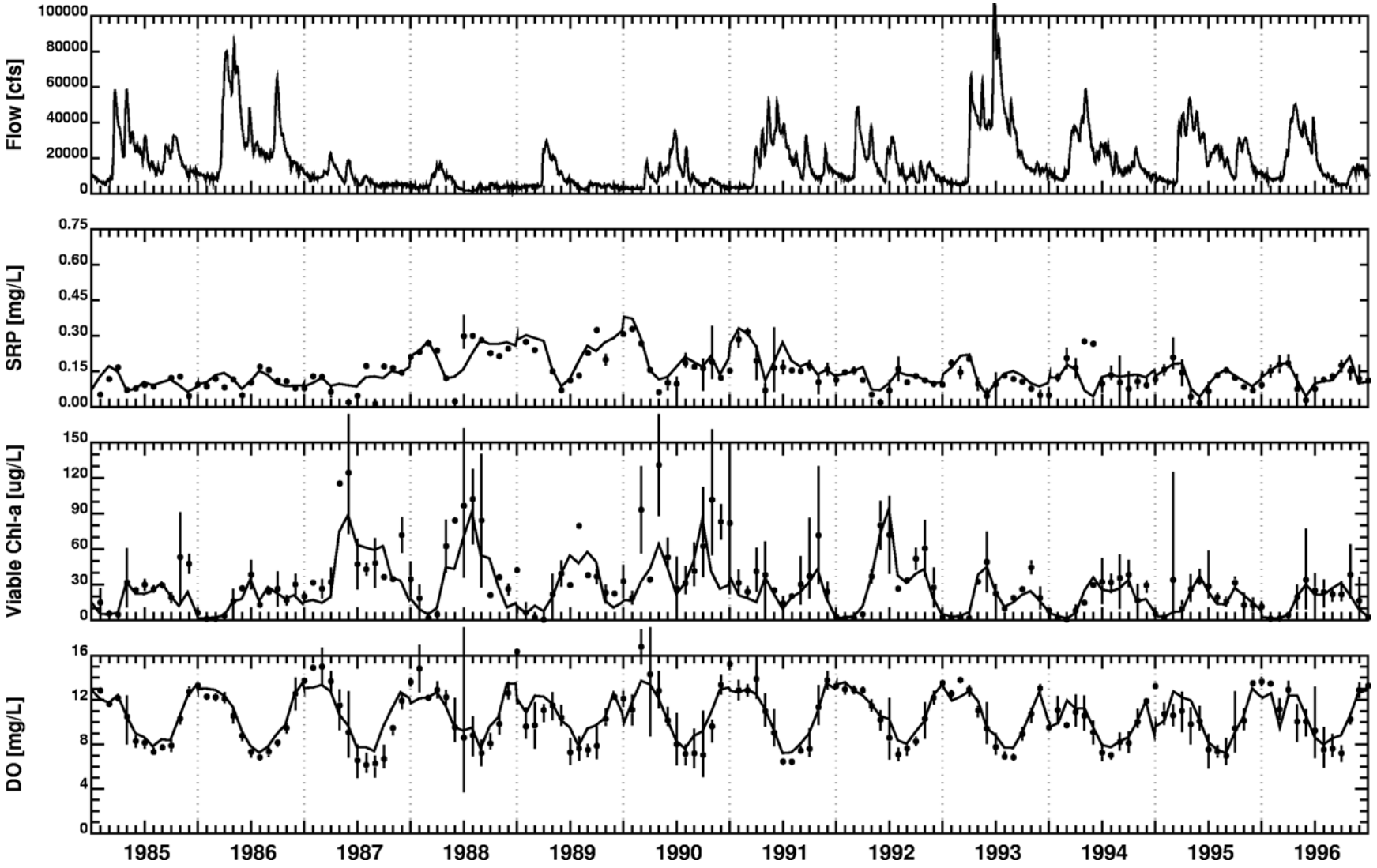
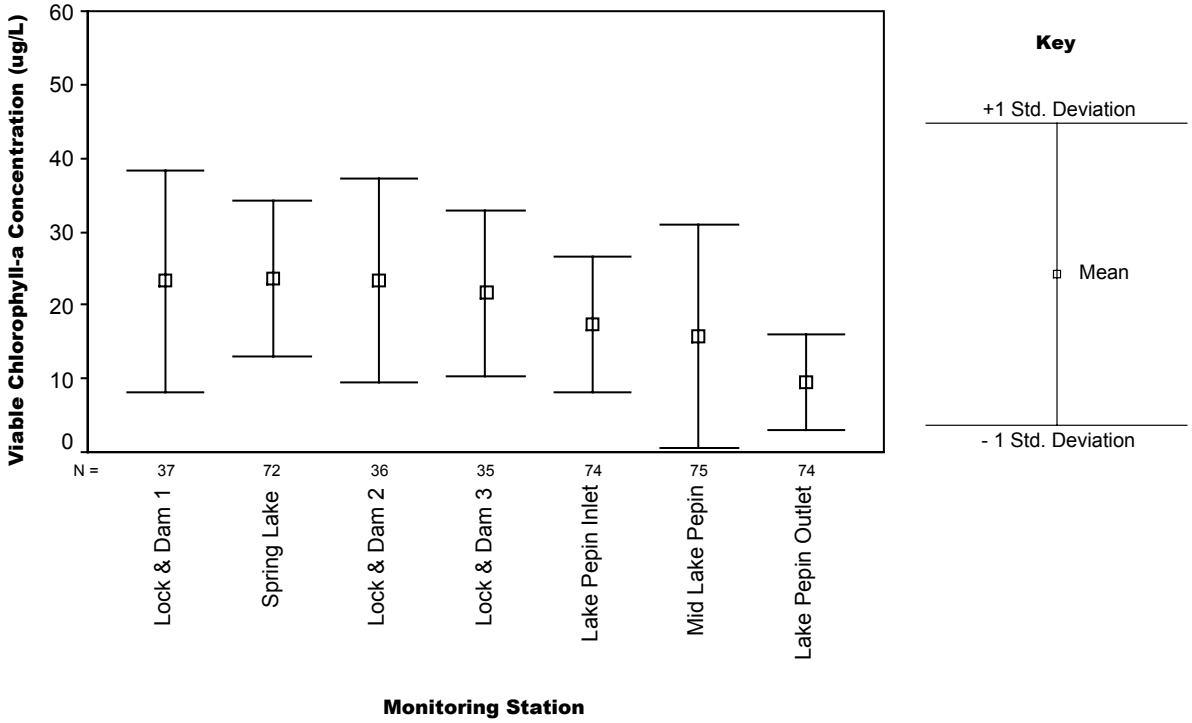


Figure 37. Error bars of viable chlorophyll *a* concentrations in the Mississippi River at Lock and Dam Nos. 1, 2, and 3 and at selected sites in Spring Lake and Lake Pepin, May through October, 1994–96 (Data source: USAE-WES).



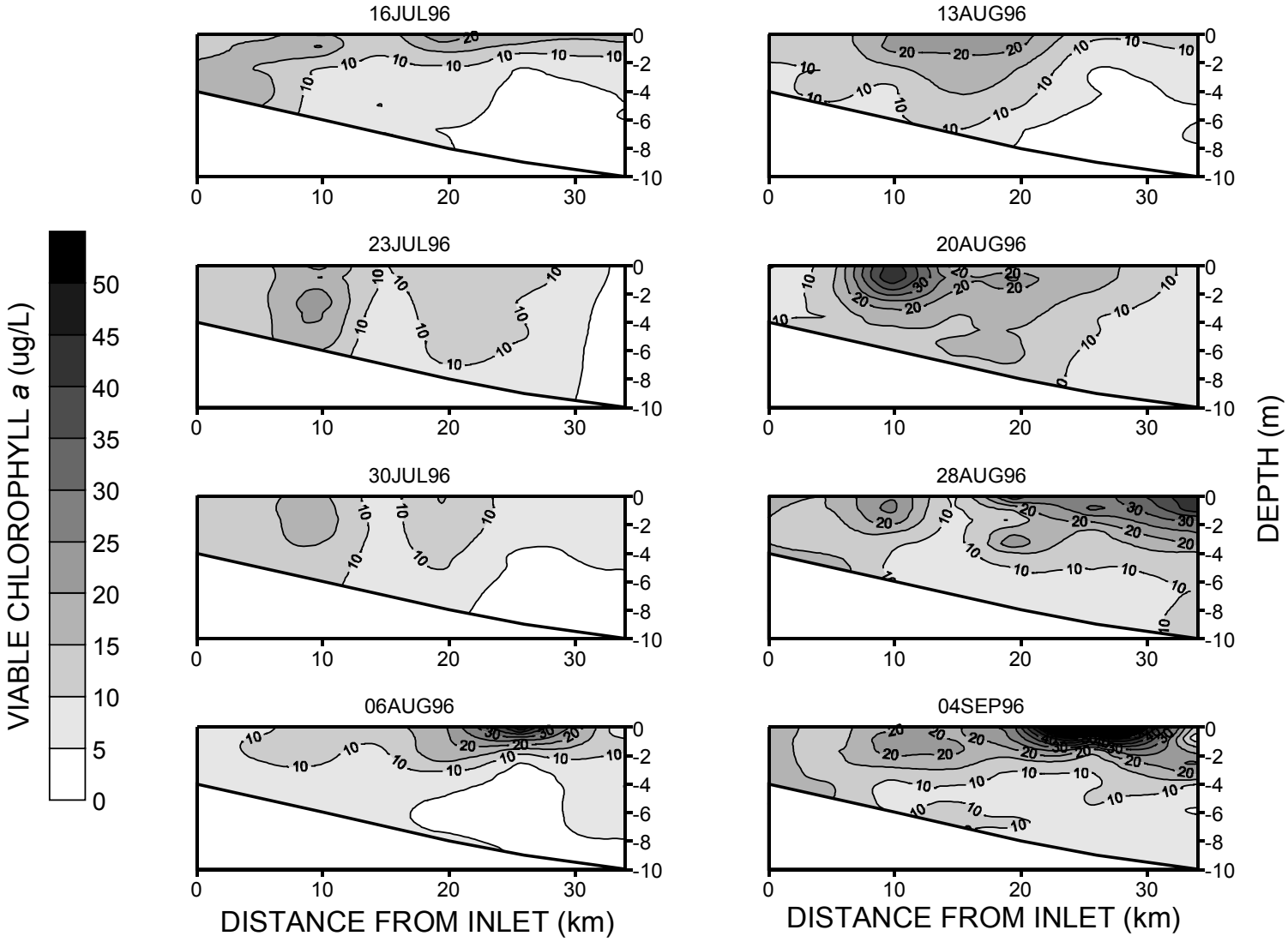
concentrations were higher at the lower end of Lake Pepin. River flows in 1998 were generally lower than the preceding four years. Over the entire five-year period of the MWBAC program, mean viable chlorophyll *a* concentrations in Spring Lake (23.6 µg/L) were slightly higher than in Lake Pepin as a whole (22.3 µg/L), but the upper end of Lake Pepin (25.6 µg/L) displayed higher concentrations than Spring Lake (Force and Macbeth, 2001).

In Lake Pepin, viable chlorophyll *a* concentrations varied greatly both spatially and temporally as seen in Figure 38, which displays cross-sectional plots of concentrations from the inlet to the outlet of Lake Pepin for eight days in the summer of 1996 (James *et al.*, 1998). James *et al.* (2000) examined seasonal patterns of algal levels and productivity in Lake Pepin during 1994–96. Maximum concentrations of viable chlorophyll *a* and maximum rates of net primary productivity were observed in Lake Pepin after peaks in flows and loads and during intermittent periods of thermal stratification. During these periods, mean flow-weighted chlorophyll *a* concentrations often exceeded 30 µg/L at several stations. Net primary productivity was greatest during late April through May and July through August. Viable chlorophyll *a* patterns generally coincided with productivity patterns, with concentration peaks in April–May and July.

Data collected from 1991 through 1996 by the MDNR as part of the Long Term Resource Monitoring Program indicated relatively high winter primary productivity in Lake Pepin in some years (Burdis and Popp, 1996). Mean winter concentrations of viable chlorophyll *a* in Lake Pepin ranged from less than 5 µg/L in 1996 to nearly 30 µg/L in 1995 and over 60 µg/L in 1991. Winter chlorophyll *a* concentrations were strongly correlated with mean flows and mean percent snow cover ($r^2 = 0.78$, $p<0.05$).

Heiskary and Vavricka (1993) compiled and evaluated viable chlorophyll *a* concentrations for Lake Pepin from nine summers between 1976 and 1991. While sampled at different locations and frequencies and by different agencies, these data provide a historical perspective of summer-time algal levels in Lake Pepin over different flow regimes. Mean summer concentrations ranged from 22 µg/L in 1978 to 57 µg/L in 1988. Chlorophyll *a* concentrations in the

Figure 38. Longitudinal and vertical variations in viable chlorophyll *a* concentrations in Lake Pepin on eight days in July, August, and September 1996 (from James *et al.*, 1998).



low flow years of 1976 and 1988 were significantly higher than in high flow years. In general, chlorophyll concentrations tended to decrease as river flows and flushing rates increased. Maximum summer concentrations of viable chlorophyll *a* ranged from 51 µg/L in 1979 to 202 µg/L in 1988 and 1991. Concentrations tended to be lower in the downstream end of the lake, where mixing to greater depths may have removed algae from optimal light conditions.

Heiskary and Vavricka (1993) also documented a distinct relationship between monthly mean viable chlorophyll *a* concentrations and residence times in Lake Pepin. At very short residence times (less than 15 days), phytoplankton tended to be removed from the system before reaching their maximum growth potential. As residence times increased from 5 to 15 days, chlorophyll *a* concentrations increased markedly. At longer residence times (more than 15 days), chlorophyll concentrations appeared to be independent of flushing rates. In Figure 39, temporal plots of viable chlorophyll *a* concentrations in upper Lake Pepin (UM778), generated from the results of the advanced eutrophication model of 1985–96, also demonstrate the year-to-year and seasonal variations in algal levels and their relationship to flow, phosphorus, and dissolved oxygen (HydroQual, 2002a).

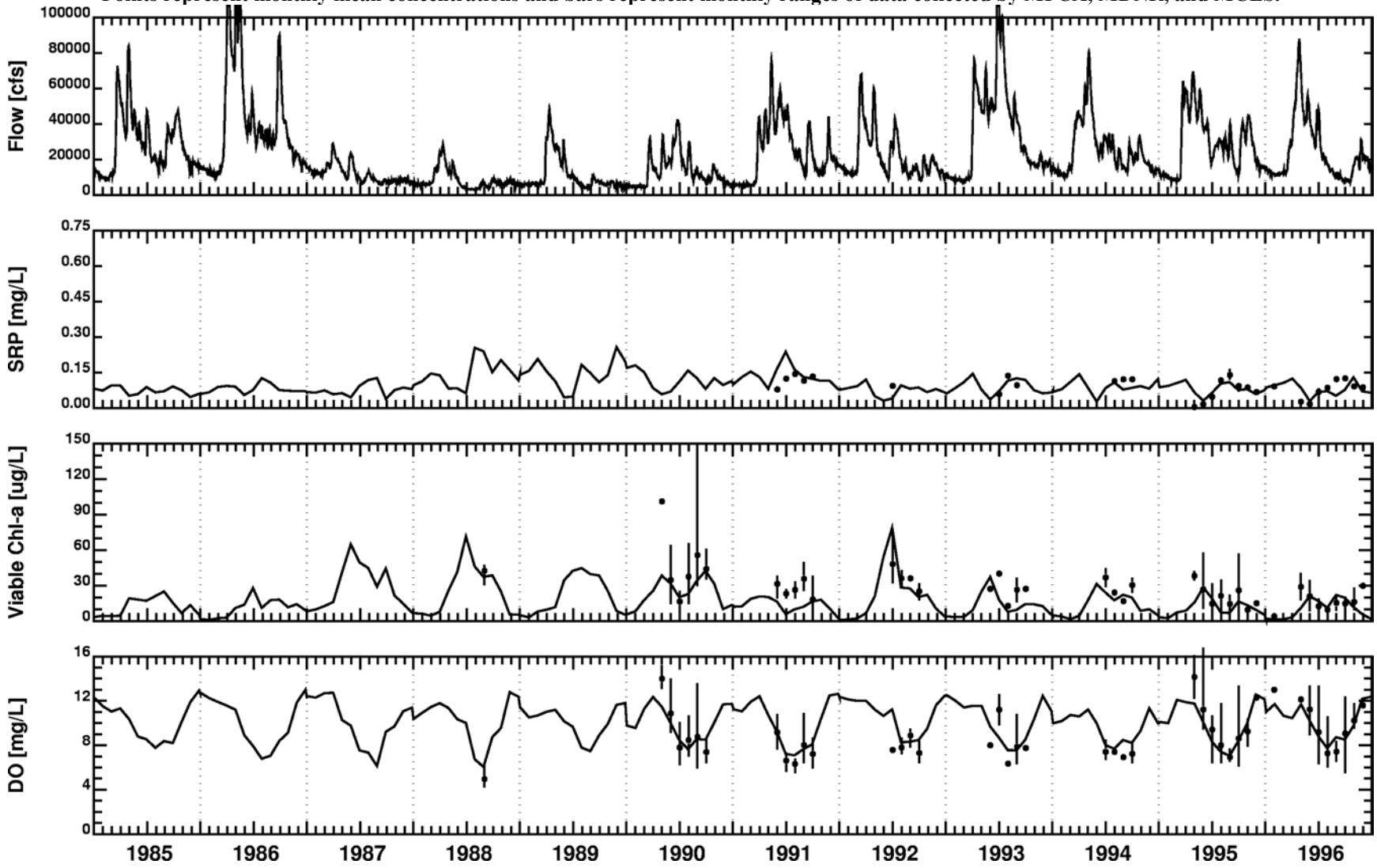
2.2.2.3 Chlorophyll Loading Sources, Production, and Loss

Meyer and Schellhaass (2002) studied sources of chlorophyll *a* loads to the Mississippi River upstream of Lake Pepin. During 1976–96, the Mississippi River at Lock and Dam No. 1 contributed 51 percent (212 mt/yr) of the total chlorophyll *a* load to the study area, while the Minnesota and St. Croix Rivers contributed 42 and 7 percent (174 and 29 mt/yr), respectively. On average over the same period, the Mississippi, Minnesota, and St. Croix Rivers contributed approximately 44, 30, and 26 percent, respectively, of the water income at Lock and Dam No. 3. The Mississippi and Minnesota Rivers contributed proportionately more chlorophyll *a* with respect to flow, while the St. Croix River contributed much less. Meyer and Schellhaass (2002) concluded that nutrient abatement programs should not be limited to the Minnesota River but should extend to other productive systems like the Mississippi River above Lock and Dam No. 1. Relative contributions by the three rivers varied from year to year with river flows. For example, in the low flow year of 1988, the portion contributed by the Minnesota River dropped to 33%, while the St. Croix portion rose to 13%. Autochthonous and allochthonous sources of phytoplankton were not evaluated, but external loads and inlake production may both be important factors contributing to phytoplankton levels in lower Pool 2 and Lake Pepin.

James *et al.* (2000) compiled chlorophyll *a* loads and prepared chlorophyll *a* budgets for the navigation pools and Lake Pepin during 1994–96. The Mississippi River (at Lock and Dam No.1), Minnesota River, and St. Croix River contributed approximately 41, 46, and 8 percent, respectively, of the viable chlorophyll *a* load to the study area, while contributing approximately 40, 31, and 24 percent of the water income. In this three-year period, chlorophyll loads were again disproportionately high in the Minnesota River and disproportionately low in the St. Croix River with respect to flow. In general, viable chlorophyll *a* loads to Pool 2, Pool 3, and the headwaters of Pool 4 were equal to discharges from the pools on annual and seasonal bases. Loads to Lake Pepin were similar to loads to the upstream pools. There was little net retention or export of viable chlorophyll *a* except in Lake Pepin, where concentrations decreased in a downstream direction. During 1994–96, roughly 40% of the viable chlorophyll *a* load was retained in Lake Pepin. As observed by Heiskary and Vavricka (1993), mixing to greater depths in Lake Pepin may remove algae from light, resulting in death and settling.

At times, algal production in lower Pool 2 may be an important factor affecting the water quality of Lake Pepin. On an annual basis, Pool 2 exported roughly 15% more viable chlorophyll *a* than entered the pool during 1994–96 (James *et al.*, 2000). This percentage may increase during low flow years. For example, the average annual load of total chlorophyll *a* increased by 26% (43 mt) in 1988 and by 76% (90 mt) in 1976 between Upper Grey Cloud Island (UM826.7) and Lock and Dam No. 2 (UM815.6) (Scott Schellhaass, MCES, personal communication). Algal biomass in lower Pool 2 can represent a significant oxygen demand as it moves downstream and settles in the deeper portions of Lake Pepin (HydroQual, 2002b). Decomposition of algae, in turn, can lead to lower DO concentrations above the sediment bed in Lake Pepin and higher SRP release rates from the sediment. The decline in algal biomass over the length of Lake Pepin and subsequent decomposition may also result in a shift in phosphorus forms from particulate organic phosphorus to dissolved inorganic phosphorus, contributing to higher SRP concentrations at the outlet of Lake Pepin.

Figure 39. Temporal distributions of mean monthly flows and concentrations of soluble reactive phosphorus, viable chlorophyll *a*, and dissolved oxygen in Lake Pepin near Frontenac, Minnesota (UM778), 1985–96 (from HydroQual, 2002a). Lines represent monthly means computed by the model. Points represent monthly mean concentrations and bars represent monthly ranges of data collected by MPCA, MDNR, and MCES.



2.2.2.4 Factors Controlling Algal Growth and Community Composition

Under current conditions, phosphorus is not limiting algal growth in Lake Pepin. James *et al.* (2000) measured high SRP concentrations (above 50 µg/L) and extremely low levels of alkaline phosphatase activity during the summers of 1994–96. Alkaline phosphatase activity increases to higher levels in algae as phosphorus becomes limiting, but this heightening of activity was not observed in Lake Pepin because adequate supplies of SRP were available during this period. Total phosphorus concentrations were consistently above 100 µg/L in the model simulation of Lake Pepin during 1985–96, and SRP concentrations did not decrease below 30 µg/L (HydroQual, 2002b). At these high concentrations, phosphorus limitation of algal growth was negligible. Nitrate concentrations were also generally high, so nitrogen limitation was only seen briefly in the model simulation of 1988.

James *et al.* (2000) discovered that increases in viable chlorophyll *a* concentrations during 1994–96 could be partially explained by the occurrence of temporary stratification, longer water residence time, increased hydrologic stability, and the storage of heat in the water column. The researchers concluded that hydrological, climatological, and physical factors—not phosphorus concentrations—are currently regulating phytoplankton biomass in Lake Pepin. Physical factors include light and temperature. This was also the general conclusion of three modeling studies (HydroQual, 2002b; EnviroTech, 1993; Heiskary *et al.*, 1993). The effects of zooplankton and zebra mussels on algal populations were not studied.

This is not to say that phosphorus or nitrogen, if reduced to sufficiently low levels, couldn't potentially limit algal growth in Spring Lake and Lake Pepin. During the initial phosphorus study, Barr Engineering Company (1993) conducted a dilution bioassay study in the laboratory on water samples collected from the two lakes. Phosphorus or nitrogen was added to 0, 25, 50, and 75 percent dilutions of lake water, and the algal response was measured over 28 days. The initial phosphorus concentrations did not appear to control the algal growth rates, even in solutions with 25% lake water; however, phosphorus did ultimately limit the growth rate after algal uptake reduced SRP concentrations to low levels. Nitrogen became limiting before phosphorus in the Lake Pepin samples.

James *et al.* (2000) examined the composition of the algal community in Lake Pepin from 1994 to 1996. During this period of normal river flows, diatoms dominated the algal community (Fig. 40). Brief exceptions occurred in June 1994 and in late summer of 1996 when the majority of algal biomass was composed of blue-green algae. Heiskary and Vavricka (1993) found similar algal communities in Lake Pepin during 1990 and 1991. Diatoms, in particular *Stephanodiscus* and *Melosira* species, were frequently the dominant algae. In 1990 blue-green algae, especially *Aphanizomenon* species, became prominent from mid-July to September, while in 1991 blue-green algae tended to comprise less than 20 percent of the phytoplankton community during these months. Based on limited data, blue-green algae appeared to be more abundant than other groups in 1988.

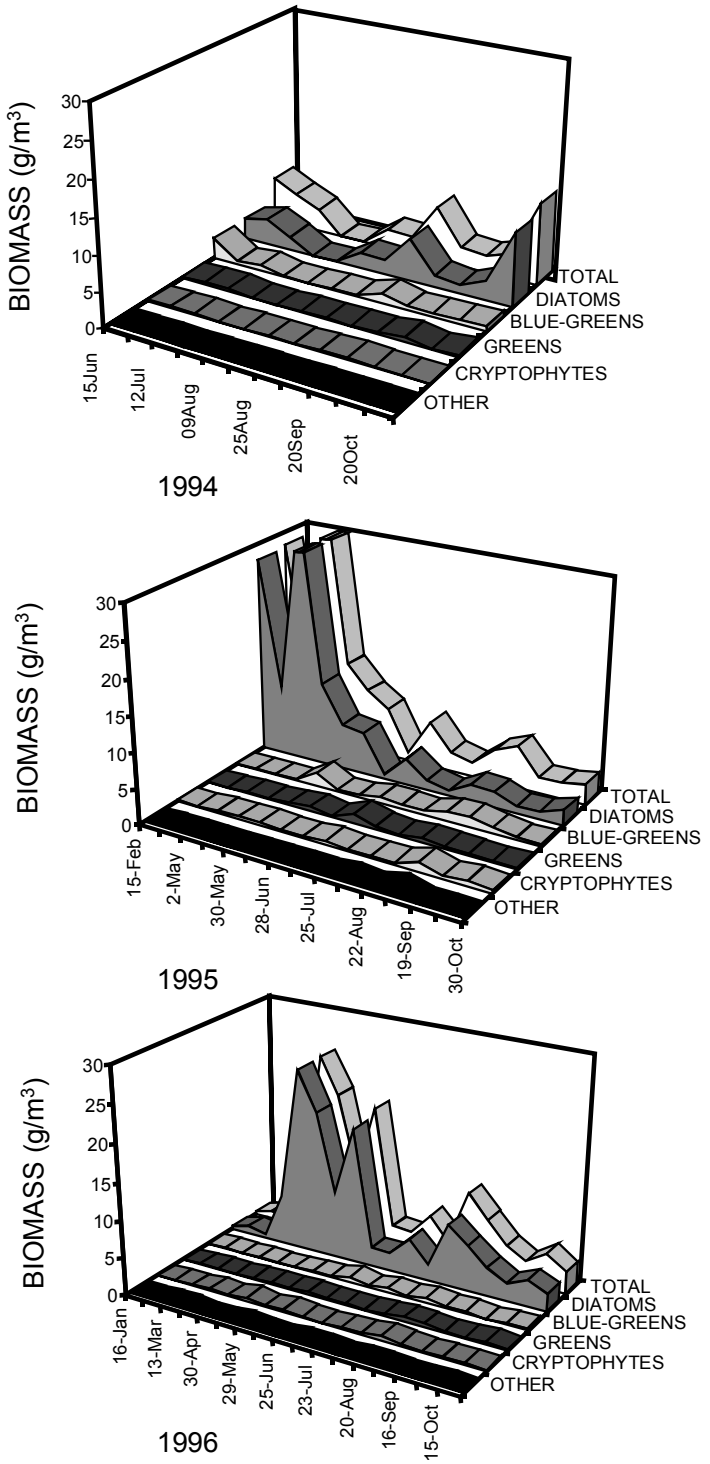
Engstrom and Almendinger (2000) examined diatom taxa in sections of a sediment core from lower Lake Pepin. In the uppermost section, which represented deposits from the most recent decade, planktonic species outnumbered benthic species by nine to one. The greater abundance of planktonic diatoms increases shading and, coupled with high turbidity due to watershed erosion, results in the loss of clear-water benthic diatom taxa. The current diatom community is dominated by small *Stephanodiscus* species with high phosphorus optima, which are common in eutrophic systems.

Due to the high flow conditions of the 1990s, little information was obtained on the factors controlling the composition of the algal community in Lake Pepin. In the water-quality model, very sparse data on the composition of algal communities at the loading sources and no information on the recruitment of blue-green algae from the sediment limited the ability to independently calibrate differences in algal kinetic rates among blue-green algae and other algal groups in the summer (HydroQual, 2002a). Additional monitoring, research, and modeling will be needed to answer questions about the composition of phytoplankton communities in the Mississippi River and Lake Pepin.

2.2.3 Suspended Solids

Suspended solids and riverbed sediment became a growing concern in the first phase of the Lake Pepin Phosphorus Study (1990–92). Suspended solids are particles suspended in the water column, which may include inorganic matter (such as clay, silt, and sand) and organic matter (such as algae). In the early 1990s, the Minnesota River Assessment Project documented very high levels of suspended solids in

Figure 40. Seasonal variations in total phytoplankton biomass and the biomass of major taxonomic groups in Lake Pepin near Maiden Rock, Wisconsin (UM781), 1994–96 (from James *et al.*, 2000).



the Minnesota River, which had serious impacts on water quality in this major tributary and likely downstream in the Mississippi River (MPCA, 1994). In the Lake Pepin Phosphorus Study, 1990–92, suspended solids were shown to reduce water transparency and light penetration, thereby reducing algal growth rates in the Mississippi River (EnviroTech, 1993; Heiskary *et al.*, 1993). Inorganic turbidity and algal self-shading were major factors controlling algal growth in lower Pool 2 and Lake Pepin. Suspended solids were also suspected as an important factor in transporting phosphorus via the sorption of orthophosphate to small inorganic particles. The settling of particulate forms of phosphorus in Lake Pepin would explain the high phosphorus concentrations and SRP releases rates that were measured in the sediment bed by the USAE-WES in 1992 (James *et al.*, 1993). These and other concerns about the impacts of suspended solids on the ecological integrity of the Mississippi River gave more weight to studying suspended solids and riverbed sediment in the second phosphorus study.

All six major components of the Lake Pepin Phosphorus Study, 1994–98, examined suspended solids or sediment to some degree. Section 2.1.1 provides the historic rates of sediment accumulation in Lake Pepin (Engstrom and Almendinger, 2000) and possible explanations for increased rates over time due to human activities (Mulla *et al.*, 2000). Meyer and Schellhaass (2002) compared concentrations, loads, and yields of suspended solids in the three major river basins and examined trends and patterns over the 21-year period of 1976–96. James *et al.* (2000) studied sources and fluxes of suspended solids in the Mississippi River, Pool 2 through Lake Pepin, during 1994–96 and constructed sediment balances for Pool 2, Pool 3, headwaters of Pool 4, and Lake Pepin. Joining the primary monitoring agencies, MWBAC volunteers monitored transparency, turbidity, and suspended solids in Spring Lake and Lake Pepin during 1994–98 and also recorded their subjective ratings of suspended sediment (Force and Macbeth, 2001). Finally, HydroQual (2002a, 2002b) developed a sediment transport model of the Mississippi River, Lock and Dam No. 1 through Lake Pepin, for the 12-year period from 1985 to 1996. The sediment transport model was linked to the water-quality model, and algorithms describing phosphorus sorption and light attenuation in the water-quality model were tied to suspended solids concentrations and custom fit to conditions in the study area.

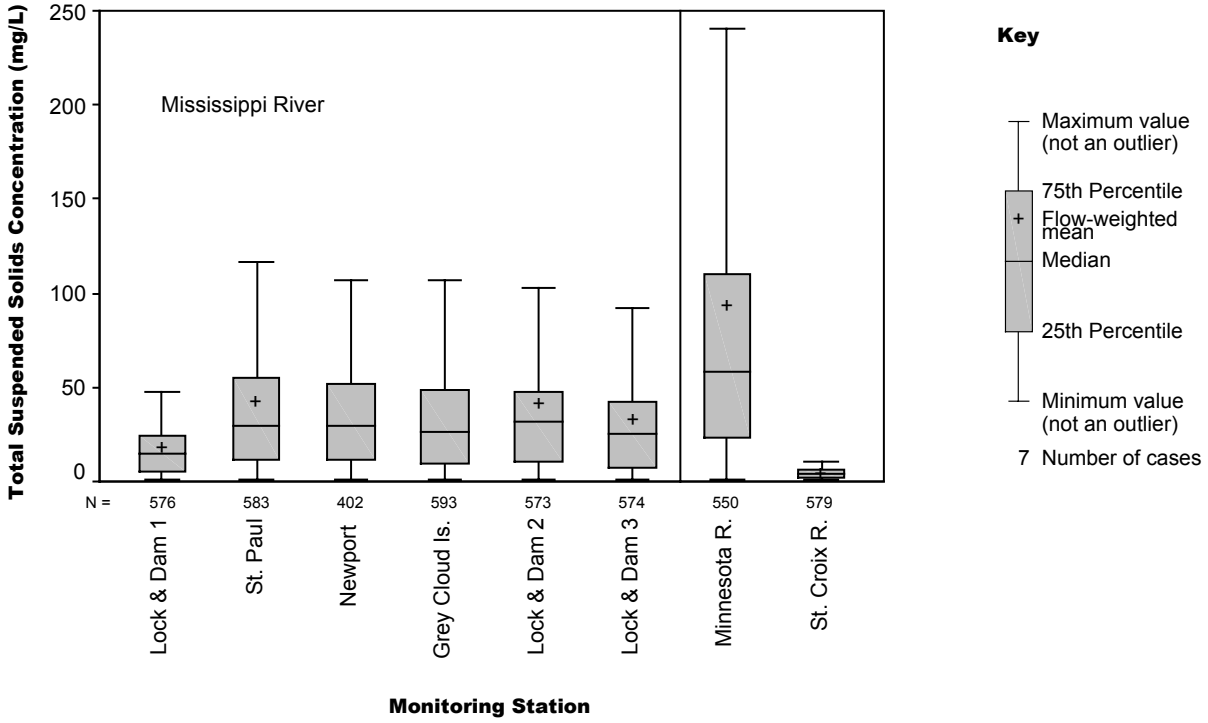
Findings about recent conditions of suspended solids in the study area are summarized in the following sections. Section 2.2.3.1 describes current concentrations of suspended solids in the Mississippi, Minnesota, and St. Croix Rivers, while Section 2.2.3.2 describes concentrations in Spring Lake and Lake Pepin. Sources of suspended solids and the trapping of sediment in the Mississippi River are discussed in Section 2.2.3.3. The importance of sorption, settling, deposition, and sediment-water interactions to phosphorus dynamics was discussed earlier in Section 2.2.1.5.

2.2.3.1 Suspended Solids Concentrations in the Mississippi River, Lock and Dam Nos. 1–3

Meyer and Schellhaass (2002) examined the concentrations of total and volatile (organic) suspended solids in the three major rivers during 1976–1996. Flow-weighted mean concentrations of total suspended solids (TSS) in the Mississippi River at Lock and Dam No. 1 and in the Minnesota and St. Croix Rivers near their mouths were 19, 93, and 5 mg/L, respectively (Fig. 41). On average, suspended solids at the three locations were composed of 31%, 11%, and 50% organic matter, respectively. The Minnesota River displayed the highest TSS concentrations and lowest organic content, while the St. Croix River had the lowest TSS concentrations and highest organic content. TSS concentrations and organic content in the Mississippi River at Lock and Dam No. 1 fell between levels in the Minnesota and St. Croix Rivers. Due to high suspended solids loads from the Minnesota River, the mean flow-weighted TSS concentration in the Mississippi River increased from 19 to 42 mg/L between Lock and Dam Nos. 1 and 2, and organic content decreased from 31 to 20%. At Lock and Dam No. 3, downstream of the St. Croix River, the mean flow-weighted TSS concentration dropped to 33 mg/L, while organic content increased to 23%.

Minnesota has state water-quality standards for turbidity but not total suspended solids. The turbidity standard for Metro Area reaches of the Minnesota, Mississippi, and St. Croix Rivers is 25 nephelometric turbidity units (NTU). For assessing the water quality of surface waters, MPCA (2001) found it possible to use TSS values as surrogates for turbidity. Regression analyses show that regional TSS concentrations of 58 mg/L in southwestern Minnesota and 66 mg/L in central Minnesota relate to the turbidity standard of 25 NTU. Excess turbidity can degrade the aesthetic qualities of waterbodies, make water more expensive to treat for drinking or other uses, and harm aquatic life.

Figure 41. Boxplots of total suspended solids concentrations at selected sites on the Mississippi River, Lock and Dam Nos. 1–3, and near the mouths of the Minnesota and St. Croix Rivers, January through December, 1976–96 (Data source: MCES).



TSS concentrations varied from year to year in response to rainfall and runoff. In Figure 42 note the comparatively low TSS concentrations in the Minnesota and Mississippi Rivers during the drought period of 1987–89 and high concentrations in the preceding high flow years of 1985–86. Reduced inorganic turbidity during the drought may have enhanced light conditions for algal growth. Meyer and Schellhaass (2002) found statistically significant decreases in TSS concentrations over the 21-year period in all three rivers, with the weakest trend in the Minnesota River and the strongest trends in the St. Croix and Mississippi Rivers. From 1976 to 1996, mean annual TSS concentrations decreased from approximately 115 to 70 mg/L in the Minnesota River, 28 to 11 mg/L in the Mississippi River (at Lock and Dam No. 1), and 8 to 3 mg/L in the St. Croix River. However, contrary to these findings, Sullivan (2000) did not detect a significant change in TSS concentrations at Lock and Dam No. 3 when applying a seasonal Kendall analysis on monthly flow-adjusted data from 1977–98.

Mean monthly flow-weighted TSS concentrations in the Minnesota River near its mouth were greatest in June and July at 196 and 153 mg/L, respectively (Meyer and Schellhaass, 2002). In early spring, by comparison, average TSS concentrations in March and April were high but substantially lower at 124 and 127 mg/L, respectively. Rain events in early summer—after fields have been tilled and planted but before the crop canopy is fully developed—can lead to large sediment loading events in this highly agricultural watershed. Mean flow-weighted TSS concentrations in the Mississippi River at Lock and Dam No. 1 were greatest in June, July, and August at 39, 29, and 31 mg/L, respectively. Mean monthly TSS concentrations in the St. Croix River near its mouth varied little, ranging from 5 to 7 mg/L during March–November.

Figure 43 shows median monthly TSS concentrations at Lock and Dam Nos. 1–3 and at the mouths of the two major tributaries during 1976–96. In general, the patterns agree with Meyer and Schellhaass (2002) with the exception of concentrations at Lock and Dam No. 1, which peaked in June and gradually tapered off during the remainder of the year. At Lock and Dam Nos. 2 and 3, median monthly concentrations sharply increased in April and decreased in November but generally ranged between 30 and 50 mg/L throughout the open-water season of April–October. TSS concentrations were highest at these two sites in June, likely in response to TSS loads from the Minnesota River. High algal levels may contribute to a second TSS peak in September.

Figure 42. Median annual total suspended solids concentrations in the Mississippi River at Lock and Dam Nos. 1, 2, and 3 and near the mouths of the Minnesota and St. Croix Rivers, 1976–96 (Data source: MCES).

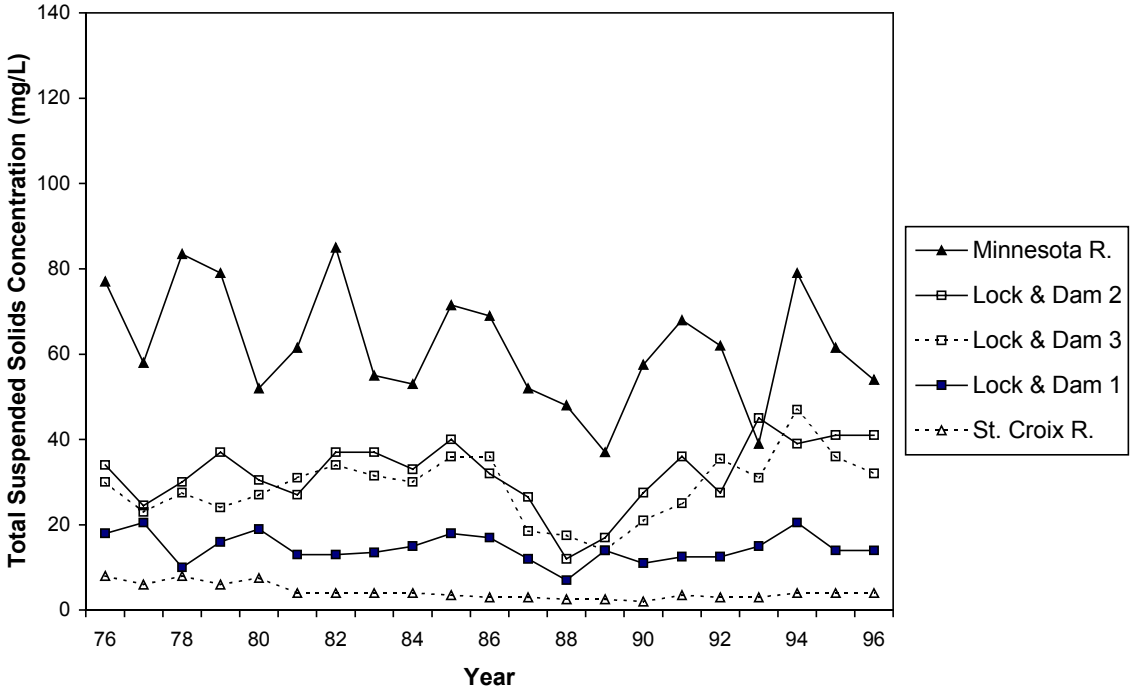
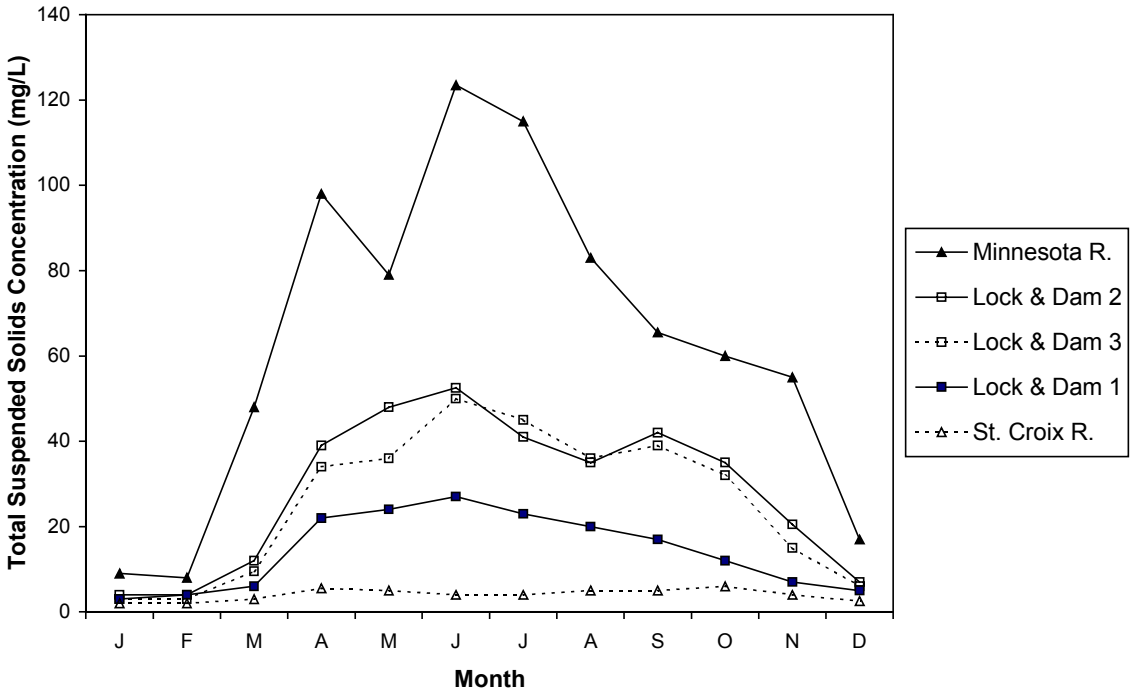


Figure 43. Median monthly total suspended solids concentrations in the Mississippi River at Lock and Dam Nos. 1, 2, and 3 and near the mouths of the Minnesota and St. Croix Rivers, 1976–96 (Data source: MCES).



2.2.3.2 *Suspended Solids Concentrations in Spring Lake and Lake Pepin*

During three recent years (1994–96) under normal flow conditions, the USAE-WES measured high levels of total suspended solids at two locations in Spring Lake and similarly high levels at Lock and Dam No. 2, due primarily to high loads from the Minnesota River (James *et al.*, 1998). Figure 44 shows the results for the May-October period, when the majority of USAE-WES lake samples were collected and most recreation occurs. Median TSS concentrations in Spring Lake and at Lock and Dam No. 2 were 59 and 63 mg/L, respectively, compared to 22 mg/L at Lock and Dam No. 1. Downstream of the St. Croix River, median TSS concentrations decreased to 42 mg/L at Lock and Dam No. 3. Concentrations decreased from 45 mg/L at the inlet of Lake Pepin to 10 mg/L at the outlet. Compared to Pool 2, TSS concentrations were lower in Lake Pepin, but the organic content of the suspended solids was somewhat higher.

James *et al.* (2000) further demonstrated and discussed the striking spatial differences in suspended solids concentrations within Lake Pepin. A gradient of decreasing TSS concentrations through the lake indicated the loss of solids to the sediment. The longitudinal gradient was most pronounced during periods of high flows and loads and steepest between river miles UM787.0 and UM775.0, suggesting the greatest rates of sediment deposition at the headwaters (Fig. 45).

MWBAC volunteers also discovered differences in suspended solids between Spring Lake and Lake Pepin over roughly the same period (May–September, 1994–96; Macbeth and Gostovich, 1998). Summary statistics for suspended solids were segregated by flows above or below 20,000 cfs (570 m^3/s). The results at lower flows are described here, but average concentrations at higher flows were similar. The mean summer concentration of nonvolatile suspended solids (NVSS, representing inorganic solids) was significantly higher in Spring Lake than in Lake Pepin (39 and 19 mg/L, respectively). Mean summer turbidity was also significantly higher in Spring Lake than in Lake Pepin (32 and 17 NTU, respectively).

Figure 44. Boxplots of total suspended solids concentrations in the Mississippi River at Lock and Dam Nos. 1, 2, and 3 and selected sites in Spring Lake and Lake Pepin, May through October, 1994–96 (Data source: USAE-WES).

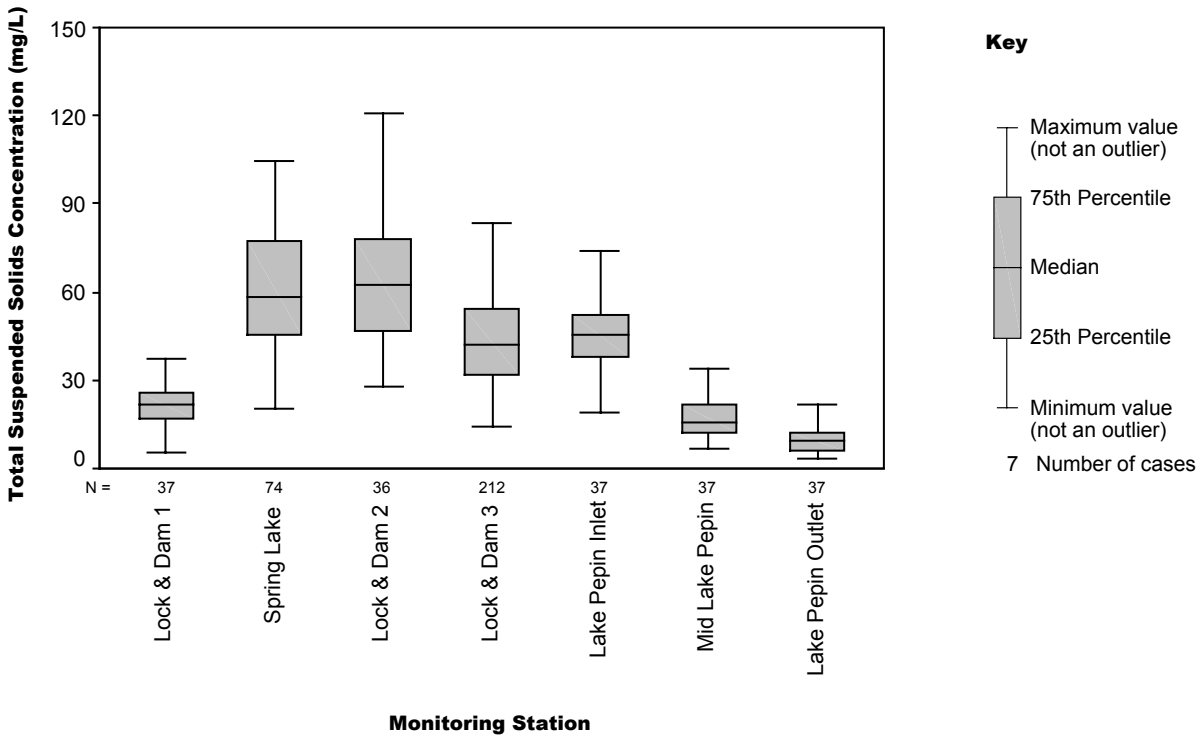
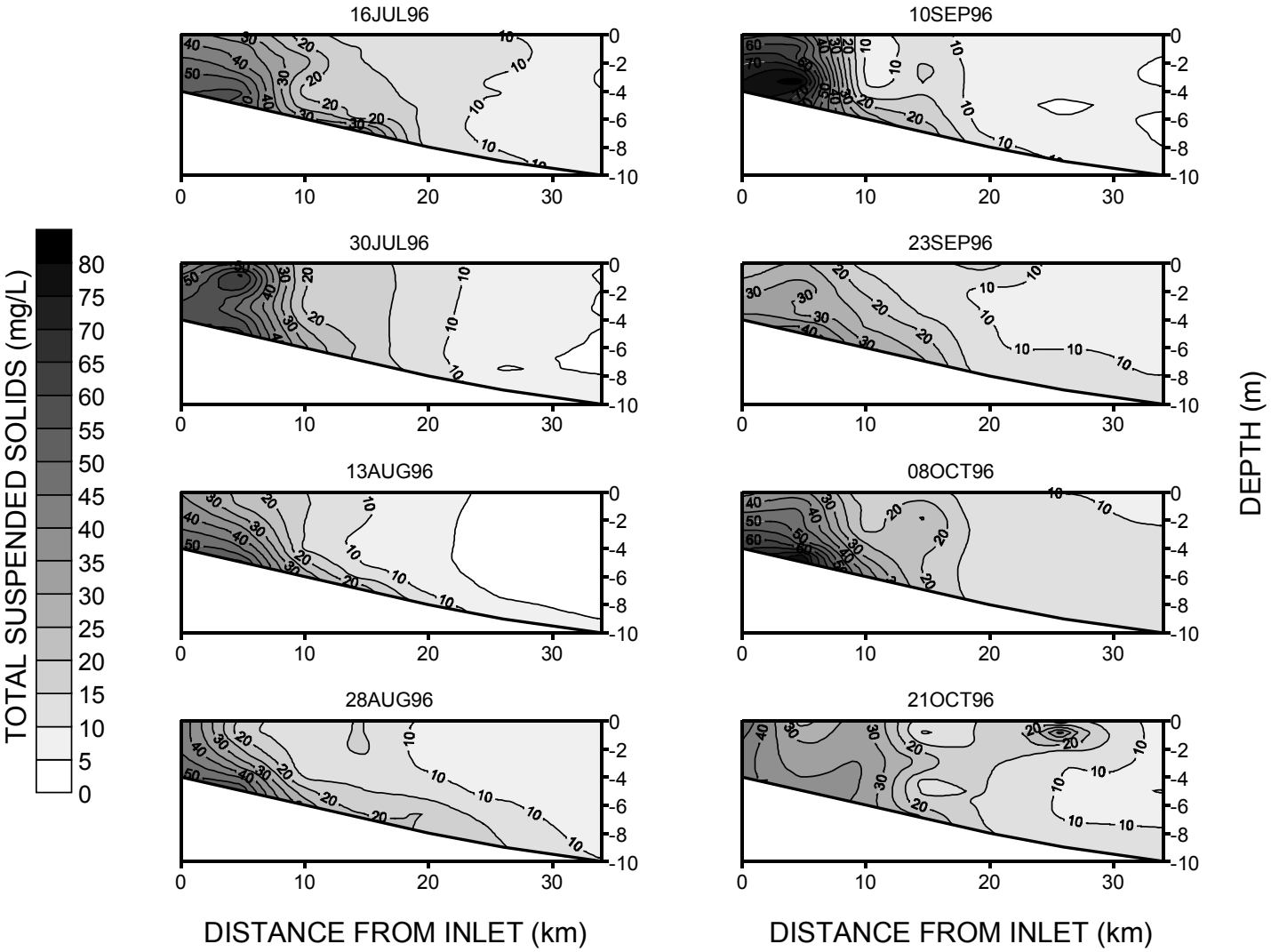


Figure 45. Longitudinal and vertical variations in total suspended solids concentrations in Lake Pepin on eight days during July–October, 1996 (from James et al., 1998).



Turbidity in Spring Lake often exceeded the state water-quality standard of 25 NTU. Secchi disk transparency measurements compared favorably with the NVSS and turbidity results: the average Secchi measurements in Spring Lake (0.3 m) was less than half that in Lake Pepin (0.7 m).

During the same three summers (May–September, 1994–96), MWBAC volunteers also recorded differences in suspended solids concentrations between the upstream and downstream portions of Lake Pepin. At flows less than 20,000 cfs (570 m^3/s), NVSS concentrations and turbidity were significantly higher in upper Lake Pepin, and Secchi measurements were significantly lower (Macbeth and Gostovich, 1998). Between the upper and lower portions of Lake Pepin, mean NVSS concentrations dropped from 40 to 7 mg/L, turbidity decreased from an average of 34 to 10 NTU, and Secchi depths doubled from 0.4 m to 0.8 m.

Results from the entire five-year MWBAC program were similar; however, it was noted that upper Lake Pepin was more closely aligned in water quality to Spring Lake than lower Lake Pepin, especially under low flows (Force and Macbeth, 2001). For example, at flows under 20,000 cfs (570 m^3/s) during 1994–98, mean TSS concentrations were 46.4 mg/L in Spring Lake, 46.6 mg/L in upper Lake Pepin, and 11.3 mg/L in lower Lake Pepin.

Heiskary and Vavricka (1993) also found significant differences in TSS concentrations between the inlet and outlet of Lake Pepin from their analysis of MWCC, MPCA, and MDNR data collected during 1977–91. Concentrations averaged 41 mg/L at the inlet with an interquartile range of 33–47 mg/L, compared to a mean of 11 mg/L at the outlet with an interquartile range of 8–12 mg/L. Also, TSS concentrations at the inlet tended to increase with river flow. They attributed the difference in concentrations between upper and lower Lake Pepin to sedimentation and possibly more resuspension in the shallower, upper portion. It was also noted that higher TSS concentrations in the upper lake tend to limit light transparency to a greater degree.

2.2.3.3 Suspended Solids Loading Sources and Trapping

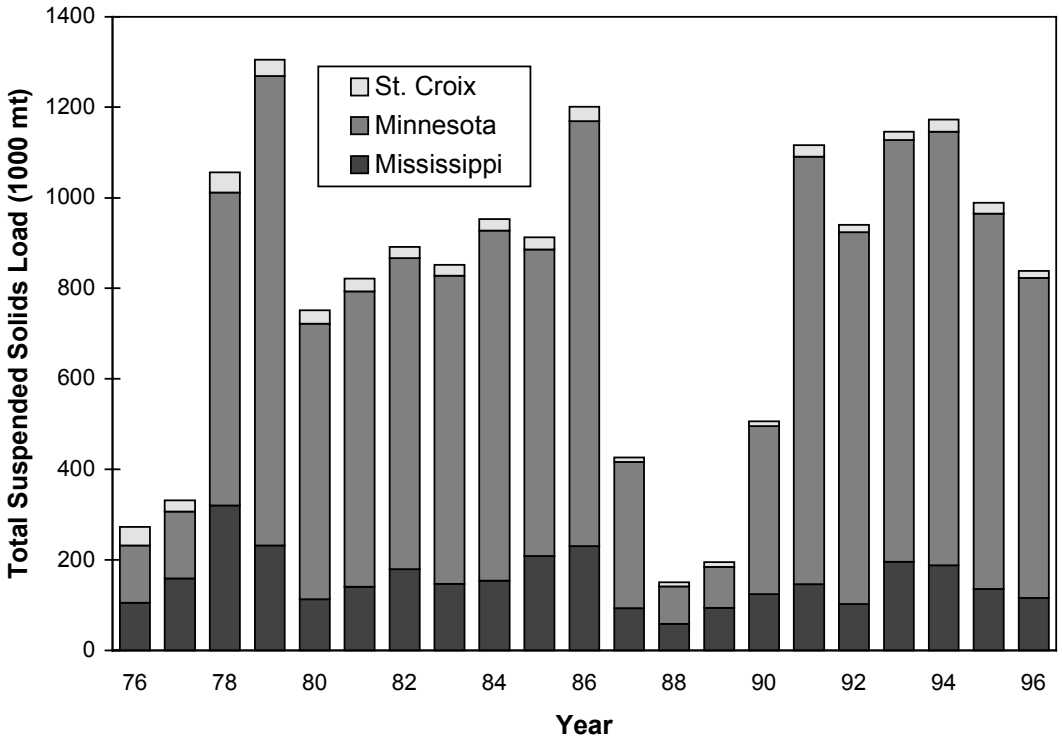
Compiled from the MCES river monitoring database, 1976–96, annual TSS loads were consistently much greater from the Minnesota River than the Mississippi and St. Croix Rivers (Fig. 46; Meyer and Schellhaass, 2002). Annual TSS loads of the Minnesota River ranged from 80,000 to 1,000,000 mt/yr, while loads from the Mississippi River at Lock and Dam No. 1 ranged from 60,000 to 320,000 mt/yr. TSS loads from the St. Croix River ranged from 10,000 to 45,000 mt/yr—much lower than both the Minnesota and Mississippi Rivers. Comparatively low TSS loads from the St. Croix River are due in part to lake-like conditions in the lower 37 km (23 mi) of the river, which allow sedimentation to occur. The small loads also reflect the relatively undisturbed nature of the watershed. TSS loads in all three rivers were very dependent on precipitation and flow conditions. For example, annual loads were substantially less during the dry periods of 1976–1977 and 1987–1990 compared to wetter years.

Over the entire 21-year period, mean annual TSS loads from the Minnesota, Mississippi and St. Croix Rivers were 623, 155, and 24 thousand mt/yr, respectively, or 78%, 19%, and 3% of the combined load (Meyer and Schellhaass, 2002). Yields of total suspended solids from the Minnesota, Mississippi, and St. Croix River Basins were 158, 41, and 15 kg/ha/yr, respectively. In contrast, contributions from point sources were very small. For example, during 1994–96, the Metropolitan, Blue Lake, and Seneca WWTPs contributed only 0.0008% of the combined TSS load from the Minnesota, Mississippi, and St. Croix River Basins.

In the Minnesota River Basin, high rates of field and streambank erosion, highly erodible soils, extensive tile drainage, and drainage of wetlands appear to be the primary factors contributing to high TSS concentrations and loads (Meyer and Schellhaass, 2002). The displacement of perennial plants by annual row crops in approximately 90% of the basin has greatly increased rates of soil erosion. In contrast, the St. Croix River Basin exhibits runoff and loading characteristics that mimic an undisturbed, natural system.

From 1976 to 1996, there was substantial retention of total suspended solids in lower Pool 2, comprising 28% of the incoming load or approximately 250 thousand mt/yr (Meyer and Schellhaass, 2002). During the 21-year period, the year with the highest sediment accumulation in lower Pool 2 was 1979 (652 thousand mt), which ranked 7th highest in flow. The year with the highest percent retention was 1981 at 57%. During the high flow years of 1986 and 1993, sediment retention rates were approximately 35% and 12%, respectively. During years of low flow, such as 1988 and 1989, TSS loads entering and exiting Pool 2 were roughly the same. Deposition in low flow years may be offset by wind resuspension or

Figure 46. Mean annual total suspended solids loads in the Mississippi River at Lock and Dam No. 1 and in the Minnesota and St. Croix Rivers near their mouths, 1976–96 (after Meyer and Schellhaass, 2002).

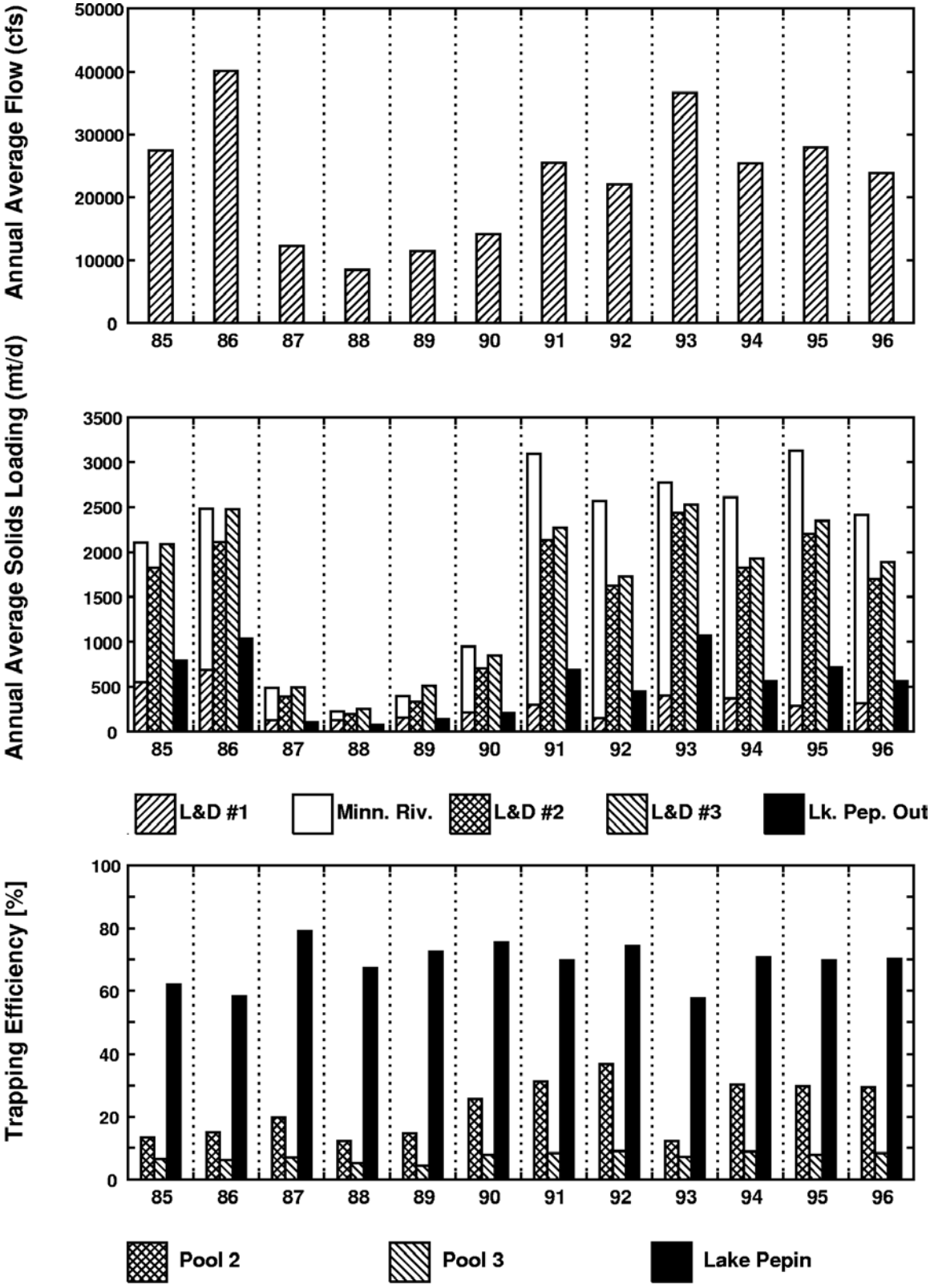


algal production. Overall, lower Pool 2 is acting as a "sedimentation pond" for the Mississippi River, thereby protecting Lake Pepin from higher sediment loading rates.

The sediment transport model, one of three components of the advanced eutrophication model, tracked the movement of inorganic suspended solids in Pools 2–4 over the 12-year period from 1985 to 1996 (HydroQual, 2002a). Model results for this period indicated that the trapping efficiency of Pool 2 ranged from 17% in 1993 to 38% in 1992 (Fig. 47). On average, Pool 2 retained a quarter of the inorganic solids entering the pool, which agrees with estimates for solids trapping in Pool 2 by Meyer and Schellhaass (2002). Retention was minor in Pool 3, averaging less than 10% each year. Lake Pepin, on the other hand, retained nearly 70% of the inorganic solids entering the lake. Trapping efficiencies for the lake ranged from 57% to 80% during the 12-year period. This agrees closely with high TSS retention rates for Lake Pepin calculated by the USAE-WES for the years 1994–96: 72–76% on an annual basis and 81–85% in the summer (James *et al.*, 2000).

According to the results of the sediment transport model, an estimated 400 thousand metric tons per year of inorganic solids were deposited in Lake Pepin during 1985–96 (HydroQual, 2002a). If organic content was 20% (the 21-year average at Lock and Dam No. 3), this would approximate a half million metric tons of total suspended solids deposited per year. USAE-WES estimates for 1994–96 (normal flow years) were somewhat higher: total sediment accumulation rates of 550–750 thousand mt/yr (James *et al.*, 2000). The estimate from the sediment coring study for the most recent period (~1990–96) was even higher: 900 thousand mt/yr (Engstrom and Almendinger, 2000). This period includes several high flow years, including the 1993 flood. All three studies agreed that a spatial gradient exists in Lake Pepin with the greatest deposition occurring at the upper end of the lake—a typical pattern in impoundments. In the model, the average sedimentation rates for the 12-year period were 1.4 cm/yr in the upper third of the lake, 0.9 cm/yr in the middle third, and 0.4 cm/yr in the lower third (HydroQual, 2002a). Sedimentation rates varied greatly with annual fluctuations in flows and solids loads. For example, rates in the upper third of the lake ranged from 0.3 cm/yr in 1988 to over 2.0 cm/yr in 1995.

Figure 47. Annual average flow, inorganic suspended solids loads, and sediment trapping efficiencies in Pools 2 and 3 of the Mississippi River and Lake Pepin, 1985–96 (from HydroQual, 2002a).



2.2.4 Lake Users' Perceptions of Water Quality

The water quality of a lake most directly affects people who live near the lake or who use the lake for recreation. To gauge the opinions of local residents about lake water quality, the Minnesota-Wisconsin Boundary Area Commission coordinated a volunteer monitoring program for Lake Pepin and Spring Lake. During 1994–98, twenty-five volunteers were recruited and trained by the MWBAC to monitor 13 locations in Lake Pepin and three in Spring Lake every other week from mid-May through September. During each visit, the volunteers rated the lakes on their physical condition (from 1 "crystal clear" to 5 "severely high algal levels"), recreational suitability (from 1 "beautiful, could not be better" to 5 "nearly impossible"), and level of suspended sediment (low, average, or high). The volunteers also measured temperature and Secchi transparency in the lakes and collected water samples for laboratory analysis. Data were later examined for relationships between subjective ratings and chemical measures of water quality. Evaluating water-quality goals from the standpoint of user expectations was another objective of this program.

Force and Macbeth (2001) reported the results from the volunteer monitoring program for 1994–98. The authors cautioned that the results should be reviewed with two important caveats in mind. First, low flow conditions did not occur frequently and, therefore, were not adequately surveyed. Daily average river flows fell within the targeted range of 4,600–20,000 cfs (130–570 m^3/s) on 41 percent of the days during June–September, 1994–98. [The targeted range of flows came from the Lake Pepin water-quality goal (Section 1.2).] However, flows at the lower end of this range (4,600 to 10,000 cfs or 130 to 280 m^3/s) occurred only eight percent of the time, and extended low-flow conditions as in 1988 did not occur. Second, the 25 volunteers were recruited and not selected at random, so their perceptions may not be representative of the general populace.

When river flows were within the targeted range (4,600–20,000 cfs or 130–570 m^3/s), volunteers generally rated algal levels as moderate (3.0 on a scale of 1 to 5) in Spring Lake. Lower algal levels were perceived in Lake Pepin, with average ratings of 2.4 for the whole lake, 2.7 for the upper end, and 2.3 for the lower end. On these days, viable chlorophyll *a* concentrations averaged 29.5 µg/L in both Spring Lake and upper Lake Pepin and 23.4 µg/L in lower Lake Pepin. For comparison, the water-quality goal for Lake Pepin is 30 µg/L. Recreational suitability increased in a downstream direction from "substantially reduced" in Spring Lake to midway between "slightly impaired" and "excellent" in upper Lake Pepin and "excellent" in lower Lake Pepin (3.9, 2.5, and 2.1, respectively, on a scale of 1 to 5). Ratings of the amount of suspended sediment observed in the water decreased in the same direction: 2.4 (average–high), 2.0 (average), and 1.4 (low–average) in Spring Lake, upper Lake Pepin, and lower Lake Pepin, respectively. Average turbidity measurements at the three locations were 24.1, 23.5, and 7.1 NTU, respectively. When flows surpassed 20,000 cfs, mean water-quality ratings were similar to those at lower flows. In summary, the volunteers found the water quality of Spring Lake significantly more impaired than Lake Pepin, and upper Lake Pepin more impaired than lower Lake Pepin.

Another important result of the MWBAC program was the ability of volunteers to detect subtle differences in water quality through observation alone. A good linear relationship ($r^2 = 0.768$, all flows) existed between the subjective ratings of physical condition and measurements of viable chlorophyll *a* when concentrations were less than 55 µg/L. It appears that volunteers were able to perceive changes in algal levels in the range of the water-quality goal for Lake Pepin (30 µg/L), which should provide help in evaluating the goal after more data are collected. Volunteers were also able to detect changes in suspended solids concentrations ($r^2 = 0.822$, all flows). However, no strong relationship was seen between the ratings of recreational suitability and either chlorophyll *a* or solids concentrations, leading the authors to conclude that the factors behind this perception may be more complex.

2.3 Future Conditions

The Phosphorus Study Cooperators Group wanted not only to understand the current effects of phosphorus loads on water quality but also to project the benefits of reduced loads in the future. The key issue was setting an appropriate phosphorus effluent limit for the Metro Plant in the next discharge permit (1998). Beyond this, the group wanted to develop a predictive tool to evaluate different phosphorus management strategies for point and nonpoint sources across the Lake Pepin watershed and answer the following questions:

- What are the projected water-quality benefits of reduced phosphorus loads from point and nonpoint sources?

- Specifically, what is the benefit of phosphorus removal to 1.0 or 0.4 mg/L at the Metro Plant?

- What are the projected short and long-term responses of sediment SRP flux in Lake Pepin to reduced phosphorus loads?

The successful calibration of the advanced eutrophication model for the 12-year period from 1985 to 1996 demonstrated the appropriateness of applying the model to evaluate responses to nutrient controls at point and nonpoint sources (HydroQual, 2002a and 2002b). The model reproduced water-quality conditions in the Mississippi River and Lake Pepin throughout this period, which included a wide range of hydrologic conditions from extreme low flows in 1988 to floods in 1993. By accounting for sediment transport, phosphorus sorption, and sediment flux, the modeling framework bridged the connection between phosphorus loading and deposition during high flow periods and sediment phosphorus release during low flow periods.

The projection model, phosphorus reduction scenarios, and predicted water-quality benefits are summarized in the following sections and described in more detail by HydroQual (2002a and 2002b). The model and scenarios are described in Section 2.3.1. The projected results for a future low flow summer, with weather and flow conditions identical to 1988, were of particular interest and are highlighted in Sections 2.3.2. Projected long-term benefits over a 12-year period are provided in Section 2.3.3. In addition to HydroQual's projections of future water-quality conditions, Engstrom and Almendinger (2000) applied current sediment accumulation rates to project the gradual infilling of Lake Pepin, which is discussed in Section 2.3.4.

2.3.1 Projection Model and Phosphorus Reduction Scenarios

HydroQual (2002a) applied the model calibrated for the years 1985–96 to simulations of future water-quality conditions under several scenarios of reduced nutrient loads from point and nonpoint sources. Hydrodynamic models of the original 12 years were repeated through two cycles to simulate a typical range of hydraulic conditions during a future 24-year period (1998–2021). River flows during 1985–96 were fairly representative of historical flows. The water-quality model was also duplicated to represent the years 1998–2021, but loads to the model were adjusted in separate runs to test and compare different phosphorus management scenarios. Thirteen scenarios were simulated. Phosphorus reductions at the Metro Plant were tested separately and in combination with phosphorus reductions at other point and nonpoint sources across the Lake Pepin watershed.

MCES designed the following four scenarios for total phosphorus concentrations in the effluent of the Metro Plant (HydroQual, 2002a):

1. Annual average TP concentration of 1.0 mg/L implemented in 2008

2. Annual average TP concentration of 1.0 mg/L implemented in 2003

3. Monthly average TP concentration of 1.0 mg/L implemented in 2003

4. Monthly average TP concentration of 0.4 mg/L implemented in 2003

To meet monthly average TP concentrations of 1.0 and 0.4 mg/L, the Metro Plant would need to be designed to meet annual average TP concentrations of 0.65 and 0.32 mg/L, respectively. In the model, annual average effluent flows at the Metro Plant were adjusted to service projected population increases and industrial growth during 1998–2021. In the baseline scenario, which tested the alternative of no future phosphorus reductions, the annual average phosphorus concentration in the Metro Plant effluent was set to 3.0 mg/L.

Scenarios 1 and 2 (annual average TP concentration of 1.0 mg/L) represented a 67 percent reduction in Metro Plant phosphorus loads from the baseline scenario. An effluent limit of 1.0 mg/L could be achieved with biological phosphorus removal. The difference between Scenarios 1 and 2 was simply the year (2003 or 2008) when phosphorus removal was projected to be implemented. Scenario 3 (monthly average TP concentration of 1.0 mg/L) matched the typical permit language for effluent phosphorus limitations in the early 1990s. This scenario represented a 78 percent reduction in Metro Plant phosphorus loads. Meeting an annual average versus a monthly average TP concentration of 1.0 mg/L would provide more operational flexibility at less cost. Scenario 4 (monthly average concentration of 0.4 mg/L) represented a phosphorus reduction of 89 percent from the

baseline Metro Plant loads. This level of phosphorus removal was considered the limit of technology and would have required expensive effluent filtration and some chemical phosphorus removal. For the various forms of phosphorus (e.g., dissolved and particulate, organic and inorganic), MCES engineering consultants recommended concentrations that might be expected under each of the four scenarios. Other effluent characteristics, such as nitrogen, were described with 1996 data for the Metro Plant.

The MPCA designed the following two scenarios for phosphorus reductions at other point and nonpoint sources across the Lake Pepin watershed (MPCA, 1998; HydroQual, 2002a):

A. For point sources, an annual average TP concentration of 1.0 mg/L. For nonpoint sources, 50–80% implementation of selected agricultural best management practices.

B. For point sources, an annual average TP concentration of 1.0 mg/L (same as A). For nonpoint sources, 25–50% implementation of selected agricultural best management practices.

For point sources outside of the Metro Area, the MPCA estimated current (~1996) phosphorus loads from point sources in the Mississippi, Minnesota, and St. Croix River Basins. Current loads were then adjusted to fit the phosphorus reduction scenarios. Discharges with no current phosphorus effluent limits or with limits greater than 1.0 mg/L were reduced to an annual average concentration of 1.0 mg/l. These reductions were implemented in the same year in which phosphorus reductions were projected for the Metro Plant (2003 or 2008). No load adjustments were made for discharges with current phosphorus effluent limits equal to or less than 1.0 mg/L as a monthly or annual average concentration.

For Metro Area WWTPs other than the Metro Plant, HydroQual adjusted phosphorus loads according to the MCES Phosphorus Strategy, which calls for the phasing-in of phosphorus removal to 1.0 mg/L with planned facility expansions. In the projection model, effluent phosphorus concentrations were set to 1.0 mg/L at the South Washington County WWTP in 2002, at the Empire WWTP in 2009, and at the Hastings WWTP in 2010, according to facility plans at the time. Chemical phosphorus removal was implemented at the St. Croix Valley WWTP in 1973, and phosphorus reductions have been achieved through process controls at the Blue Lake and Seneca WWTPs since the mid-1990s. Model inputs for the Mississippi River at Lock and Dam No. 1 and for the Minnesota and St. Croix Rivers were adjusted to reflect reduced point-source phosphorus loads for WWTPs inside and outside of the Metro Area.

The two scenarios for nonpoint-source reductions represented "most optimistic" (A) and "medium optimistic" (B) levels of adopting selected best management practices for agriculture across the Lake Pepin watershed, as listed in Table 4 (MPCA, 1998; HydroQual, 2002a). To compile nonpoint-source load reductions for the three major river basins, the MPCA applied a water-quality model of the Le Sueur River watershed (one of 12 major watersheds in the Minnesota River Basin) and extrapolated the results to the entire Minnesota River Basin, as well as to the St. Croix Basin and that portion of the Mississippi River Basin upstream of Lock and Dam No. 1. The extrapolations were based on land use in the three basins. Loads were adjusted by flow quartile and season with recognition of the dependence of loads on rainfall and seasonal differences. Loads and the resulting reductions were greatest at high flows and minimal during low flows. Nonpoint-source reductions were also greatest in the Minnesota River Basin (highly agricultural) and the least in the St. Croix River Basin (mostly forests and grasslands). While the point-source scenarios only applied to phosphorus, the nonpoint-source scenarios also applied to nitrogen, chlorophyll *a,* total organic carbon, dissolved oxygen, biochemical oxygen demand, and suspended solids.

Table 4. Percent adoption of selected best management practices for agriculture under three phosphorus reduction scenarios (MPCA, 1998).

Best Management Practice	Scenario		
	Baseline: 1996 Levels	A: Most Optimistic	B: Medium Optimistic
Conservation Tillage	3%	80%	50%
Nutrient Management	0%	50%	25%
Feedlot Management	25%	75%	50%

Note that the levels of phosphorus reduction in the scenarios were very different for point and nonpoint sources. Scenarios A and B represented a 58% reduction in annual phosphorus loads from point sources in the three major river basins (MPCA, 1998). This percentage does not include phosphorus load reductions at the Metro, South Washington County, Hastings, Empire, or Wisconsin WWTPs, which were 67% or greater. In contrast, reductions in phosphorus loads from nonpoint sources varied from 0 to 21% in Scenario B ("Medium Optimistic") and from 0 to 43% in Scenario A ("Most Optimistic") depending on the basin, season, and flow (MPCA, 1998). Load reductions from nonpoint sources were negligible during low flow summers.

2.3.2 Water Quality in a Future Low Flow Summer

Figure 48 shows the results of the 13 phosphorus reduction scenarios for Lake Pepin during a future low flow summer. The top panel displays projected mean phosphorus concentrations, the middle panel displays projected mean viable chlorophyll *a* concentrations, and the bottom panel displays the projected percent of days when viable chlorophyll *a* concentrations will exceed the water-quality goal of 30 µg/L. The results of selected scenarios are discussed in this section. The complete results are documented in HydroQual (2002a and 2002b).

Not surprisingly, if no further reductions in phosphorus loads are made beyond baseline (1996) levels at either point or nonpoint sources, water-quality conditions in Lake Pepin during a future low flow summer will likely be similar to those in 1988, including severe nuisance algal blooms and the potential for fish kills (Fig. 48: Baseline). Under the baseline scenario (no reductions), lakewide average concentrations are projected to be 0.36 mg/L for total phosphorus and 42.7 µg/L for viable chlorophyll *a,* compared to 0.36 mg/L and 40.8 µg/L, respectively, in the summer of 1988. Algal levels would be excessive—that is, above 30 µg/L as viable chlorophyll *a*—for approximately three-quarters (74%) of the summer.

If effluent phosphorus concentrations at the Metro Plant are reduced to 1.0 mg/L as an annual average in 2003, water-quality conditions in Lake Pepin during a future low flow summer are projected to improve somewhat, but excessive algal blooms are still likely to occur during nearly two-thirds (64%) of the summer (Fig. 48; Scenario Metro 2, Metro Plant Only). Lakewide average phosphorus concentrations are projected to decrease 25% to 0.27 mg/L; however, average concentrations of viable chlorophyll *a* would drop only 7% to 39.5 µg/L. This translates to a gain of 12 days with algal levels below 30 µg/L in comparison to the baseline scenario. Despite a 67% reduction in phosphorus loads from the Metro Plant, phosphorus concentrations remain high enough to support excessive algal growth in Lake Pepin. If phosphorus removal is implemented at the Metro Plant five years later in 2008, projected phosphorus and chlorophyll concentrations in Lake Pepin during a future low flow summer are only slightly higher: 0.28 mg/L and 39.6 µg/L, respectively (Fig. 48: Scenario Metro 1, Metro Plant Only).

What if phosphorus concentrations at all point sources in the Lake Pepin watershed are reduced to 1.0 mg/L as an annual average, and moderate reductions in phosphorus loads from nonpoint sources are also achieved? This was generally considered the most likely scenario by the cooperating agencies. Basin-wide phosphorus reductions would roughly double the improvement seen with reductions at the Metro Plant alone (Fig. 48: Scenario Metro 2, Basin B). Mean concentrations in Lake Pepin during a future low flow summer would decrease to 0.22 mg/L for total phosphorus and 35.7 µg/L for viable chlorophyll *a,* with the gain of 18 days of algal levels below 30 µg/L over the baseline scenario. Still, algal levels would be excessive on 59 percent of the summer days. The additional improvement would be mostly due to phosphorus reductions at point sources, as runoff and loads from nonpoint sources would be greatly diminished during drought conditions.

What if effluent phosphorus concentrations are reduced to 0.4 mg/L as a monthly average at the Metro Plant and 1.0 mg/L as an annual average at other WWTPs, and greater reductions in nonpoint source loads are achieved? This scenario represents the maximum level of reductions tested in the model. Lakewide average concentrations during a future low flow summer would further decrease to 0.17 mg/L for total phosphorus and 31.0 µg/L for viable chlorophyll *a* (Fig. 48: Scenario Metro 4, Basin A). Excessive algal levels would occur on 42 percent of the summer days, representing a gain of 39 days of algal levels below 30 µg/L over the baseline scenario.

Figure 49 displays the results of the 13 scenarios for Spring Lake during a future low flow summer. Under the various load-reduction scenarios, phosphorus concentrations are projected to decrease dramatically in Spring Lake during a future low flow summer, from 0.51 mg/L with no reductions (Baseline)

Figure 48. Projected mean total phosphorus and viable chlorophyll *a* concentrations and percent of days when viable chlorophyll *a* concentrations will be greater than 30 µg/L in Lake Pepin during a future low flow summer under different phosphorus reduction scenarios (Data source: HydroQual, 2002a).

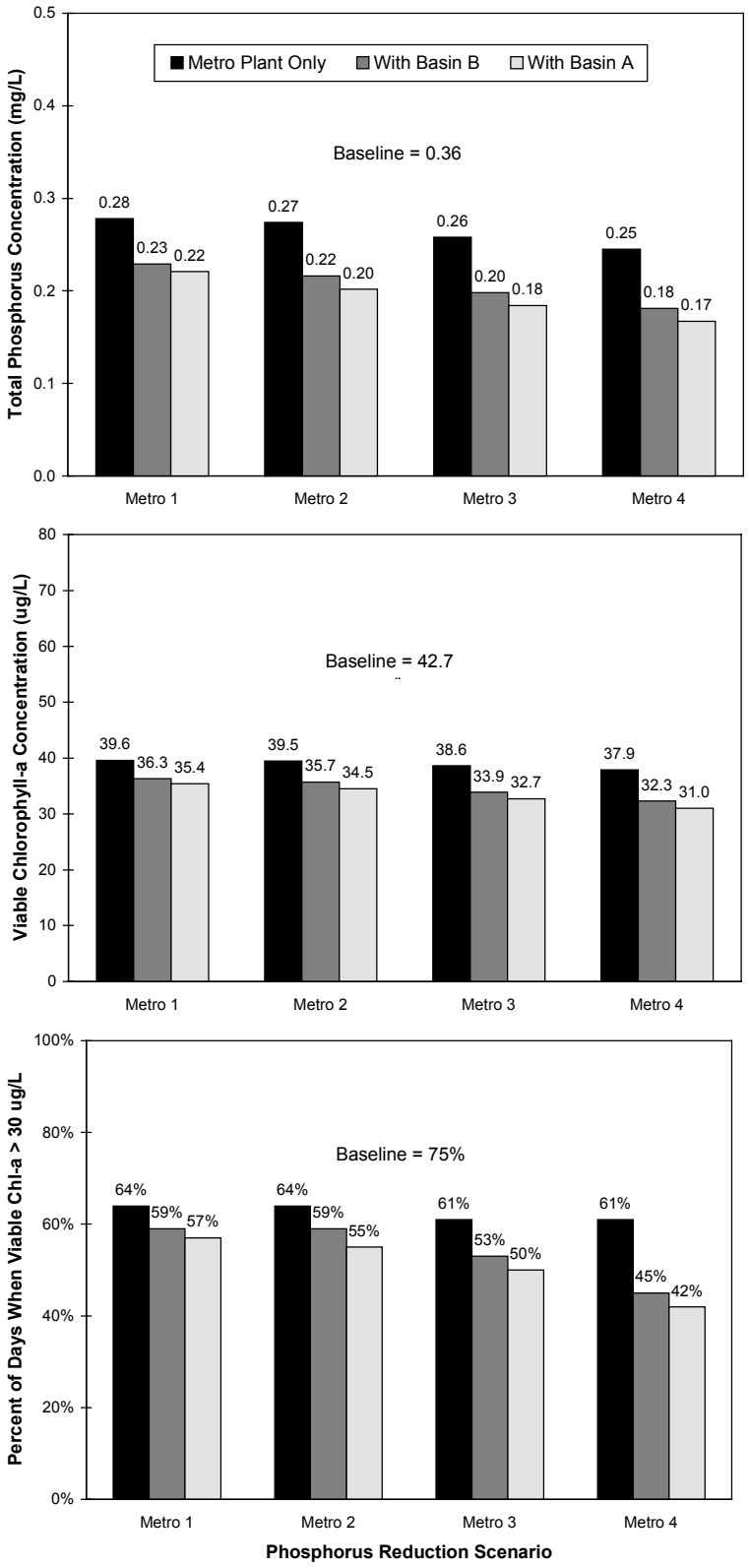
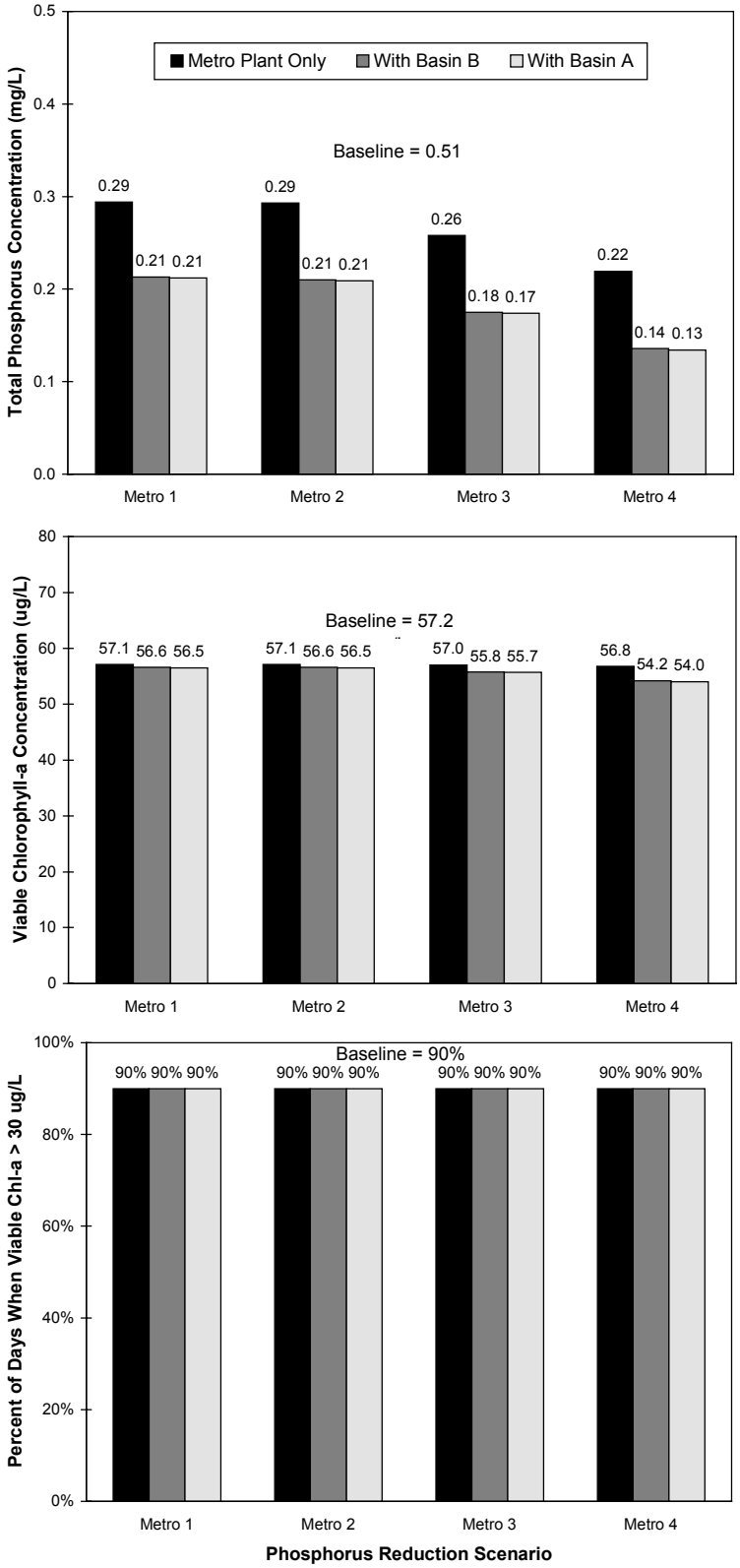


Figure 49. Projected mean total phosphorus and viable chlorophyll *a* concentrations and percent of days when viable chlorophyll *a* concentrations will be greater than 30 µg/L in Spring Lake during a future low flow summer under different phosphorus reduction scenarios (Data source: HydroQual, 2002a).



to

- 0.29 mg/L with an effluent TP limit of 1.0 mg/L at the Metro Plant (Metro 2, Metro Plant Only),
- 0.21 mg/L with an effluent TP limit of 1 mg/L at all point sources and moderate nonpoint-source reductions (Metro 2, Basin B), and
- 0.13 mg/L with an effluent TP limit of 0.4 mg/L at the Metro Plant and 1.0 mg/L at other point sources plus greater nonpoint-source reductions (Metro 4, Basin A).

However, algal levels are projected to remain very high—54–57 µg/L as a summer average—under all scenarios. For example, with a 67% reduction at the Metro Plant (Metro 1 or 2) and basin-wide reductions (Basin A or B), the projected improvement in mean summer viable chlorophyll *a* concentrations is less than 1.0 µg/L.

Spring Lake is a naturally more productive system than Lake Pepin because it is shallower. Algae are mixed to greater depths in Lake Pepin, especially in the downstream end, and can be transported to depths below the photic (light) zone. While projected phosphorus concentrations in Spring Lake approach those in Lake Pepin, algal levels remain much higher in Spring Lake. Further, somewhat greater reductions in algal levels are predicted for Lake Pepin because phosphorus limitation of algal growth is reached more often than in Spring Lake due to greater spatial variation in phosphorus concentrations in Lake Pepin.

The response of sediment SRP release rates in Lake Pepin to the various phosphorus reduction scenarios is very different than the response seen in water-column SRP concentrations (HydroQual, 2002a and 2002b). In the water column of Lake Pepin, the largest reduction in SRP concentration occurs with the first level of phosphorus control at the Metro Plant (i.e., 1.0 mg/L as an annual average). In the sediment of Lake Pepin, the largest reduction in SRP release rates occurs with the first level of basin-wide phosphorus controls at both point and nonpoint sources. There is also a substantial difference in SRP release rates between the two levels of nonpoint-source reductions.

With no further reductions in phosphorus loads, the mean SRP release rate from the Lake Pepin sediment is projected to be 39.3 mg/m^2/d during a future low flow summer (Fig. 50: Baseline Scenario). With phosphorus removal to 1.0 mg/L as an annual average at the Metro Plant, the SRP release rate is projected to decrease only 6% to 36.8 mg/m^2/d in a future low flow summer (Scenario Metro 2, Metro Only). Adding moderate phosphorus controls to point and nonpoint sources across the Lake Pepin watershed would decrease the SRP release rate to 31.4 mg/m^2/d, a 20% reduction from the baseline rate (Scenario Metro 2, Basin B). Achieving a higher level of load reductions from nonpoint sources would decrease rates to 28.7 mg/m^2/d or by 27% (Scenario Metro 2, Basin A). With maximum phosphorus reductions at the Metro Plant (i.e., 0.4 mg/L as a monthly average), percent reductions in SRP release rates would be 11%, 29%, or 36% if combined with no, moderate, or high basin-wide phosphorus reductions, respectively (Scenario Metro 4 with Metro Plant Only, Basin A, or Basin B).

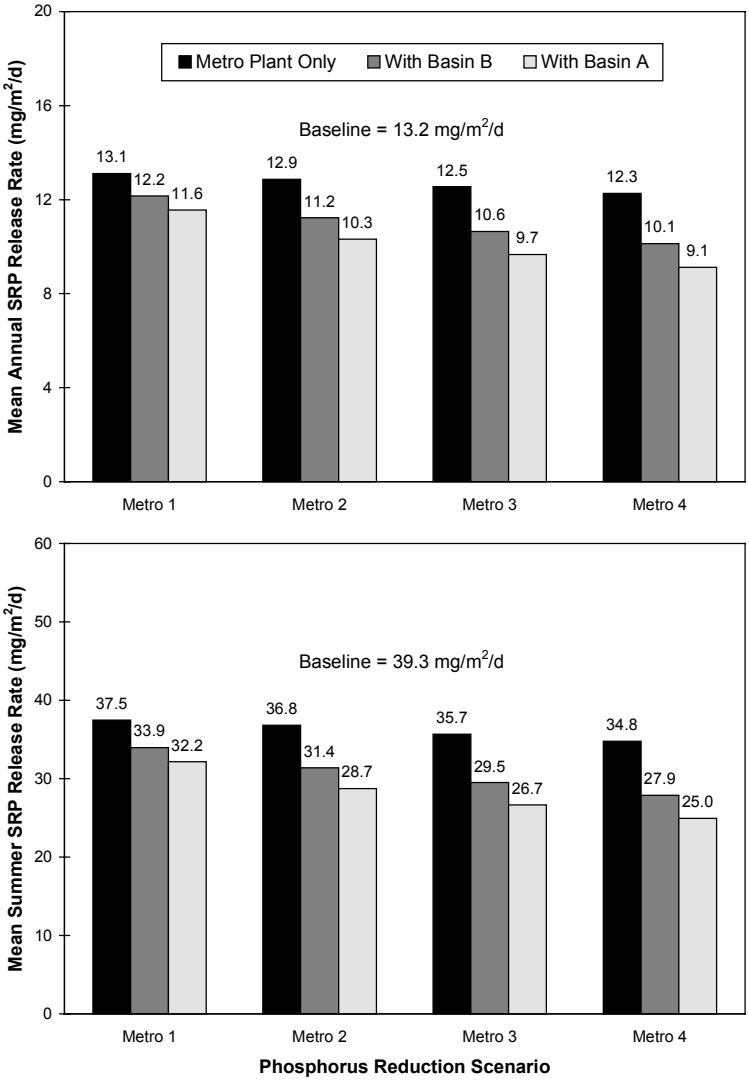
Two factors are mainly responsible for the decreases in sediment SRP release rates. First, reductions in suspended solids from nonpoint sources lead to decreases in the deposition of sorbed inorganic phosphorus in Lake Pepin. Second, basin-wide phosphorus reductions lead to reductions in algal biomass production in lower Pool 2 and Lake Pepin. With less algal biomass settling to the sediment and generating an oxygen demand through decomposition, DO concentrations increase at the sediment-water interface, reducing SRP release rates.

During a future low flow summer, the benefit of reduced phosphorus loads from nonpoint sources is evident not in decreased external SRP loads to Lake Pepin, but in decreased internal SRP loads. Internal loads accounted for 68% of the total SRP load to Lake Pepin in the summer of 1988 (Section 2.2.1.5). Phosphorus loading and deposition in high flow years affect SRP release rates in subsequent low flow years. The combined reduction in internal and external loads with phosphorus controls leads to increases in phosphorus limitation and, consequently, decreases in algal levels. However, the effect of reduced internal SRP loads is dampened somewhat because chlorophyll concentrations decrease as Lake Pepin deepens from the inlet to the outlet, while SRP release rates increase. Where internal SRP loading rates are highest (lower Lake Pepin), algal levels are lowest.

2.3.3 Water Quality over a Projected 12-Year Period

In addition to compiling modeling results for a future low flow summer, HydroQual (2002a and 2002b) summarized the projected water-quality results for a future 12-year period (2010–2021) representing the

Figure 50. Projected mean annual and summer SRP release rates from the sediment in Lake Pepin during a future low flow year under different phosphorus reduction scenarios (after HydroQual, 2002a).



same range of flows and climatic conditions that occurred during 1985–96. Under all scenarios, reductions in viable chlorophyll *a* concentrations in Lake Pepin are projected to be fairly small. The main benefit over a 12-year period would be to reduce extremely high algal levels, which occur infrequently and arise mainly under extreme low flows.

For example, with biological phosphorus removal to 1.0 mg/L at the Metro Plant, reductions in viable chlorophyll *a* concentrations of over 5 µg/L are projected only when baseline chlorophyll *a* concentrations are over 70 µg/L. In the baseline scenario, concentrations over 70 µg/L occur only two percent of the time during the 12-year period. Chlorophyll *a* reductions as high as 20 µg/L are projected when baseline chlorophyll *a* concentrations reach their maximum near 100 µg/L. Ninety-five percent of the time, when chlorophyll concentrations are below 50 µg/L, improvement in algal levels, if any, would be negligible (< 2 µg/L). Similarly, dissolved oxygen concentrations in the bottom layer of Lake Pepin are projected to increase only when dissolved oxygen concentrations are low. For example, with phosphorus removal to 1.0 mg/L at the Metro Plant, bottom-layer DO concentrations would improve only when baseline DO concentrations are less than 3.0 mg/L, which occurs approximately 10 percent of the time. The improvement would be less than 0.5 mg/L and would not correct hypoxic conditions, which threaten aquatic life.

In Spring Lake, SRP concentrations are projected to rarely decrease below 0.01 mg/L, and then

only under the most stringent phosphorus load reductions. An SRP concentration of 0.01 mg/L would result in a nine percent reduction in the algal growth rate. In all phosphorus reduction scenarios, very little change in chlorophyll or dissolved oxygen concentrations in Spring Lake is predicted during the 12-year period. Reductions in viable chlorophyll *a* concentrations are projected only when baseline chlorophyll *a* concentrations exceed 100 µg/L, which occur only 1–2% of the time. Even then, the decrease is less than 10 µg/L and Spring Lake remains hypereutrophic.

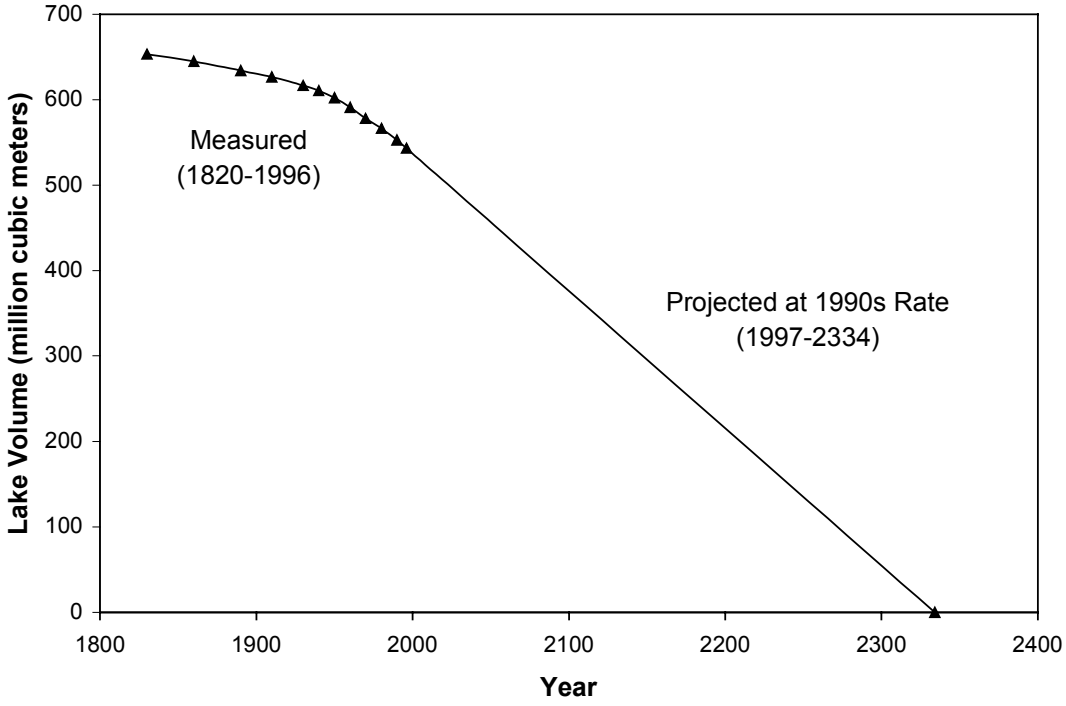
The effectiveness of phosphorus controls varies from year to year based on environmental conditions, of which river flow is particularly important. During low flow summers, the greatest changes in SRP concentrations in Lake Pepin and Spring Lake are achieved with phosphorus load reductions at the Metro Plant. Some additional improvement is evident with phosphorus reductions at all point sources in the Lake Pepin watershed, but very little additional improvement is apparent with either of the two levels of nonpoint-source reductions. In higher flow years, nonpoint-source load reductions become more significant, and differences in water-quality improvements between the two levels of nonpoint-source reductions become more apparent.

2.3.4 Projected Infilling of Lake Pepin with Sediment

Engstrom and Almendinger (2000) estimated sediment accumulation rates in Lake Pepin from the 1500s to the 1990s and applied these rates to projections of past and future volume losses in the lake (i.e., losses through the replacement of water with sediment). About 17% of the lake's volume in 1830 has already been replaced by sediment, and at current accumulation rates, the remainder of the lake will be filled in another 340 years (Fig. 51). The upper one-third of the lake, with its higher sediment accumulation rate, will be gone in a century. Without this acceleration in sediment loading rates, Lake Pepin would be on average one meter deeper today and could persist another 4000 years.

These predictions of future lake volume losses use sediment accumulation rates from the 1990s when river flows were higher than average, especially in the Minnesota River. Because the Minnesota River Basin contributes over 80% of the sediment loads to Lake Pepin, the infilling rate may be overestimated and the projected life of Lake Pepin may be underestimated.

Figure 51. Volume loss in Lake Pepin due to sedimentation measured for the period 1820–1996 and projected for the period 1997–2334 using sedimentation rates from the 1990s (after Engstrom and Almendinger, 2000).



3 SUMMARY AND CONCLUSIONS

At the completion of the Lake Pepin Phosphorus Study, the Cooperators Group reviewed the study results and adopted a list of study conclusions and recommendations, which are presented in Section 3.1. The discharge permit for the Metro Plant was reissued in November 1998 with several new provisions relating to phosphorus control, which are described in Section 3.2. During the tenure of the Lake Pepin Phosphorus Study, several strategies to manage phosphorus were launched by the Metropolitan Council, State of Minnesota, State of Wisconsin, and federal government. Section 3.2 summarizes the actions of the various agencies.

3.1 Consensus of Cooperators

In October 1999 MCES presented an integration of the results of the six components of the 1994–98 study along with a draft list of consensus items to the Phosphorus Study Cooperators Group. Members discussed and reviewed the results and submitted comments over the next several months. Comments were evaluated and changes were made where appropriate. This section presents the study conclusions adopted with consensus by the Phosphorus Study Cooperators Group in February 2000. These conclusions are based on the results of the six study components: Engstrom and Almendinger, 2000; James *et al.,* 2000; HydroQual, 2002a; Force and Macbeth, 2001; Meyer and Schellhaass, 2002; and Mulla *et al.,* 2000.

Past Conditions and Historical Changes. Over the past 200 years, algal communities in Lake Pepin have changed from clear-water benthic and mesotrophic planktonic taxa to mostly planktonic assemblages characteristic of highly eutrophic conditions. Factors explaining these changes are likely increased phosphorus concentrations and decreased light from algal self-shading and higher suspended solids concentrations.

Since European settlement, phosphorus loads to Lake Pepin have increased more than five-fold to over 4000 mt/yr in the 1990s. Driven by population growth and modulated by precipitation and river flow, wastewater discharges and fertilizer applications to agricultural lands are likely the most important anthropogenic factors in changes to phosphorus loads over the past 200 years. Phosphorus concentrations in Lake Pepin, as reconstructed from diatom assemblages, have increased approximately four-fold, from 50 to 200 µg/L, over this same period. Sediment loads have increased ten-fold to nearly 900,000 mt/yr in the wet 1990s, most likely due to increases in the amount of area planted to row crops. The greatest changes in sediment, phosphorus, and algae in Lake Pepin have occurred since 1940.

Current Conditions. The major nutrients for algae (phosphorus, nitrogen, and silica) are currently abundant in the Mississippi River, from Lock and Dam No. 1 through Lake Pepin, and rarely decline to concentrations low enough to limit algal growth. During 1976–1996, mean concentrations of total phosphorus were 0.10, 0.23, and 0.18 mg/L at Lock and Dam Nos. 1, 2, and 3, respectively. When physical and hydrological conditions are favorable, such as during low flow summers, severe nuisance algal blooms occur, especially in lower Pool 2 and Lake Pepin. These algal blooms, dominated by blue-green algae, are characterized by viable chlorophyll *a* concentrations greater than 30 µg/L. Under these conditions, oxygen consumption by living algae and decomposing detritus can lead to hypoxia and fish kills, as evidenced in Lake Pepin in the summer of 1988.

Relative Contributions of Phosphorus. During periods of low river flows, point sources contribute the majority of phosphorus loads to the Mississippi River upstream of Lake Pepin (e.g., 88.5% from all point sources and 47.3% from the Metro Plant in 1988). However, at high flows, phosphorus loads from nonpoint sources dominate this reach (e.g., 74.5% from all nonpoint sources and 58.3% from nonpoint sources in the Minnesota River Basin in 1993). At average flows, phosphorus loads are roughly split between point and nonpoint sources. The Metro Plant is the largest point source of phosphorus upstream of Lake Pepin, contributing approximately 20% of the total phosphorus and 40% of the soluble reactive phosphorus during the past two decades. The Minnesota River Basin is the largest contributor of phosphorus loads from nonpoint sources.

Algal Concentrations. Algal levels are already elevated upstream of Lake Pepin, as documented by long-term monitoring data for the period from 1976 to 1996. Mean viable chlorophyll *a* concentrations at monitoring stations in Pools 2 and 3 ranged between 24 and 32 µg/L over the 21-year period. Concentrations were particularly high in the Minnesota River, averaging 45 µg/L at the mouth. The Mississippi River at Lock and Dam No. 1 and the Minnesota River are the largest external sources of algal biomass to Pools 2–4. The contribution by the Minnesota River is disproportionately high with respect to its

water volume.

Phosphorus Fate and Transport. Only a small fraction of phosphorus is retained in Pools 2–4 of the Mississippi River. Most phosphorus is flushed through this reach and transported downstream of Lake Pepin rather than retained as sediment or biomass. During 1985–1996, the overall retention rate of phosphorus in Lake Pepin was approximately 10%. In all 12 years, Lake Pepin was a net sink of particulate phosphorus and a net source of soluble reactive phosphorus. Both inorganic and organic forms are important components of phosphorus flux to the Lake Pepin sediment. Levels of phosphorus are high in the sediment bed (mean TP = 1.219 mg/g dry wt) and sediment porewater (mean SRP = 1.083 mg/L), which results in a high potential for internal SRP loading to the lake.

Internal SRP Loading. In most years, the net exchange of phosphorus between the sediment and water column of Lake Pepin represents a small fraction of the mass of phosphorus flowing into and out of the lake. For example, internal loads represented roughly a tenth of the total SRP load to Lake Pepin during 1985–1996. This fraction can climb to a third in low flow years and two-thirds in low flow summers (e.g., 1987–1989). Seasonal differences, including temperature, and dissolved oxygen concentrations are major factors controlling SRP release rates in Lake Pepin sediment. While roughly five times lower than rates under anoxic conditions, SRP release rates under oxic conditions are substantial (in lab at 20°C, mean oxic rate = 2.9 mg/m^2/d and mean anoxic rate = 14.5 mg/m^2/d). Algal production in lower Pool 2 may also be a factor affecting SRP release rates in Lake Pepin, as algal biomass contributes to oxygen demand in the deeper portions of Lake Pepin.

Future Conditions With Phosphorus Reductions. With reduced phosphorus loads, water-quality conditions in Lake Pepin during a future low flow summer are expected to improve somewhat. Phosphorus concentrations will decrease dramatically, but levels will remain high enough to support excessive algal growth (i.e., viable chlorophyll *a* > 30 µg/L). Even with phosphorus removal to 1.0 mg/L at all point sources and moderate phosphorus controls at nonpoint sources, algal levels in Lake Pepin would remain excessive during nearly three-fifths (59%) of the summer. The main benefit would be to reduce peak algal levels during low flow periods. Basin-wide phosphorus reductions roughly double the improvement in algal levels observed with phosphorus reductions at the Metro Plant alone. Very little improvement in algal levels is predicted for Spring Lake. The benefit of reduced phosphorus loads from nonpoint sources is primarily evident in reduced internal SRP loads in Lake Pepin.

Phosphorus Reduction Scenarios for Point and Nonpoint Sources. In the scenarios applied in the water-quality model, phosphorus reductions projected for the Metro Plant were 67–89% year-round and represent different levels of technology in wastewater treatment. The greatest reduction (89%) represents the current limit of technology (i.e., filtration to 0.4 µg P/L). Phosphorus reductions for nonpoint sources ranged from 0–43% depending on the scenario, river flow, season, and watershed. Reduction scenarios for nonpoint sources have not been tested to the limit of technology and deserve further evaluation.

Future Conditions Without Sediment Reductions. Sediment loads pose a serious threat to Lake Pepin. Given the rate at which sediment is currently accumulating, the projected life of the lake has been reduced from thousands to hundreds of years. The upper third of the lake, with its higher sediment accumulation rate (1.4 cm/yr), could be gone in a century. Sediment deposition in lower Pool 2 and sediment reduction strategies for the watershed were not directly addressed in this study but may affect sediment accumulation rates in Lake Pepin.

Uncertainty. A certain degree of uncertainty is associated with each of the individual analyses conducted as a part of this study. The individual reports provide more information on this subject. In general, uncertainty increases as the studies extrapolate further beyond the available data set toward both the past and future. However, the study conclusions are generally strong and were based on the best available tools and data. The strength of the conclusions is bolstered by the strong agreement among results from different study components that approached the problem using different methods. The degree of variability does not change the fundamental study findings.

Recommendations for Future Work. The continuation of a technical advisory committee, similar to the Phosphorus Study Cooperators Group, would be an important step in supporting basin management initiatives that reduce phosphorus inputs to the rivers. With representatives from responsible agencies and institutions in Minnesota and Wisconsin, this group could provide critical oversight and emphasis to the necessary course of actions required to restore the ecological integrity of the Minnesota and Mississippi River Basins. The committee could expand beyond

phosphorus and address other important issues, such as suspended solids, nitrogen, and exotic species. This group may best fit under MPCA basin coordination.

As to phosphorus, long-term monitoring is needed to document changes in the water quality and trophic status of the Mississippi River and Lake Pepin, especially as phosphorus reduction strategies are implemented in the Lake Pepin watershed. Does the river respond as predicted? A critical need still remains for data collected under low flow conditions to further understand nutrient and algal dynamics, including changes in the algal community and sediment SRP release rates. User perspectives also need to be evaluated under low flow conditions. Phosphorus sorption in all flow regimes has been flagged as another area for further research. Additional modeling, including a sensitivity analysis, could provide direction for future monitoring.

3.2 Agency Policies and Actions

The following sections describe major government policies and actions that affect phosphorus management in the Lake Pepin watershed. Section 3.2.1 describes the current discharge permit for the Metro Plant and its provisions regarding phosphorus removal. Sections 3.2.2, 3.2.3, 3.2.4, and 3.2.5 describe phosphorus management strategies adopted by the Metropolitan Council, Minnesota, Wisconsin, and federal government, respectively.

3.2.1 Metro Plant Discharge Permit

In November 1998, the MPCA reissued the discharge permit (# MN0029815) for the Metro Plant. The five-year permit contains several requirements pertaining to phosphorus. Biological phosphorus removal, active in a quarter of the secondary treatment units since 1998, will be fully implemented and applied to the entire secondary wastewater treatment process by the end of 2003. By that time, the Metro Plant must meet a monthly average effluent P limitation of 3.0 mg/L, a 25% reduction from the current phosphorus limitation of 4.0 mg/L. By the end of 2005, after additional experience is gained in managing biological P removal, the Metro Plant will be required to meet an annual average effluent P limitation of 1 mg/L.

As in past permits, effluent phosphorus monitoring is required on a daily basis throughout the year. Both total and dissolved phosphorus are analyzed in 24-hour flow-composited samples. Also, by March 1 of each year, MCES must provide an annual report to the MPCA on progress toward phosphorus removal and the results of any additional water-quality studies. A portion of the two million dollars committed by the Metropolitan Council in 1993 to the environmental studies of phosphorus in the Mississippi River have been reserved for low flow monitoring and additional research.

3.2.2 Metropolitan Council Phosphorus Strategy

In May 1997, the Metropolitan Council adopted a strategy to reduce phosphorus loads to surface waters in the seven-county Metro Area. The phosphorus strategy was adopted as a part of the Metro Plant Master Plant, which was submitted to the MPCA on June 26, 1997. The goal of the strategy is to develop the most effective balance of phosphorus controls on point and nonpoint sources to achieve long-term improvements in water quality.

Regarding point-source controls, the strategy calls for reductions of phosphorus loads discharged by the eight WWTPs owned and operated by the Council. Currently, a third of the municipal wastewater produced in the Metro Area is treated to remove phosphorus before it is discharged to local rivers. Biological phosphorus removal is currently implemented in a quarter of the Metro Plant on the Mississippi River. Through process controls, phosphorus is reduced to less than 2 mg/L (as an annual average) at the Blue Lake and Seneca WWTPs on the Minnesota River. Chemical phosphorus removal is fully implemented at the St. Croix Valley WWTP on the St. Croix River. This facility has an effluent phosphorus limitation of 0.8 mg/L and a mass cap of 17.5 kg/d.

The phosphorus strategy sets a goal of achieving phosphorus removal to 1 mg/L as an annual average at all WWTPs operated by the Council by 2015 or sooner. Phosphorus removal will be implemented at the same time wastewater treatment facilities are expanded, saving roughly $100 million in capital costs with additional savings in operating expenses. As discussed in Section 3.2.1, phosphorus removal to 1 mg/L will be fully implemented at the Metro Plant by the end of 2003.

Since there is less information about the cost and effectiveness of reducing phosphorus from nonpoint sources, the Metropolitan Council is working with other agencies and groups to develop a broad-based plan that will outline the best methods of controlling phosphorus from numerous sources across the

state. To further promote nonpoint-source initiatives, the Metropolitan Council entered an agreement with the Minnesota Center for Environmental Advocacy in 1998 to commit $7.5 million over five years (1999–2003) to reduce pollutant loads from nonpoint sources in the Metro Area. The Metro Environment Partnership (MEP) annually solicits proposals and issue grants to selected recipients. MEP is designed to support a variety of results-oriented activities and initiatives, including direct assistance to organizations for implementation of projects in the areas of environmental education, technical assistance, and research. Funding priority is given to projects that leverage other resources through cooperative approaches, to achieve greater environmental benefit for the least cost.

3.2.3 Minnesota Phosphorus Strategy

In 1997, recognizing a growing concern over excess phosphorus in Minnesota lakes and rivers, the MPCA began forming a strategy for reducing phosphorus loads from point and nonpoint sources (MPCA, 2000a). The following seven action steps were developed and are currently being implemented:

1. Develop education, outreach, and information on environmental impacts of phosphorus.

2. Co-sponsor basin-wide phosphorus forums.

3. Use basin management as the main policy context for implementing the phosphorus strategy.

4. Broadly implement Minnesota's point-source phosphorus controls.

5. Broadly promote lake protection initiatives.

6. Address phosphorus impacts on rivers.

7. Modify water-quality standards, if necessary.

In support of the fourth action step, the MPCA developed a strategy for addressing phosphorus in National Pollutant Discharge Elimination System (NPDES) permits for WWTPs and other point sources (MPCA, 2000b). The strategy provides a consistent framework for applying phosphorus controls in NPDES permits and provides guidance for staff and stakeholders on how phosphorus concerns will be considered in the permitting process. Decisions regarding phosphorus limits, monitoring, and management plans are tied to the permitting cycle and framed in the context of basin-wide phosphorus management.

3.2.4 Wisconsin Phosphorus Strategy

Wisconsin has been successful in greatly reducing point sources of phosphorus over the past 25 years. About 60 municipal dischargers tributary to the Great Lakes received phosphorus effluent limits of 1 mg/L as a part of the Great Lakes International Agreement in the 1970s. Municipal dischargers to the Fox River have been removing phosphorus since the early 1980s to reduce loads into the Fox chain of lakes in northeastern Illinois. In 1992, Wisconsin adopted rules expanding phosphorus requirements statewide for both industrial and municipal dischargers. The rules require all significant point sources to meet an effluent phosphorus limitation of 1 mg/L as a monthly average, with somewhat higher limits allowed for facilities using biological phosphorus removal. As of 1997, there were 231 municipal and 76 industrial dischargers with phosphorus limits.

For much of the St. Croix River basin, Wisconsin provides additional protection beyond the basic phosphorus requirements for all state waters to safeguard against the effects of new or expanded point-source phosphorus loads. Wisconsin has classified a large portion of the St. Croix River and selected tributaries as outstanding resource waters or exceptional resource waters for the application of water quality standards under the state's antidegradation rules. "Outstanding resource water" is a special designation that recognizes some of the highest quality waters in the state. The "exceptional resource water" designation recognizes high quality waters where wastewater discharges may already exist. New or increased wastewater discharges to outstanding resource waters are not permitted unless the effluent quality is the same or better than the receiving water quality. New discharges to exceptional resource waters may be permitted from formerly unsewered communities if it is the best way to solve a public heath or groundwater contamination problem.

The Wisconsin Nonpoint Source Program addresses nutrient-related problems from urban and rural runoff. The program has had three primary components: priority watershed and other financial assistance programs, a stormwater management program, and an animal waste program. Since the priority watershed program began in 1978, 86 of Wisconsin's 330 large-scale watersheds have been designated as priority watershed and lake projects. These projects address agricultural runoff using a voluntary approach with cost incentives. The storm water management program, based on statutory regulations adopted in 1993, has issued storm water permits to

Milwaukee and Madison and to more than 3,400 industrial facilities. Approximately 400 storm water permits are also issued each year for construction sites. The animal waste program regulates all livestock operations with 1,000 animal units or more as well as smaller facilities that significantly affect water quality. New permitted animal waste facilities that may potentially impact impaired, outstanding, or exceptional waters are required to control both nitrogen and phosphorus loads.

Although Wisconsin has made significant progress since the late 1970s in managing nonpoint-source pollution, the program is currently being redesigned to address persistent problems in both rural and urban areas. The most significant program change is the introduction of statewide standards and prohibitions to help the state meet water-quality standards. Other changes include giving local governments more power to control nonpoint-source pollution, providing a framework for new grant programs, establishing stronger links between agencies and programs addressing polluted runoff, and changing nonpoint-source pollution control to a requirement rather than a voluntary effort in selected watersheds. Water bodies that still do not meet water-quality standards will be addressed though the Total Maximum Daily Load (TMDL) program. Wisconsin has identified waters that are impaired due to nutrients as well as other pollutants. Management plans to address these problems will be developed over the next 15 years.

3.2.5 National Nutrient Criteria Program

One of the major objectives of President Clinton's Clean Water Action Plan in 1996 was to address the overenrichment of surface waters in the United States by establishing nutrient criteria. As directed by the plan, the USEPA established the National Nutrient Criteria Program. The national strategy consists of five key elements (USEPA, 1998):

1. Nutrient criteria need to be established on a regional basis and need to be appropriate for different waterbody types (e.g., lakes, rivers, estuaries, and wetlands). One set of criteria cannot fit all regions and aquatic systems.

2. EPA will prepare technical guidance manuals for establishing nutrient criteria on a regional basis for the various waterbody types. Where data are available, EPA will also provide target regional nutrient ranges for phosphorus, nitrogen, and possibly other parameters.

3. Using the EPA technical manuals and target ranges as a guide, States and Tribes will develop and adopt numerical nutrient criteria into their water-quality standards by the end of 2003. This deadline has since been extended to the end of 2004. States and Tribes may use their own databases or employ their own approach to develop nutrient criteria, if the data and methods are scientifically defensible.

4. A National Nutrient Team will manage the national nutrient criteria program. In addition, each of the EPA Regions will have a Nutrient Coordinator and Technical Assistance Group to provide help and guidance to the States and Tribes.

5. States and Tribes will be expected to monitor and evaluate the effectiveness of nutrient management programs implemented on the basis of the nutrient criteria.

Once adopted as a part of State or Tribal water-quality standards, nutrient criteria will become the basis for identifying impaired waters, making management decisions to reduce excessive phosphorus and nitrogen levels, and implementing these decisions through regulations and programs.

Minnesota and Wisconsin are participating in a Regional Technical Advisory Group (RTAG), led by EPA Region 5. The group also includes other Region 5 states, tribes, and federal partners. The charge of the RTAG is to help USEPA develop nutrient criteria recommendations for different ecoregions and subecoregions in Region 5 and to explore other means of developing and implementing nutrient criteria. Minnesota and Wisconsin will, most likely, develop state-specific approaches.

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APPENDIX A.

Upper Mississippi River and Lake Pepin
Continuing Environmental Studies, 1993–1998

Mission, Definitions, and Questions to Address

Mission

To study the effect of phosphorus loadings from the Metropolitan Wastewater Treatment Plant (MWTP) and other sources on the water quality of the Mississippi River, specifically algal blooms in Lake Pepin and Spring Lake, and to project the water quality benefits to the river of reduced phosphorus loadings from the MWTP and other sources.

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Definitions

Study Area. Unless stated otherwise, the objectives apply to the study area of the Mississippi River, Lock and Dam No. 1 through the outlet of Lake Pepin. Special attention will be given to two lakes in the study area: Lake Pepin (high priority) and Spring Lake (lower priority).

Water Quality Goal. Water quality effects and benefits will be measured against the goal established for Lake Pepin by the Phosphorus Study Cooperators, as follows:

> An average chlorophyll-a goal of 30 µg/l (corrected for pheophytin) is recommended for Lake Pepin for the summer period (June–September). This goal is to be applied as a whole-lake average for summer river flows ranging from 4,600 to 20,000 cfs at the USGS gage at Prescott, Wisconsin.

The goal was based strictly on a review of lake users' perceptions. The goal's attainability has not been assessed, but it may be addressed in part by the model projections.

Priorities. The continuing environmental studies of phosphorus were mandated in the MWTP's 1993 NPDES permit. Priorities were established within the confines of the permit-required studies and the resources allocated to them. They do not reflect the priorities of other ongoing initiatives by the cooperating agencies.

Sources. Sources of phosphorus will be studied in the following order of priority:

1. Metropolitan Wastewater Treatment Plant
2. Major tributaries to the study area:
   - Minnesota River at its mouth
   - Mississippi River at Lock & Dam Nos. 1 & 3.
   - St. Croix River at its mouth
3. Minor point and nonpoint sources to the study area:
   - Other MCES wastewater treatment plants
   - Other point sources
   - Minor tributaries (e.g., Vermillion, Cannon, and Rush Rivers)
4. Sources outside the study area:
   - Minnesota River Basin[1]
   - Upper and Lower Mississippi River Basins[1]
   - St. Croix River Basin[1]

Reduced phosphorus loadings will be estimated at the mouths of the major tributaries using the best available information and assistance from the Cooperators Group. The benefit will be projected by the water quality model.

[1] Basins as described in "Basin Management Implementation Strategy," Minnesota Pollution Control Agency, Water Quality Division, September 1995.

Questions to Address

Priority 1

- What is the effect of phosphorus loadings on the water quality of Spring Lake and Lake Pepin?
  - Specifically, what is the effect of MWTP phosphorus loads?
- What are the dynamics and rates of phosphate flux from the sediment bed under different conditions?
- What is the fate and transport of phosphorus from the different sources?
- What are the relative contributions of the different sources to the phosphorus balance in Lake Pepin?
- What are the projected short and long-term responses of the phosphate flux from the sediment bed to reduced phosphorus loadings?
- What are the projected water quality benefits of reduced phosphorus loadings from the different sources?
  - Specifically, what is the benefit of phosphorus removal at the MWTP to 1.0 or 0.4 ppm?

Priority 2

- What factors currently and may potentially control blue-green algal blooms in Lake Pepin?
- How does algal composition and biomass in Lake Pepin and Spring Lake change with the following (in order of priority):
  1. Phosphorus limitation
  2. Nitrogen limitation
  3. Flow (that is, refine the flows of concern)
- What are the dynamics of different algal groups in the study area and what controls the composition of the algal community?
- How do lake users view the current water quality of Lake Pepin?

Questions to Address <continued>

Priority 3

- o How have phosphorus loadings to the sediment bed in Lake Pepin changed over time in response to human activities?

- o How has the water quality of Lake Pepin changed over time in response to human activities?

- o Given the following:

  - Phosphorus removal at the MWTP to 1.0 or 0.4 ppm and
  - Projected water quality improvements in the major river basins (outside scope of study, but may be derived from other studies),

  Is the water quality goal for Lake Pepin attainable? If not, what is a reasonable goal?

Outside Scope of Study

- x What are the projected water quality benefits of initiatives to reduce point and non-point sources of pollution in the Minnesota, St. Croix, Upper Mississippi, and Lower Mississippi River Basins? That is, watershed modeling is outside the scope of this study.

- x What is the projected economic benefit of the reduction of phosphorus loads to the study area?

- x What are MCES rate payers willing to pay for reduced algal levels in the study area?

- x What inlake treatment options may benefit the water quality of Lake Pepin?