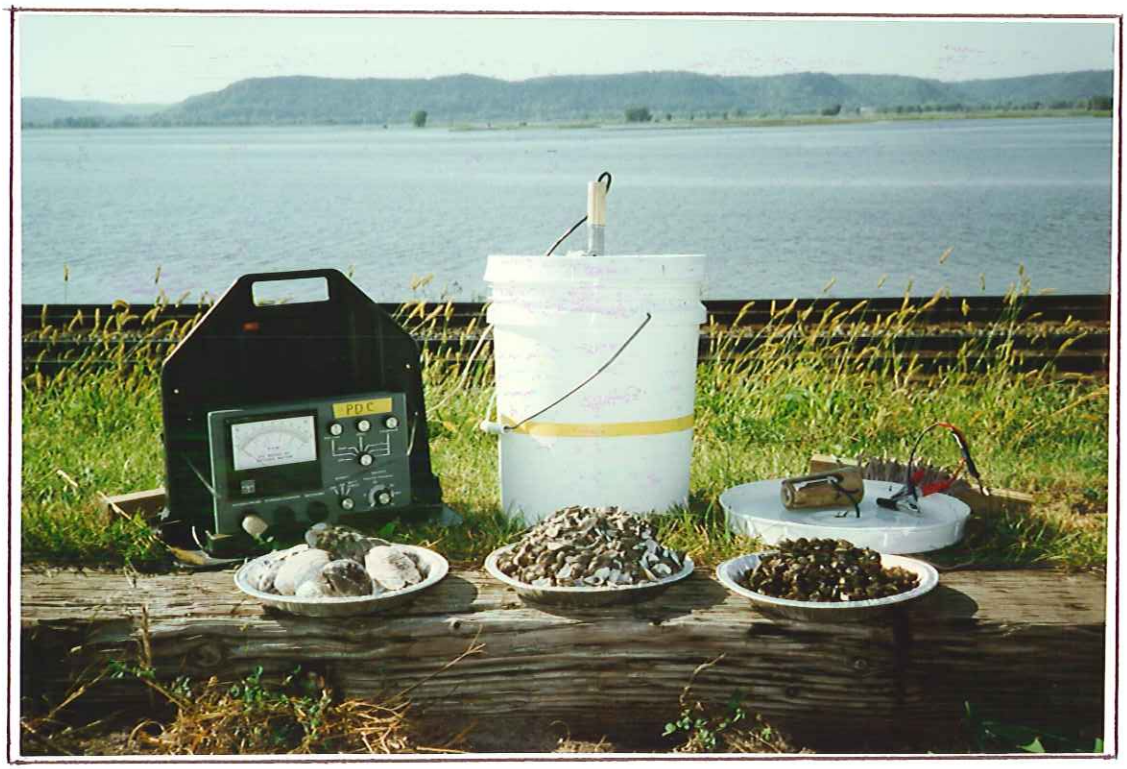
Zebra Mussel-Induced Water Quality Impacts in the Mississippi River Observed during the Summer of 1997



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INTRODUCTION

Zebra mussels (*Dreissena polymorpha*) were first observed in Wisconsin's Mississippi River border waters at La Crosse, Wisconsin in September of 1991. Over the last several years, this bivalve has greatly expanded its range and density throughout the Upper Mississippi River (Cope et al. 1997). Zebra mussels typically colonize hard surfaces and may form high densities (5,000 - 700,000/m^2) as a result their high reproductive capacity under favorable conditions (Mackie et al. 1989, Mackie and Schloesser, 1996 and Snyder et al. 1997).

Zebra mussels are highly efficient filter feeders that remove plankton, organic and inorganic particulate matter from water. This typically results in reduced suspended particulate matter concentrations and improved water clarity (Mackie et al. 1989). Changes in water column particulate levels, excretion of dissolved nutrients by zebra mussels and decomposition of zebra mussel feces and pseudofeces influences nutrient cycling. In particular, dissolved phosphorus and ammonia nitrogen concentrations may increase in rivers with high infestations (Effler et al. 1996). Zebra mussels may reduce dissolved oxygen (DO) concentrations as a result of their respiratory activity. Serious DO depletion has been reported in riverine systems infested with high densities of zebra mussels (Effler and Siegfried 1994, Effler et al. 1996, and Whitney et al. 1995).

In October of 1996, the Wisconsin Department of Natural Rescouses discovered a blanket of zebra mussels several centimeters thick in portions of Harpers Slough at Harpers Ferry, IA (Welke and Kenyon, 1997). This slough is a secondary side channel of the Mississippi River bordering Iowa in upper Pool 10. The density of this bed was not determined. Plans were developed to prepare a detailed DO budget in this side channel the following summer to evaluate potential water quality impacts associated with this recent infestation.

Summer 1997 Observations

In mid- to late June 1997, fishery researchers for the U.S. Geological Survey (USGS), Midwest Science Center (Knights and Dewey, 1997) discovered unusually low DO concentrations of 1.4 to 2.3 mg/L in the main channel border of the Mississippi River in upper Pool 10 near Prairie du Chien, WI (Figure 1). These samples were collected near the bottom in 2.8 to 7.8 m of water. Water current velocity ranged from about 0.1 to 0.2 m/sec and water temperature

varied from 24.0 to 27.6 °C. Main channel bottom waters (3.8 to 4.8 m) had higher DO concentrations (5.2 to 5.4 mg/L) at similar water temperatures and greater current velocities (0.3 to 0.5 m/sec). These data suggest lateral and vertical DO stratification may have been present, but insufficient information was available to evaluate this. River flow was approximately 880 m^3/s at Lock and Dam 9 (LD 9) during this period which was 23% below the historic June mean flow based on the USGS gaging station at Mc Gregor, Iowa (Holmstrom et al. 1997). Knights and Dewey also noted a strong organic odor during their surveys in upper Pool 10. We also received similar reports from LD 9 personnel and residents living along the river in upper Pool 10. These latter complaints also coincided with the period of lowest DO in mid- to late June.

Bi-weekly water quality samples collected by the Long Term Resource Monitoring Program in the tailwater areas below LD 11 (Dubuque, IA) and LD 12 (Bellevue, IA) in late June also revealed low DO concentrations of 3.9 and 3.4 mg/L, respectively (USGS, 1997). Water temperature was approximately 27 °C. The U.S. Corps of Engineers reported a DO concentration of 4.6 mg/L and water temperature of 27.1 °C on July 1 at LD 15 (Rock Island, IL), (Bierl, 1997).

The Wisconsin Department of Natural Resources (WDNR) recorded a DO concentration of 4.4 mg/L and water temperature of 27.1 °C at LD 9 on July 2 (WDNR, 1997). This was the second lowest DO value observed at this site in the last 10-years of monthly monitoring (Figure 2). DO concentrations below 6 mg/L have been recorded in the main channel of the Mississippi River in the last 10-years, but these were either during very low (1988) or abnormally high (1993) summer flows (Figure 2 and 3).

River flow increased in July in response to basin-wide precipitation and resulted in increased DO concentrations. The high flow conditions hampered our ability to complete a detailed DO budget for Harpers Slough. As a result, we refocused our study to measure water quality impacts of zebra mussels directly by assessing their oxygen demand *in situ* using diver-deployed sediment oxygen demand (SOD) chambers. In addition, continuous DO and water temperature monitoring was conducted at LD 9 during most of July to assess diurnal DO changes. We also reviewed WDNR's long-term water quality monitoring data for LD 8 and LD 9 to determine if the recent zebra mussel population expansion on the river was influencing water quality at these sites.

METHODS

Sediment Oxygen Demand

Sediment oxygen demand was determined using a batch method (Bowman and Delfino, 1980 and Nalepa, 1975). In general, a known volume of water was sealed over a known area of sediment. The water within the chamber was continuously mixed mechanically while the DO was measured at 5- to 10-minute intervals. Linear regression was used to determine the rate (slope) of DO depletion (mg/L/min) within the SOD chambers at DO concentrations greater than 3 mg/L. This approach was used because plots of DO concentration versus time exhibited a negative linear relationship at concentrations exceeding this value. The volumetric depletion rate was transformed to an areal rate ($g/m^2/day$) based on the enclosed chamber volume, surface area of the sediment and time.

Sediment oxygen demand chambers were constructed from modified 5-gallon (18.9 L) plastic pails. The bottom of the pails were removed to allow the chamber base to be pushed into the substrate about 20 cm with the lid unattached. SCUBA divers deployed all chambers except at the Pool 5 site which could be reached by wading. Once the chamber base was secured in the substrate, the depth of water inside the chamber was determined to estimate the enclosed volume. A Yellow Springs Instrument, Inc (YSI) model 57 stirring device was added to the underside of the chamber lid. A YSI model 5739 DO probe was inserted through a small hole in the lid opposite the stirrer. The lid with stirrer and DO sensor was fastened to the top of the chamber within a few minutes after initial deployment of the chamber base. Four, 0.9-kg diving weights were placed on the lid to hold the chamber in the substrate. Care was taken to a avoid suspending bottom substrate during chamber deployment.

The volume of the SOD chambers was approximately 11.7 L during field deployments. The actual volume was calculated for each SOD measurement and depended on the depth of chamber penetration into the substrate. A volume adjustment for probe and stirrer displacement was also made. The sediment surface area at the base of the chamber was 607 cm^2. This yielded a volume (L) to surface area (m^2) ratio of 193 which was within the range reported for such *in situ* devices (Bowman and Delfino, 1980).

Two identical SOD chambers were deployed at each site and DO depletion measurements were run concurrently. Yellow Springs Instruments model 57 DO

meters were used to measure DO and temperature during the duration of the chamber deployments, usually about 1.5 hrs. The DO sensors were calibrated using the air calibration technique at ambient air pressure (WDNR, 1983). Attempts were made to measure the biochemical oxygen demand (BOD) of surface water in separate darkened chambers during SOD measurements. However, this was unsuccessful due to the short time period and low BOD. We assumed BOD was negligible and no BOD adjustments were applied to the SOD measurements.

After completion of the SOD tests, the upper 10 to 15 cm of the substrate including, sediment, rocks, mussels and other debris, were placed in bags and frozen for later evaluation. All live (shells containing soft body parts) and dead (empty shells) zebra mussels were counted. The mass and volume of zebra mussels (including shells) were quantified. Zebra mussels containing soft body parts were placed on paper towels to remove excess water before making the weight and volume (by displacement) measurements. Empty zebra mussel shells were air dried for several days prior to weighing. Zebra mussel length distributions were determined by randomly sampling about 150 individuals per site. The lengths and identification of live native mussels (unionids) encountered within the enclosures were also recorded.

The SOD measurements from the Pool 5 site near Minneiska, MN were made on experimentally-placed sediment consisting of previously-dredged river sand obtained from a nearby disposal site (RM 741.6). The zebra mussels densities for this site are inflated since colonized rocks were placed in the SOD chambers containing the sand. This was done to make direct estimates of zebra mussel oxygen demand that would not be significantly influenced by other macroinvertebrates or SOD. This sand appeared to be free of organic matter and would be expected to yield a very low SOD.

The latitude and longitude of each site was determined with a Magellan ProMark V GPS receiver attached to a Starlink model MRB-2A differential beacon receiver. About 100 position fixes were collected and averaged for each site.

Water quality and Light Penetration Data

Main channel water chemistry data were available from WDNR's monthly monitoring stations at Lock and Dams 3, 4, 8, 9 (Sullivan, 1989). Water samples were analyzed for nutrients and chlorophyll at the Wisconsin State Laboratory of Hygiene (WSLOH), Madison, WI using U.S. EPA approved procedures (WSLOH, 1996).

Surface and underwater light measurements were made with Li-Cor, Inc. quantum sensors, model 190SA and 192SA, respectively. These sensors respond to the photosynthetically active radiation (PAR) spectrum of 400 to 700 nm. The depth at which 1% of surface light penetrated (our measure of light penetration) was derived from vertical light extinction coefficients calculated following the equation described by Vollenweider (1974). Light sensor calibrations were performed by the manufacturer on approximately an annual basis.

Continuous monitoring of DO, water temperature and surface light were made in July 1997 at LD 9 using a YSI model 57 DO meter, YSI thermistor and Li-Cor surface quantum sensor, respectively. The signals from these sensors were recorded at 30 minute intervals using a Li-Cor model 1000 data logger. DO and temperature calibration checks were performed weekly during deployment using standardized field procedures (WDNR, 1983 and Sullivan, 1996).

RESULTS and DISCUSSION

Sediment Oxygen Demand Sites

Sediment oxygen demand measurements were made at six locations from Minneiska, MN (Pool 5) to Potosi, WI (Pool 11) during July and August 1997 (Figure 4). The SOD chambers were normally deployed in areas of moderate current velocity with depths ranging from 0.6 to 4.1 m. Specific habitat sampled included four main channel border sites, one secondary channel site and one impounded site (Table 1). Water current velocity was not measured but was estimated to range from about 0.1 to 0.4 m/s at chamber deployment sites.

Sampling sites were normally associated with historic unionid mussel beds. These habitats had previously been found to be infested with zebra mussels based on recently completed unionid surveys (Welke and Kenyon, 1997). Unionid mussel densities in deployed SOD chambers ranged from 16.5 to 49.4/m^2 (1 to 3 per chamber). Six different species of native unionid mussels were encountered with the three-ridge mussel, *Amblema plicata*, being the most common. Individual mussel lengths ranged from 2.0 to 14.9 cm (Table 2).

Highest zebra mussel densities (10,000 to 14,000/m^2) were found in or near unionid mussel beds at sites in lower Pool 9 and upper Pool 10 (Table 1). Zebra mussels at the Pool 5 site and the Pool 9 site below Lansing, IA were mainly associated with coarse gravel and small rock substrate. No zebra mussels were found in the SOD chambers incubated at sites in Pools 8 and 11.

However, a broader survey of the bottom at these sites by divers indicated they were present on some native mussels but were at low densities (< 3 zebra mussels/unionid).

Sediment Oxygen Demand Measurements

Sediment oxygen demand ranged from 0.8 g/m^2/day in silty substrate without unionids or zebra mussels to about 15-20 g/m^2/day in silty to coarse substrate with zebra mussel densities of 10,000 to 14,000/m^2 (Table 1). Oxygen depletion rates at sites with unionid densities of approximately 16 and 50/m^2 (without zebra mussels) yielded an SOD of 3.6 to 5 g/m^2/day, respectively. Silty riverine sediment without numerous or large benthic organisms or significant organic pollution would typically have an SOD of approximately 1 to 1.5 g/m^2/day at 25 °C (Butts, 1974 and Sullivan et al. 1978). Our measurements in silty substrate without zebra mussels or unionids were slightly lower (0.8-0.9 g/m^2/day) and was likely due to lower water temperatures (22.0 to 24.4 °C).

Water temperature ranged from 21 to 25.3 °C during the SOD measurements and should normally be considered when comparing differences between sites or between other SOD studies. However, the magnitude of the SOD differences between sites in this study was clearly associated with changes in the abundance of zebra mussels. A Spearman rank correlation analysis indicated live zebra mussel density, mass and volume were significantly ($p < 0.05$) correlated to SOD (Table 3). Zebra mussel volume provided the highest correlation ($r=0.812$) to SOD. Water temperature, unionid mussel density and the combined lengths of unionid mussels, a surrogate for total mass or volume, were not found to be significantly correlated to SOD. This was not surprising since water temperature did not differ greatly between sites and greatest SODs were measured at sites with highest zebra mussel densities.

The decrease in DO within the SOD chambers normally exhibited a linear relationship with time at DO concentrations ranging from about 8 to 3 mg/L (Figure 5). A non-linear relationship was noted when DO concentrations dropped below 3 mg/L or when the total depletion exceeding 5 mg/L. This is best illustrated in SOD measurements made at the Pool 5 site near Minneiska, MN where a longer incubation period was used (Figure 6). DO concentrations in the two chambers were allowed to fall from an initial concentration of 8 mg/L to about 0.5 mg/L over a period of approximately 3 hours. The zebra mussels were then re-exposed to oxygenated river water by flushing out deoxygenated water in the chambers with fresh river water. Measurements of DO depletion

were then immediately repeated. The zebra mussels were still very active based on a return to high respiratory oxygen demand. However, the oxygen deletion rates (between 8 and 3 mg/L) averaged about 20% less on the second run and may have indicated the zebra mussels were negatively influenced by prior exposure to the near anoxic conditions or metabolic wastes that accumulated in the test chambers.

Effler and Siegfried (1994) estimated zebra mussel oxygen demand (ZOD) in the Seneca River, NY based on a respiratory model and oxygen deficit studies in a stream reach heavily infested with zebra mussels (30,000-60,000/m^2). They estimated areal oxygen demands of 34 and 44 g/m^2/day at 25 °C based on the respiratory model and DO budget calculations, respectively. These ZOD rates correspond to a biomass-normalized (g O_2/g wet tissue weight) oxygen demand of 0.0071 to 0.0092 g/g/day based on an average biomass of 4,781 g/m^2.

A direct estimate of ZOD was possible at the Pool 5 site since these DO depletion measurements were made on a substrate of coarse sand and no other invertebrates were observed (besides zebra mussels) that would contribute to an appreciable oxygen demand. Some attached algae and organic debris was present on zebra mussels and zebra mussel-colonized rocks and could contribute to a small portion of the oxygen demand at this site. This site had an estimated zebra mussel biomass (wet weight) of 2,784 g/m^2. This was derived by applying a length-biomass model developed by Walt (1978) to the zebra mussel size distribution found for this site. A temperature correction factor of 1.33, derived from Schneider (1992), was used to adjust the *in situ* SOD measurements made in Pool 5 (Table 1) to 25 °C. This yielded an average SOD of 24.5 g/m^2/day for the Pool 5 site. Since this SOD measurement was primarily influenced by zebra mussel activity, the biomass-normalized ZOD was estimated to be 0.0088 g/g/day at 25 °C. This is within the range derived from Effler and Siegfried's studies on the Seneca River.

Other Zebra Mussel Information

Most sites had very few dead (empty shells) zebra mussels. The exception was the Pool 10 site near Harpers Ferry, IA which had an estimated dead zebra mussel density of 28,000/m^2. This mat of shells represented a layer several centimeters thick. These shells were mainly found below a surficial layer of live zebra mussels that had a density of 12,000 to 14,000/m^2 (Table 1). All juvenile zebra mussels (< 10 mm) found at this site were dead (Figure 7). We believe this site had experienced some recent mortality based on deteriorated

viscera and a large number of small (<15 mm) empty shells. This may explain the odor problems reported in this area during mid- to late June.

Of the four sites where zebra mussels were encountered, three of the sites (Pool 9 - Lansing, Pool 9 - Lynxville and Pool 10 - Harpers Ferry) had similar size distributions (Figure 7). These sites were dominated by 15 to 17 mm length zebra mussels which likely represent the 1996 cohort. No live juvenile zebra mussels were found at these sites. In contrast, zebra mussels from the Pool 5 site exhibited a definite bimodal size distribution with two distinct year classes with median lengths of 7 and 19 mm. These sizes likely reflect recruitment from 1997 and adults from the 1996 year class.

Zebra Mussel-Induced Water Quality Changes

Effler et al. (1996) described a zebra mussel water quality "signature" as a body of water that is undersaturated with respect to dissolved oxygen, has high water clarity, low phytoplankton concentrations, and is enriched with available nutrients. These conditions provide a basis to evaluate long-term water quality data to determine if recent changes are consistent with zebra mussel population expansion in the Mississippi River.

Dissolved Oxygen

The extremely low DO concentrations measured by USGS in the main channel and secondary channels of the Mississippi River in upper Pool 10 in mid- to late June (Figure 1) were very unusual. We are aware of no other studies that have found such low DO concentrations (< 3 mg/L) in the main channel or channel border (besides Lake Pepin) in the navigational pools adjacent to Wisconsin (Pools 3 to 11). There were no reported point or nonpoint source pollutant discharges that could account for these observations. The high SOD measurements made in this investigation and oxygen depletion problems reported in other zebra mussel infested river systems (Effler and Siegfried 1994 and Whitney et al. 1995), indicate zebra mussels have the potential to reduce DO concentrations when population densities are high.

We suspect the severely depressed DO concentrations observed in the Mississippi River between LD 9 and LD 12 in mid-June were influenced by zebra mussels. However, pool-wide estimates of zebra mussel densities were not available to confirm this. Potential factors contributing to zebra mussel-induced DO depletion problems could include phytoplankton removal via filter feeding (reduced oxygen production), respiratory activity, biodegradation of feces and psuedofeces, and the decay of dead zebra mussels. The negative

impact of ZOD on the river's DO resource would be expected to be greatest during periods of high river temperature (higher respiration rates and lower DO saturation) and low flows (decreased mixing and increased residence time). These thermal and hydraulic conditions were present in the Mississippi River during mid- to late June.

Continuous water quality monitoring at LD 9 during July also indicated unusually low DO concentrations (Figure 8b). Dissolved oxygen concentrations averaged 5.0 mg/L during the 19-day monitoring period and ranged from 3.8 to 6.2 mg/L. This represented an average DO deficit of approximately 3 mg/L from DO saturation. These data were surprising since river flows at LD 9 averaged 1750 m^3/s and were 54% above the July average based on the USGS gage at Mc Gregor, IA (Holmstrum et al. 1997). Dissolved oxygen concentrations below 5.0 mg/L were not observed at other WDNR main channel monitoring sites (Figure 3) or at other upstream main channel sites in Pool 4 (above and below Lake Pepin) and Pool 8 being sampled as part of the Long Term Resource Monitoring Program (USGS, 1997). In addition, DO concentrations in Pool 2, a reach historically impacted by point source wasteloads from the Twin Cities Metropolitan area, did not fall below 5 mg/L during June and July based on both continuous and bi-weekly monitoring (Schellhaass, 1997). The low DO observed at LD 9 during July was likely influenced by zebra mussel activity in Pool 9. However, runoff from tributaries and increased river flows may have also provided increased particulate and dissolved organic matter that could contribute to increased BOD and result in lower DO concentrations. Further, the small diurnal DO changes noted at LD 9 (Figure 8b) indicated low photosynthetic oxygen production by aquatic plants. This was likely due to increased flushing and decreased light penetration (higher suspended particulate matter) during this high flow period.

Light Penetration

Wisconsin has been monitoring light penetration at LD 8 and LD 9 since April of 1988 as part of its monthly ambient water quality monitoring program. Average summer (June-August) light penetration was highest in 1988 and decreased to lowest levels in 1990 (Figure 9a). This decrease was likely associated with a loss of submersed and emergent vegetation and an increase in wind-induced sediment resuspension as a result of reduced sediment stability. Further, tributary input of suspended matter increased substantially following the 1987-89 summer drought and resulted in high total suspended solid concentrations in the river in the summers of 1990 and 1991 (Sullivan, 1991 and 1996).

Since 1990, average summer light penetration increased gradually at LD 8 and 9 with a noted "jump" in 1997 (Figure 9a). The density and spatial coverage of submersed vegetation has increased over the last several years and was particularly evident in lower Pool 9 in 1997. The vegetation response was likely a result of the increase in underwater light energy due to a reduction of suspended particulate matter. Lower suspended solid concentrations are normally associated with decreased external inputs (ie. tributary inflows) and/or reduced internal sources (sediment resuspension and phytoplankton).

Large populations of zebra mussels can also contribute to reduced suspended particulate matter as a result of their filtering activities (Mackie et al. 1989). The unusually high light penetration measured at LD 9 on September 3, 1997 (Figure 9b) was likely a result of zebra mussel filter feeding. This was supported by low total chlorophyll *a* concentration, an index to phytoplankton biomass, which was unusually low (3.7 ug/L) at this site for this time of year (Figure 10a). In contrast, chlorophyll *a* was about ten fold greater upstream at LD 8 (Figure 11a) during this time and light penetration was substantially lower (Figure 9b).

Although zebra mussels may contribute to significant improvements in water clarity during brief periods, they probably have not been a major factor influencing light penetration trends observed at LD 8 and LD 9 in the last few years. External sediment inputs and wind-induced sediment resuspension are likely primary factors influencing light penetration in the river. However, if zebra mussels continue to expand and colonize larger portions of the navigation pools, especially soft substrates, their overall positive impact on light penetration will likely increase. This could be expressed by biosedimentation or increased sediment stability. Sediments could be stabilized directly by modifying the substrate (surficial shell layer) or indirectly by inducing greater submersed aquatic plant growth (improved light penetration) which would reduce wave energy and bottom shear stress.

Nutrients

Nitrogen and phosphorus are the two primary nutrients that contribute to excessive plant growth in aquatic systems. In addition, silica is an important macronutrient for diatoms, which typically represent the major portion of the phytoplankton community in riverine systems.

Dissolved phosphorus, nitrogen and silica show large seasonal fluctuations in the Mississippi River as a result of varying river flow, temperature, external and internal (sediments) inputs, and nutrient cycling. In general, lowest

concentrations of soluble reactive phosphorus, ammonia nitrogen, nitrite+nitrate nitrogen and dissolved silica were found when phytoplankton concentrations were highest. This was especially noted during low flow periods when the hydraulic residence time of the navigation pools was greater. This response reflects nutrient assimilation by phytoplankton, attached algae and submersed aquatic vegetation.

A rough index of nutrient availability to phytoplankton at LD 8 and LD 9 was considered by plotting the ratio of the above dissolved nutrients to total chlorophyll *a* (Figure 10 and 11). Highest ratios generally reflect periods of ice cover when phytoplankton biomass (chlorophyll *a*) was normally lowest. Low ratios were usually found between May and October when chlorophyll concentrations were high. An apparent anomaly in this relationship was present during August and September, 1997 at LD 9 (Figure 10b,c,d and e). Chlorophyll levels during this period were very low compared to the previous nine years and resulted in unusually high nutrient to chlorophyll ratios. A similar response was not observed at LD 8 (Figure 11b,c,d and e).

High nutrient to chlorophyll ratios reflect a surplus of nutrients relative to the amount of phytoplankton biomass present. Effler (et al. 1996) found an increase in soluble reactive phosphorus (SRP) and ammonia nitrogen and decreased chlorophyll in the Seneca River which was heavily infested with zebra mussels. They attributed the nutrient changes to a conversion of particulate forms of nutrients to dissolved forms as a result of zebra mussel filtering activity and excretion and decomposition processes. The combination of zebra mussel-induced nutrient conversion and phytoplankton consumption would be expected to contribute to high nutrient to chlorophyll ratios.

SUMMARY and CONCLUSIONS

In mid-June 1997, USGS reported unusually low DO concentrations (1.3 to 2.3 mg/l) in portions of the main channel of the Mississippi River at sites near Prairie du Chien, WI (Pool 10) to Bellevue, IA (Pool 12 tailwater) during a period of below average river flow and warm water (> 25 °C). Dissolved oxygen concentrations increased in July in response to increase river flow, but values below 5 mg/L were still present at times at LD 9. Upriver DO data collected from the Mississippi River main channel (excluding Lake Pepin) between LD 1 (Twin Cities, MN) and LD 8 (Genoa, WI) did not indicate concentrations below 5 mg/L during June and July.

In situ SOD measurements made in lower Pool 9 and Upper Pool 10 revealed very high oxygen demands of 15-20 $g/m^2/day$ during July and August 1997 in areas infested with high zebra mussel densities (10,000 to 14,000/m^2). Sediment oxygen demand rates were substantially lower (0.8 to 5 $g/m^2/day$) in silty substrates including sites with moderate unionid mussel densities of 16.5 to 49.4/m^2 where zebra mussels were absent. Based on these data and previous reports of low DO in rivers infested with zebra mussels, we believe the low DO in portions of the Mississippi River main channel in mid June and July was likely the result of zebra mussel activity.

Serious DO problems can be expected in the future if zebra mussels spatial coverage and density continues to increase in the river. This problem will likely be most severe during summer periods of below average discharge and warm water (>25 °C) in reaches with high zebra mussel densities (>10,000/m^2). Zebra mussel-induced DO problems may result in the non-attainment of our States's DO standard of 5 mg/L and may negatively impact other aquatic organisms. This problem may also have important ramifications in the regulation of point and nonpoint source discharges, especially if these organisms expand into river reaches where existing wasteloads are controlled to meet this standard.

Light penetrations measurements at LD 8 and LD 9 have indicated an increasing trend since 1990. This response likely reflects reduced sediment resuspension as a result of increased submersed aquatic vegetation and lower suspended solid contributions from tributary streams. A zebra mussel-induced increase in light penetration was likely during August and early September 1997 at LD 9, but not at LD 8. We suspect this difference was due to greater zebra mussel densities in Pool 9 which contributed to increased biosedimentation and phytoplankton removal in this pool. The combination of increased submergent vegetation and zebra mussel filter feeding may result in unusually high water clarity over what has been typically found in the river in recent years.

An increased ratio of dissolved nutrients (ammonia nitrogen, nitrite+nitrate nitrogen, soluble reactive phosphorus and dissolved silica) to chlorophyll *a* was observed during late summer 1997 at LD 9. This response is consistent with expected water quality changes associated zebra mussel filtering activity. The combination of increased light penetration and dissolved nutrient availability in zebra mussel infested waters may influence the growth of other forms of aquatic plants. These conditions could promote an increase in submersed aquatic plants, attached algae or large colonial blue green algae

(ie. *Aphanizomenon* and *Microcystis*) which are more buoyant and possibly less susceptible to filter feeding by zebra mussels.

We believe more data are needed to verify zebra mussel-induced water quality impacts on the river. Data collected by USGS's Long Term Resource Monitoring Program on the river should provide additional information to document these impacts and need to be evaluated. A detailed DO, suspended solids, chlorophyll and nutrient budget in a river reach with high zebra mussel-infestation may provide another means for assessing their impacts on water quality. River monitoring agencies need to better coordinate their monitoring efforts and quickly share information should low DO conditions reappear. More pool-wide information is needed on zebra mussel densities and spatial coverage to better quantify their impacts in the Mississippi River.

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Table 1. Summary of sediment oxygen demand (SOD) measurements and mussel densities in the Mississippi River during July and August, 1997. Site coordinates were measured using differential GPS based on North American Datum 1927.

Date	Site, Habitat Classification and Water Depth	Pool	River Mile	Latitude deg. min.	Longitude deg. min.	Substrate	Water Temp. C	Replicate 1			Replicate 2		
								Unionid* Mussels No./m²	Zebra* Mussels No./m²	SOD g/m²/d	Unionid* Mussels No./m²	Zebra* Mussels No./m²	SOD g/m²/d
7-24-97	Above Lyxville, WI Main channel border Depth 3.0 m	9	652.1	43 15.852	91 3.154	silty sand	25.0	49.4	11,200	19.4	16.5	2,500	6.9
8-05-97	Below Lansing, IA Main channel border Depth 1.4 m	9	657.9	43 19.470	91 7.739	sand & gravel	25.3	16.5	12,700	16.1	16.5	11,200	16.8
8-07-97	Above Genoa, WI Main channel border Depth 1.7 m	8	681.0	43 35.715	91 13.492	silty sand	24.4	49.4	0	5.0	0	0	0.9
8-08-97	Harpers Ferry, IA Secondary side chan. Depth 4.1 m	10	646.0	43 12.010	91 8.688	silt & shells	24.6	33.9	12,300	15.6	0	14,300	15.4
8-20-97	Potosi, WI Impounded Depth 2.2 m	11	592.8	42 39.206	90 44.288	silt & clay	22.0	0	0	0.8	16.5	0	3.6
8-21-97	Minneiska, MN Main channel border Depth 0.6 m	5	741.9	44 11.648	91 52.088	sand & gravel	21.0	0	9,600	17.0	0	11,200	19.9

* Estimated areal density of live mussels based on what was present within the sediment oxygen demand chamber (area = 0.0607 m²).

Table 2. Zebra mussels numbers, volume and mass and native mussel lengths present in sediment oxygen demand chambers.

Site	Rep.	Live Zebra Mussels			Dead Zebra Mussels (shells)			Live Unionid Mussels	
		Number	Volume* cm^3	Fresh Weight* g	Number	Volume cm^3	Dry Weight g	Species	Length cm
Lyxville	1	678	300	254	41	8	7.5	Megalonaias nervosa Megalonaias nervosa Leptodea fragilis	11.2 11.7 8.4
	2	153	90	57	11	5	3.5	Megalonaias nervosa	10.7
Lansing	1	768	290	364	120	50	79	Amblema plicata	2.0
	2	679	295	342	101	30	62	Leptodea fragilis	8.5
Genoa	1	0	0	0	0	0	0	Fusconaia flava Amblema plicata Amblema plicata	7.0 8.3 8.4
	2	0	0	0	0	0	0	None	
Harpers Ferry	1	748	225	117	1676	nd	583	Truncilla truncata Amblema plicata	2.9 6.2
	2	866	324	290	1621	nd	553	None	
Potosi	1	0	0	0	0	0	0	None	
	2	0	0	0	0	0	0	Pyganodon grandis	14.9
Minneiska	1	580	245	267	17	2	2.1	None	
	2	680	310	168	40	8	10	None	

* Includes soft tissue and shell.
nd - no data.

Table 3. Spearman rank correlations of sediment oxygen demand, water temperature, unionid mussels, and zebra mussel data.

	Sediment Oxygen Demand	Water Temp.	Zebra Mussel Density	Zebra Mussel Mass	Zebra Mussel Volume	Unionid Mussel Density
Water Temp.	0.127					
Zebra Mussel Density	0.638*	0.478				
Zebra Mussel Mass	0.726*	0.504	0.854**			
Zebra Mussel Volume	0.812**	0.273	0.854**	0.826**		
Native Mussel Density	0.118	0.516	0.042	0.034	-0.109	
Unionid Mussel Length[1]	0.029	0.410	0.138	0.174	-0.188	0.941**

[1]Combined lengths of all unionid mussels in the SOD chamber
* Significant at $p < 0.05$
** Significant at $p < 0.01$

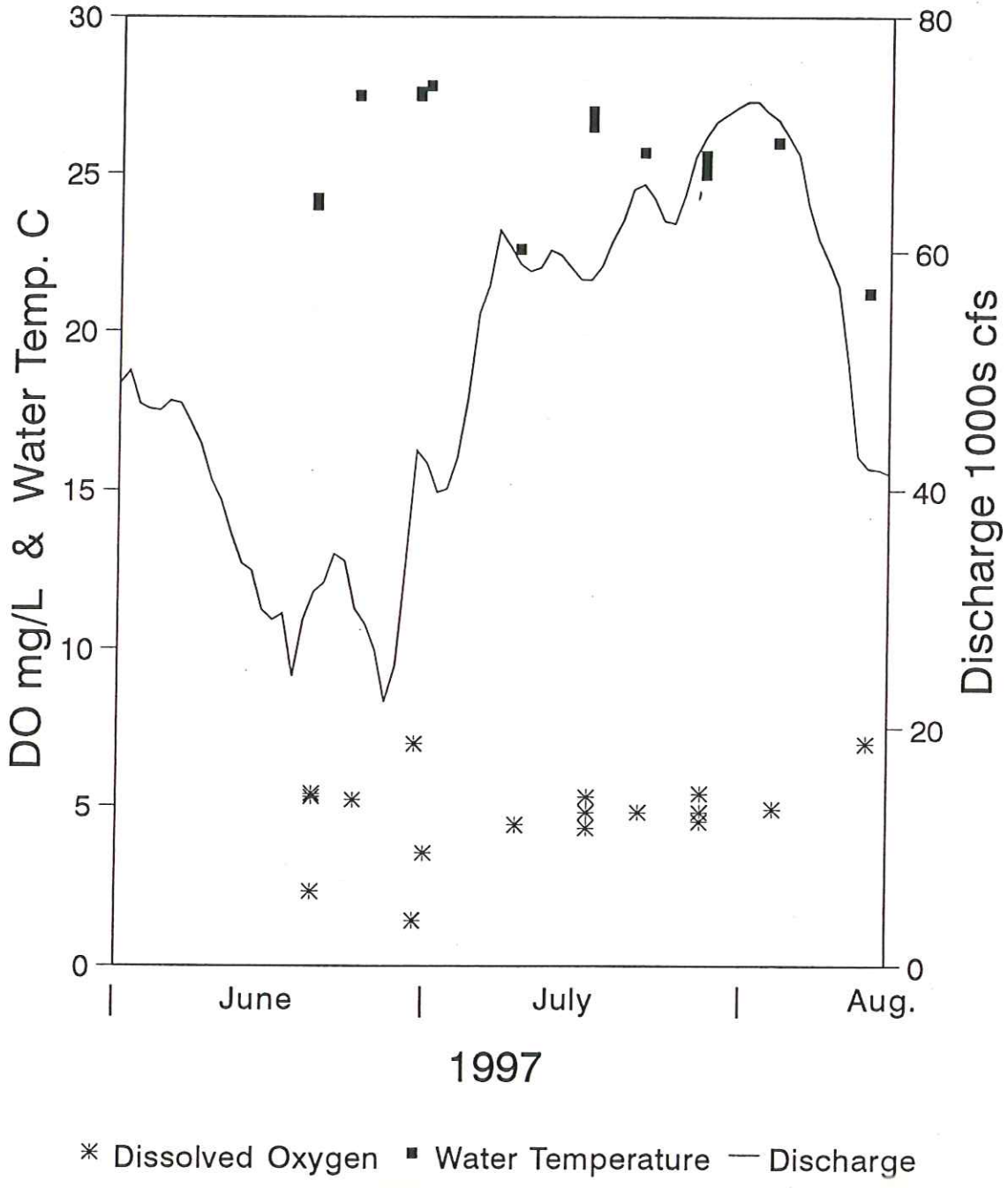

Figure 1. Water temperature and dissolved oxygen concentrations collected from Mississippi River main channel and channel border area in upper Pool 10 near Prairie du Chien, Wisconsin by the U.S. Geological Survey, Midwest Science Center between June 20 and August 13, 1997 (Knight and Dewey, 1997). River Discharge data were obtained from the U.S. Corps of Engineers for Lock and Dam 9.

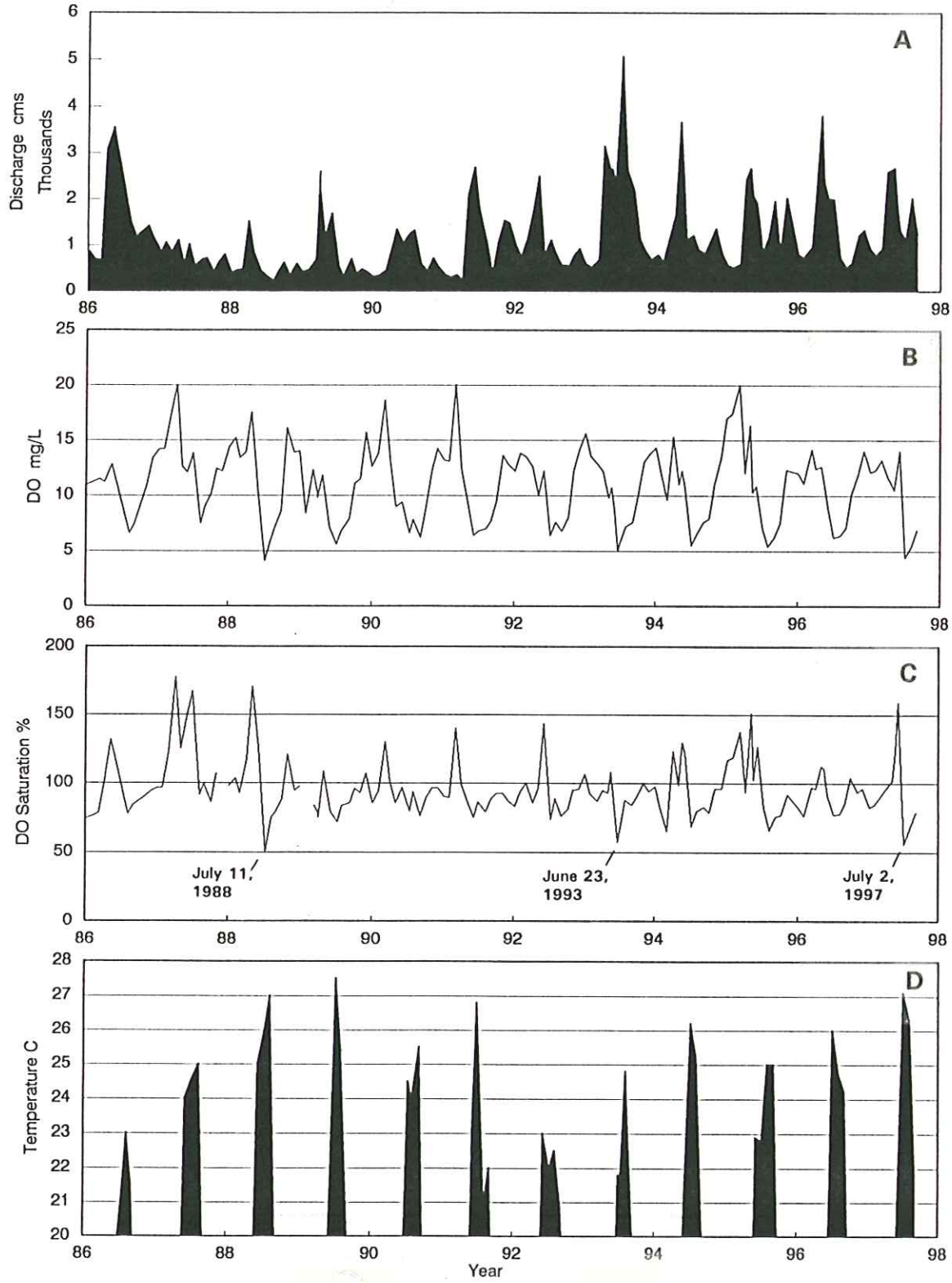

Figure 2. River discharge (A), dissolved oxygen (B), dissolved oxygen saturation (C) and water temperature (D) in the Mississippi River at Lock and Dam 9. Water quality data are based on monthly samples collected by the Wisconsin Department of Natural Resources. River discharge was obtained from the U.S. Corps of Engineers for Lock and Dam 9 and represent the discharge on the days water samples were collected.

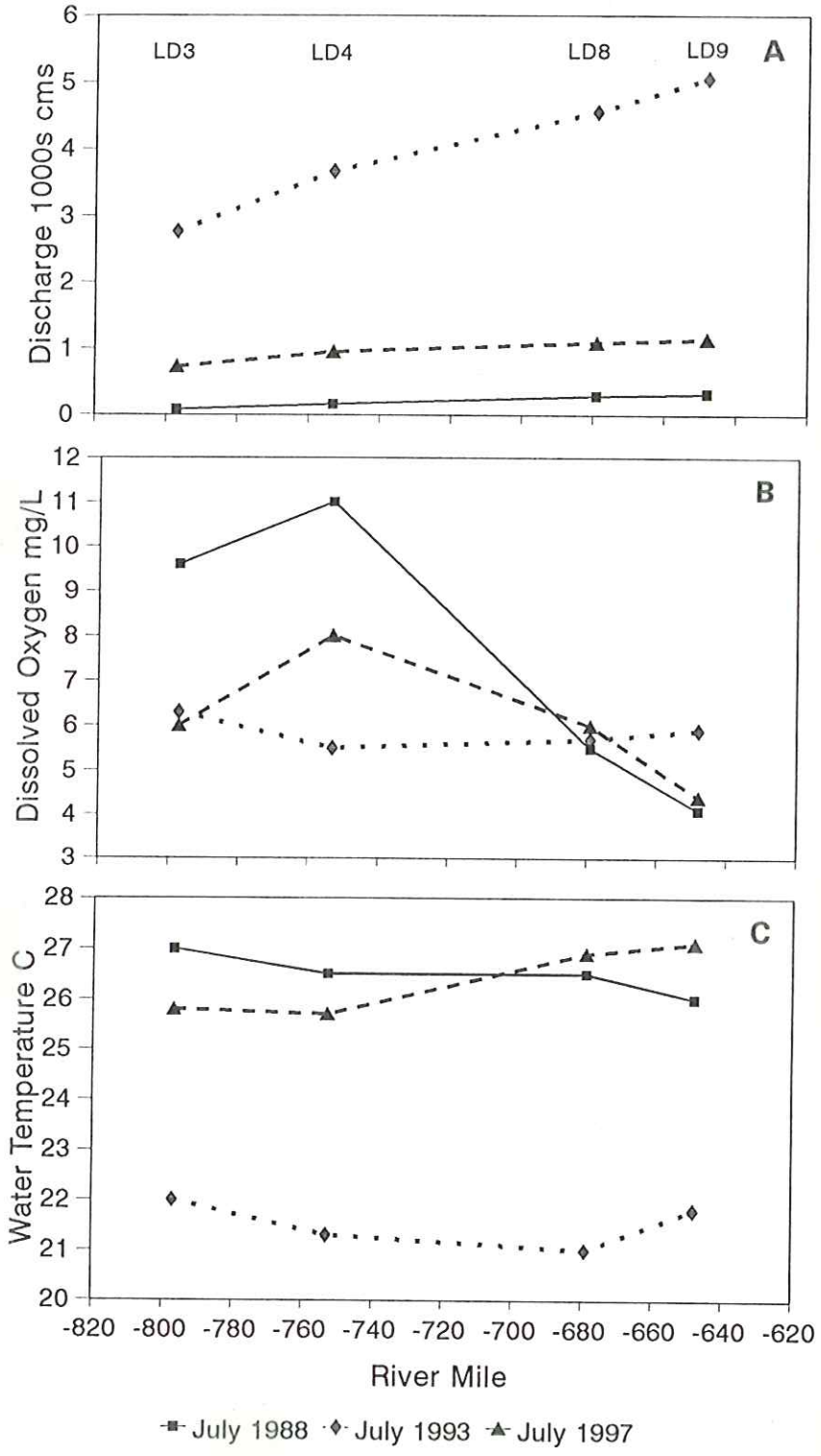

Figure 3. (**A**) River discharge, (**B**) dissolved oxygen and (**C**) water temperature at Wisconsin Department of Natural Resource's monthly water quality stations on the Mississippi River at Lock and Dam 3 (Red Wing, MN), 4 (Alma, WI), 8 (Genoa, WI) and 9 (Lyxville, WI) for July 1988, 1993 and 1997. River discharge data was obtained from the U.S. Corps of Engineers for each site on the day of sampling.

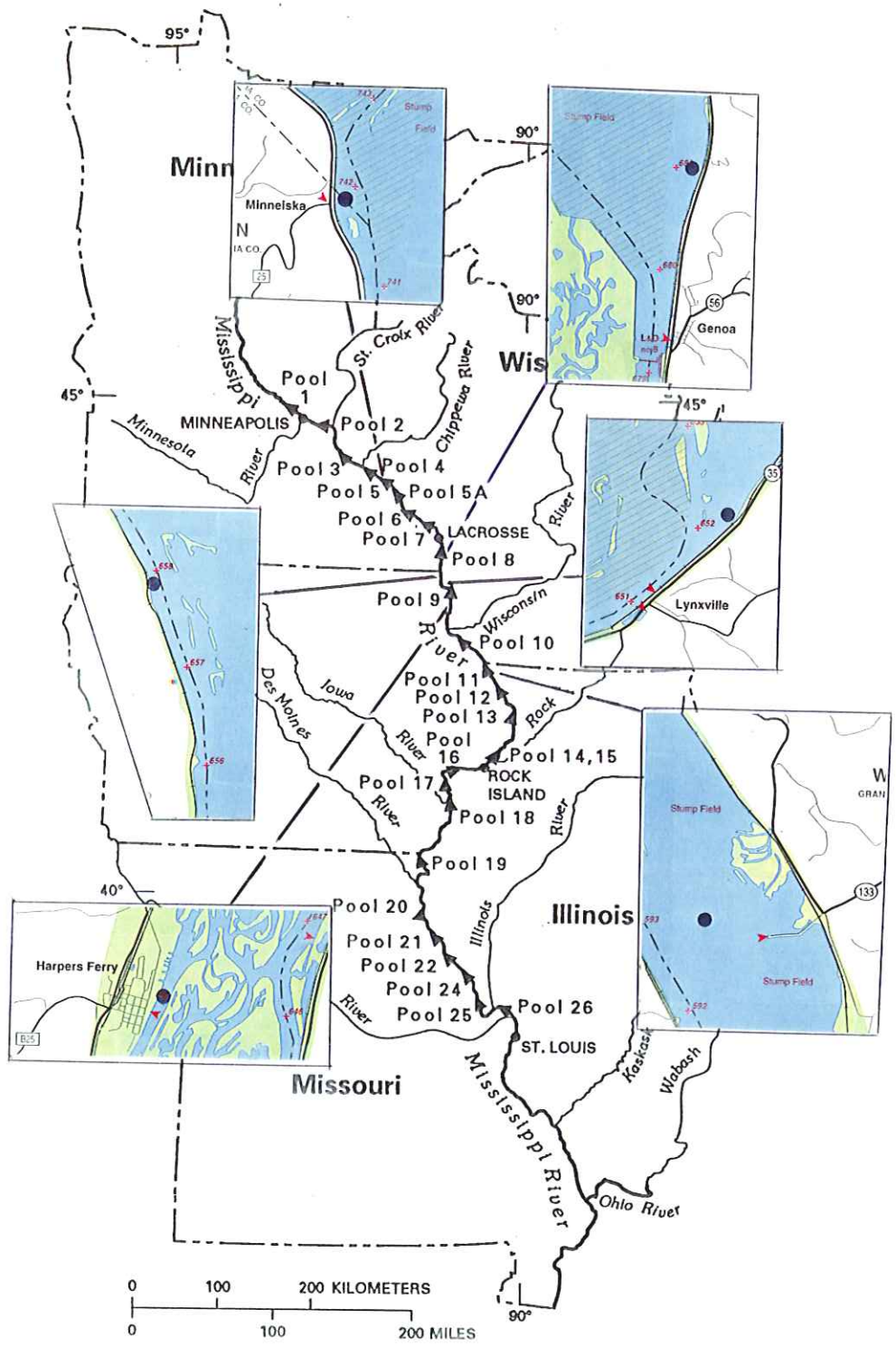

Figure 4. Mississippi River study area. Base map obtained from the U.S. Geological Survey. A solid dot (●) denotes a site where sediment oxygen demand chambers where deployed.

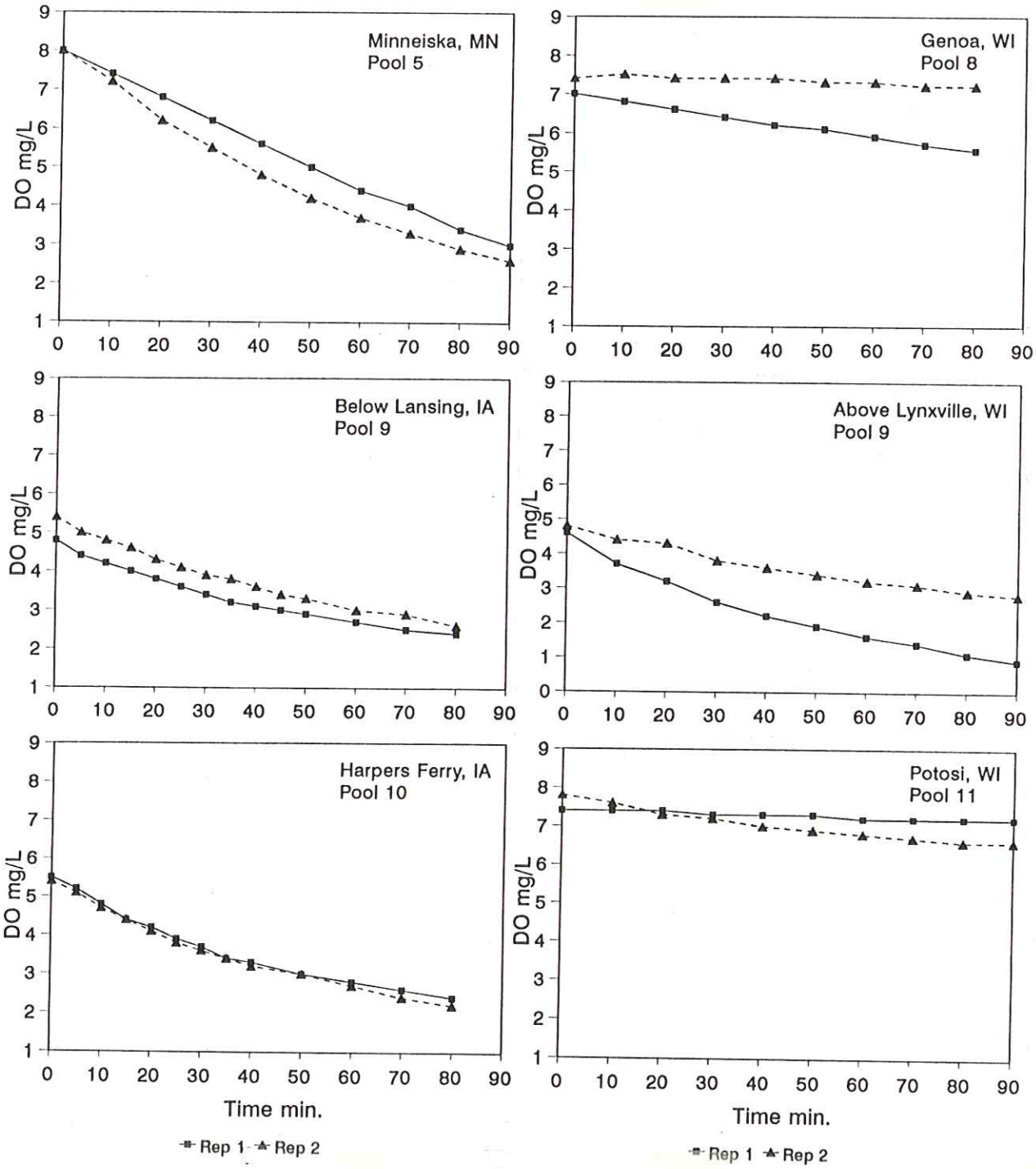

Figure 5. Dissolved oxygen measurements in sediment oxygen demand chambers deployed at six sites in the Mississippi River during July and August 1997. Two concurrent measurements (Rep 1 and 2) were made at each site.

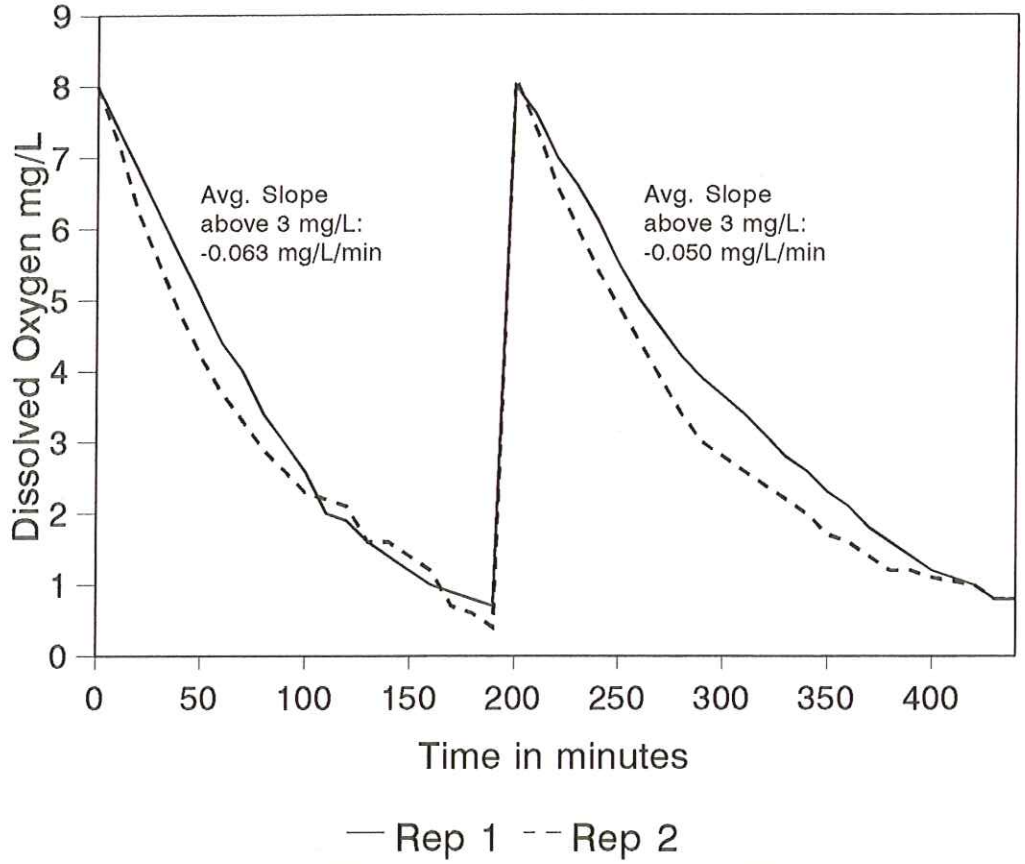

Figure 6. Dissolved oxygen measurements in sediment oxygen demand chambers deployed in Pool 5 of the Mississippi River near Minneiska, Minnesota on August 21, 1997. Two concurrent measurements (Rep 1 and 2) were made. Note: After about 190-minutes, deoxygenated water in the chambers was flushed out with fresh river water to allow for a second calculation of the DO depletion rate.

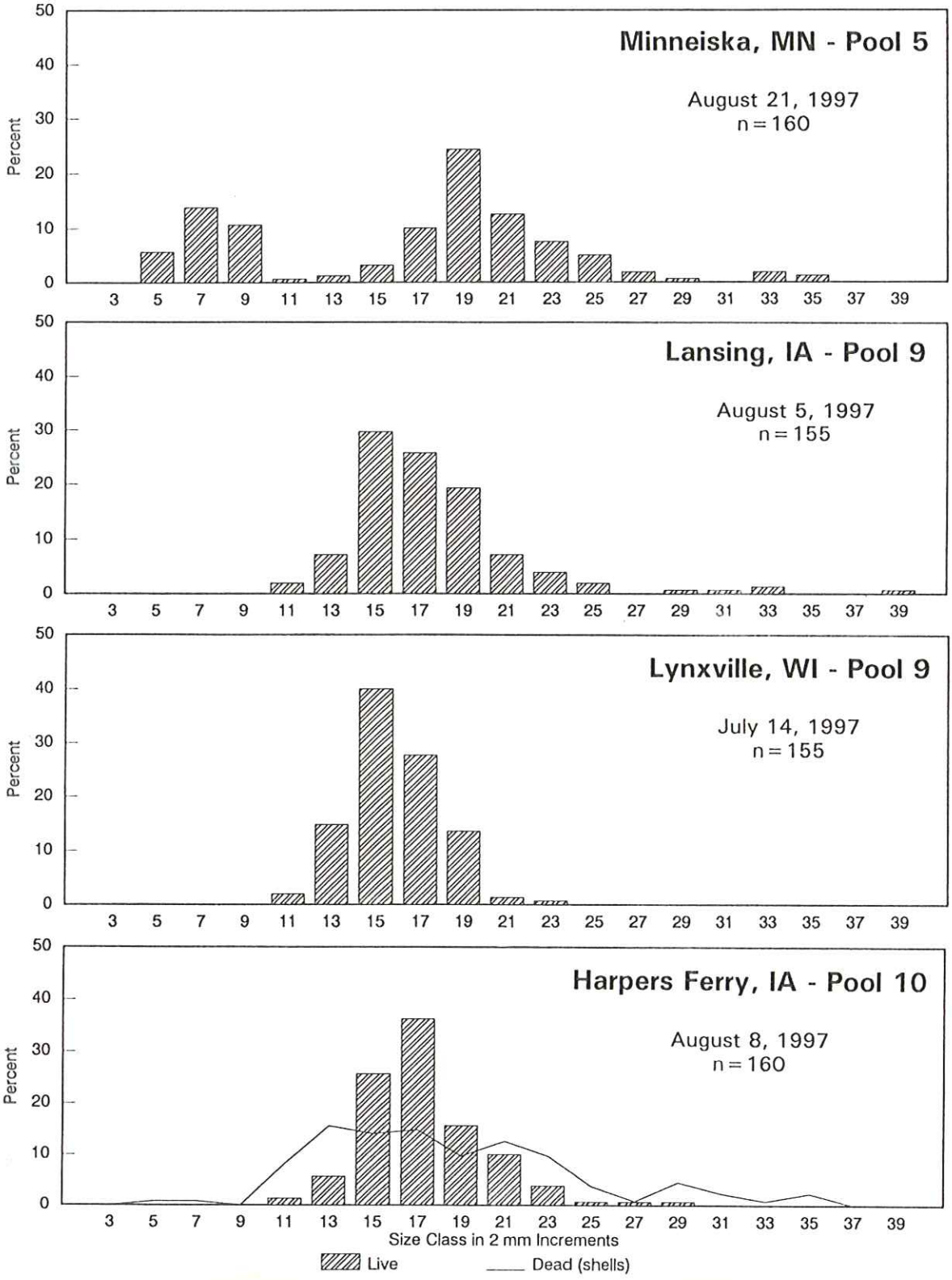

Figure 7. Zebra mussel size (length) distributions at four Upper Mississippi River sites where sediment oxygen demand studies were conducted during July and August 1997.

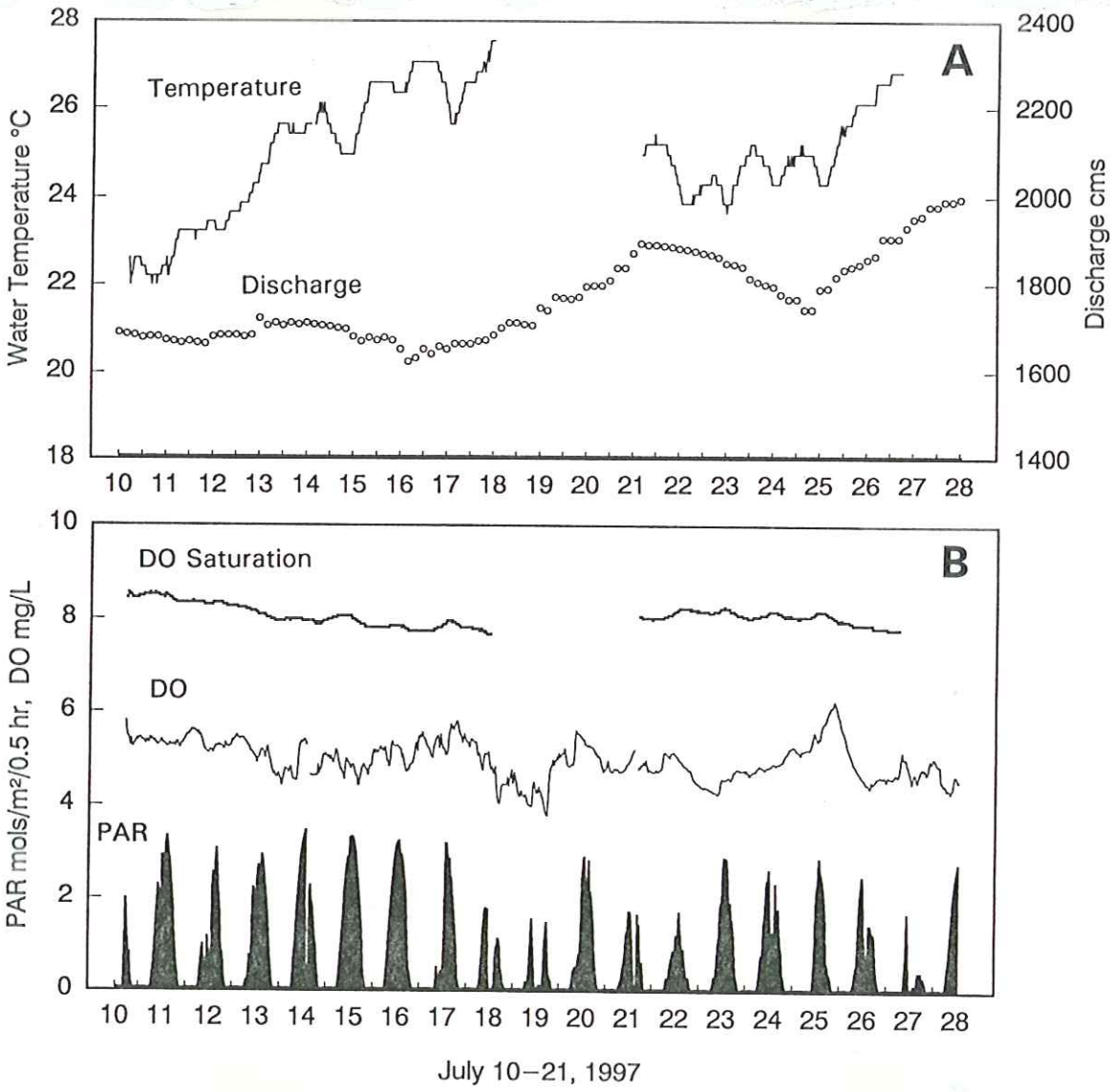

Figure 8. **A.** Water temperature and Mississippi River discharge at Lock and Dam 9 during July 1997. Discharge data were obtained from the U.S. Corps of Engineers. **B.** Dissolved oxygen (DO) saturation, DO and photosynthetically active radiation (PAR) measurements collected at Lock and Dam 9 during July 1997. Temperature, DO and PAR measurements were recorded at 30-minute intervals. Note: some temperature data are missing. Discharge measurements were recorded at 4-hour intervals.

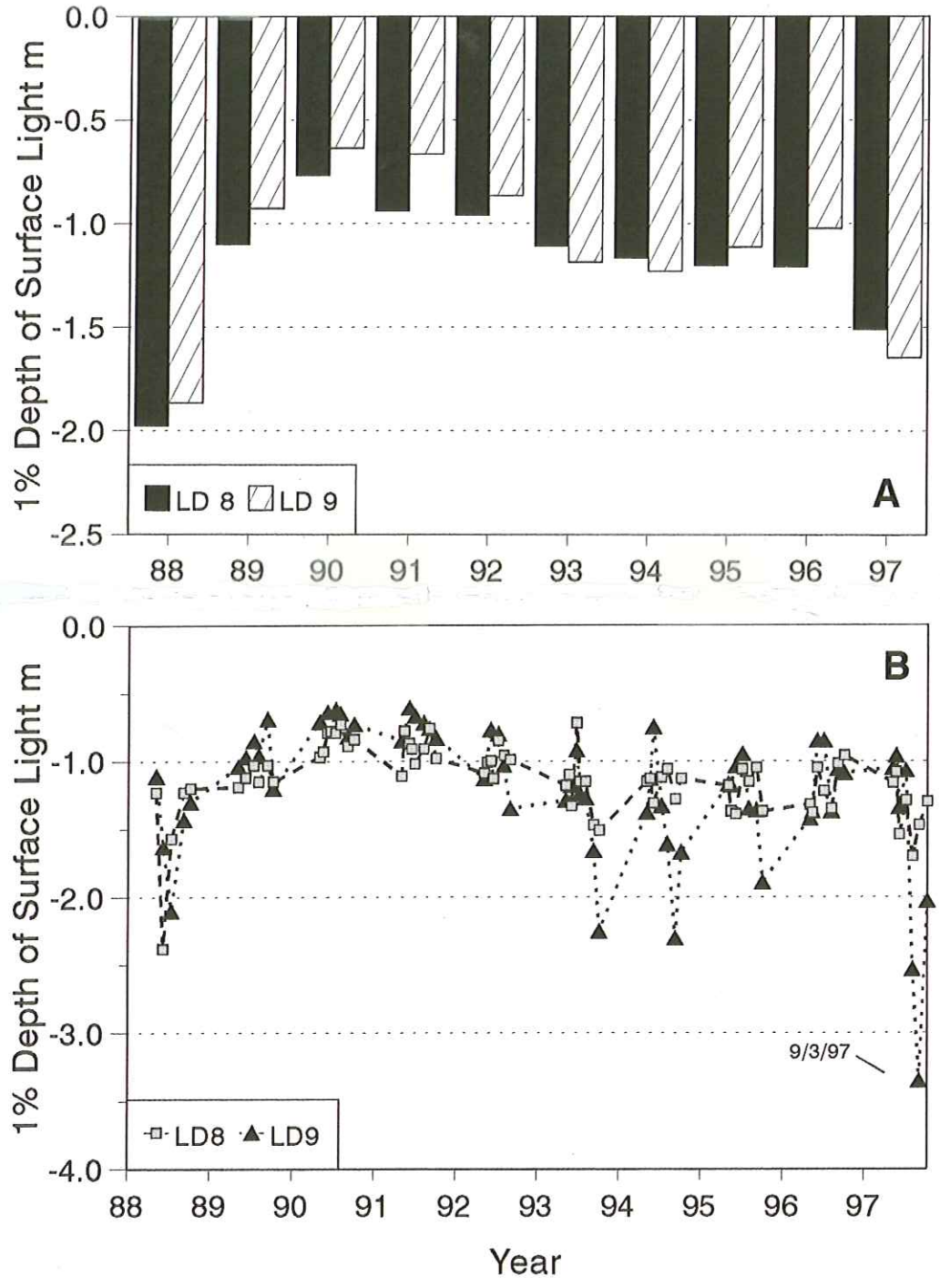

Figure 9. **A.** Average summer (June-August) light penetration measurements made at Lock and Dams 8 and 9 from 1988 to 1997. **B.** Monthly light penetration measurements made at Lock and Dams 8 and 9 during April to October for the years 1988 to 1997. Light penetration measurements represent the depth at which 1% of surface light penetrates using photosynthetically active light sensors.

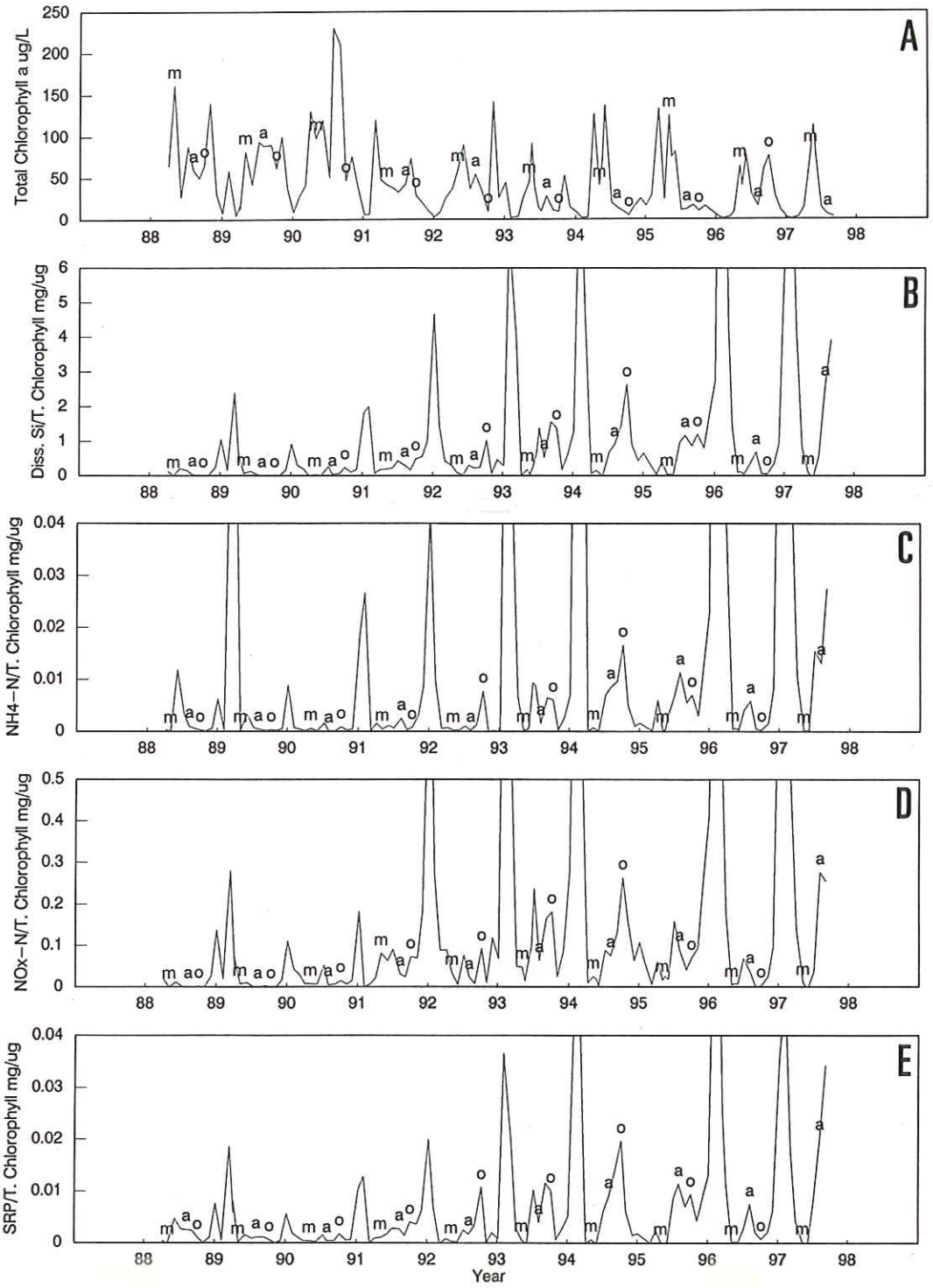

Figure 10. A. Total chlorophyll *a* concentrations at Lock and Dam 9. Ratio of dissolved silica (**B**), ammonia nitrogen (**C**), nitrite + nitrate nitrogen (**D**) and soluble reactive phosphorus (**E**) to total chlorophyll *a* at Lock and Dam 9 based on monthly water quality samples collected by the Wisconsin Department of Natural Resources. Letters in graph represent the months of May (m), August (a) and October (o).

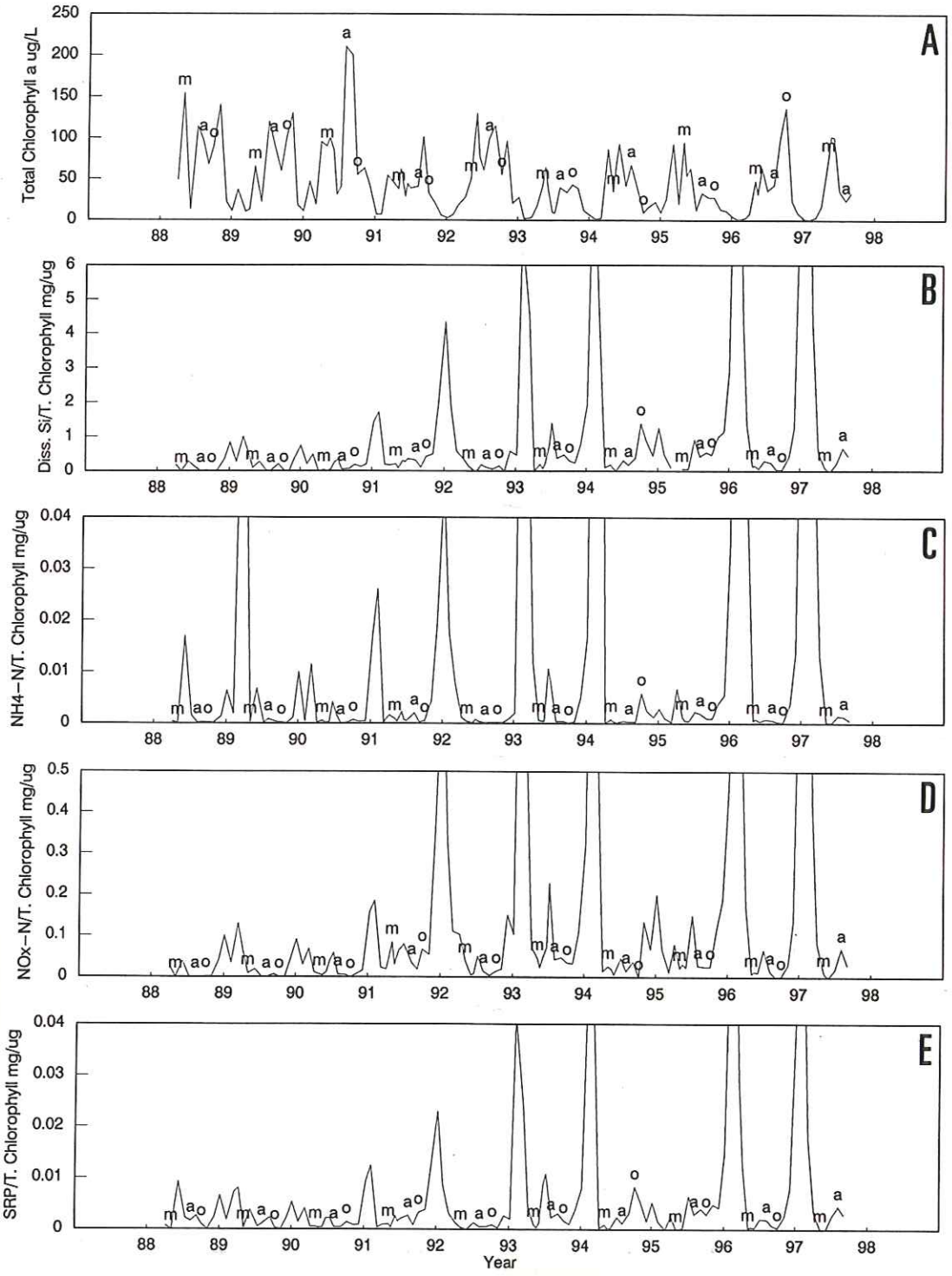

Figure 11. **A.** Total chlorophyll *a* concentrations at Lock and Dam 8. Ratio of dissolved silica (**B**), ammonia nitrogen (**C**), nitrite + nitrate nitrogen (**D**) and soluble reactive phosphorus (**E**) to total chlorophyll *a* at Lock and Dam 8 based on monthly water quality samples collected by the Wisconsin Department of Natural Resources. Letters in graph represent the months of May (m), August (a) and October (o).