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# BIOGEOCHEMICAL IMPACTS OF RESERVOIRS ON THE KALAMAZOO RIVER SYSTEM

By

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# ABSTRACT

## BIOGEOCHEMICAL IMPACTS OF MAJOR RESERVOIRS ON THE KALAMAZOO RIVER

By

Nicole J. Reid

The Kalamazoo River (Michigan, USA) has six run-of-the-river dams. The two hydropower reservoirs' residence times vary from 2 up to 11 days during the year. The four decommissioned impoundments residence times vary from a quarter of day to 1.5 days during the year. Inflows and outflows for the two hydropower reservoirs were sampled weekly in order to quantify the roles of reservoirs as sinks or transformers for nutrients. Three longitudinal river surveys from Morrow Lake inflow to Lake Allegan outflow were conducted at varying discharges. Special emphasis was placed on above and below Plainwell, Otsego, Allegan City and Trowbridge decommissioned impoundments. Despite their spatial proximity, a Total Maximum Daily Load for phosphorus (P) was deemed necessary for Lake Allegan to control summer algal blooms, whereas Morrow Lake lacks nuisance summer algal blooms. Lake Allegan outflow waters exhibited potential silica and nitrogen limitation in the late summer while Morrow Lake did not, which may explain the undesirable algal blooms in Lake Allegan. The longer residence time allows phytoplankton to build up to undesirable levels within Lake Allegan, but not in Morrow Lake. High algal abundance was observed in the Lake Allegan inflow, which may have resulted from Morrow Lake's algae transported downstream, or new algal biomass build-up as the river passed through semi-impounded reaches; the results reported here support the latter hypothesis.

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I can do all things through Christ which strengthen me (Phlip 4:13).

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**Abstract**

The Kalamazoo River (Michigan, USA) has six run-of-river dams (four small decommissioned ones and two larger ones producing hydropower). The hydropower reservoirs' residence times vary from 2 up to 11 days during the year. Lake Allegan has a longer maximum residence time of 11 days, compare to 7 days in Morrow Lake. Inflows and outflows for the two hydropower reservoirs were sampled weekly in order to quantify the roles of reservoirs as sinks or transformers for nutrients. Lake Allegan is hypereutrophic impoundment, located downstream of Morrow Lake, a eutrophic impoundment. No major tributary inputs exist between the reservoirs. Despite their spatial proximity, a Total Maximum Daily Load for phosphorus (P) was deemed necessary for Lake Allegan to control summer algal blooms, whereas Morrow Lake lacks nuisance summer algal blooms and has a more desirable fish community. During the summer, Lake Allegan inflow total phosphorus average 83 μg/L, while in Morrow Lake it averaged 54 μg/L. In both reservoirs there was a decline in soluble reactive phosphorus from, and an increase in particulate phosphorus from inflow to outflow. Nitrate decreased in both reservoirs during longer residence times, but to a higher degree in Morrow Lake as opposed to Lake Allegan, possibly due to benthic algal uptake. During the summer, the two reservoirs had decreases in the outflow calcium concentrations that affected alkalinity. Silica uptake during the summer was more marked and different timing in Lake Allegan than in Morrow Lake, and may have resulted in silica limitation of diatoms. Lake Allegan outflow waters exhibited potential

silica and nitrogen limitation in the late summer while Morrow Lake did not, which may explain the undesirable algal blooms in Lake Allegan. The longer residence time allows phytoplankton to build up to undesirable levels within Lake Allegan, but not in Morrow Lake. Ammonium, phosphorus and silica are the main nutrients potentially regulating species composition, but concentrations of these nutrients remain above limiting levels for the most part. An internal ammonium source possibly favors non-N fixing algae and if so, reducing the total phosphorus concentration may not directly affect the harmful algal blooms.

## Introduction

Globally 60% of the world's rivers have been affected by dams and diversions (WCD 2000), and reservoirs are estimated to have a combined storage capacity of as much as 100,000 cubic kilometers (Chao 1991). Michigan has over 2,500 dams and of those 103 are hydroelectric dams that impact 49 river systems (www.michigan.gov). Impoundments yield many important benefits to society by providing flood control, hydroelectricity, and water storage for agriculture, industry, and municipalities (Vorosmarty 1997). However, dams have multiple effects that extend downstream. A few major environmental impacts of dams are (1) changes in downstream river hydrology, morphology, and water quality, (2) reduction of biodiversity, (3) increased habitat fragmentation, and (4) trapping of riverine sediment and nutrients (McCully 2001).

This chapter will discuss the changes in river nutrients and major solutes as the water passes through two reservoirs on the same river and evaluate the potential for nutrient limitation of phytoplankton growth in the reservoirs. The inflow and outflow of each reservoir were sampled during spring and summer for two years. Summer was the most active period for algal growth because of the relatively long residence times reaching, 11 days for Lake Allegan and 7 days for Morrow Lake. I showed here that the DIN:TP molar ratio suggested potential N-limitation in both reservoirs, while silica limitation only occurred potentially in Lake Allegan. A phosphorus Total Maximum Daily Load was established to control harmful algal in Lake Allegan. However, other nutrients such as internal ammonium production and silica depletion may also influence in Lake

Allegan. Nevertheless, ultimately residence time controls the ability of phytoplankton to grow within Lake Allegan and nutrients are of secondary importance.

*Literature Review: Effects of impoundments on river hydrology, biogeochemistry and ecology*

Impoundments change the characteristics of a river from a fluvial environment to a more lacustrine environment, affecting physical, chemical and biological characteristics. Some of the main changes upon impoundment are increased water residence (also called retention time), sediment accumulation, nutrient transformations, and increased autochthonous primary production (Friedl and Wuest 2002). Longitudinal gradients in sedimentation, biological activity, and reservoir hydrology (residence time and water discharge) determine the fate of nutrients in a reservoir.

A longitudinal gradient develops in a reservoir as a result of basin morphology and the reservoir inflows and outflow. Basins are generally narrow and elongate with the deepest part located at the dam. Reservoirs may receive little or no influence from the surrounding watershed, with the majority of inputs from the inflowing river(s). Advective currents caused by the river inflow and outflow distribute nutrients and sediments within the reservoir. Reservoir longitudinal gradients commonly show three distinct zones: riverine, transition and lacustrine (Thornton 1980). At the upriver end, the riverine zone is a narrow, well-mixed entrance with decreasing velocity allowing coarse organic matter and sand to settle, forming a delta. Light penetration is relatively low, which limits primary production. Next, in the transition zone clays and silts settle and light penetration gradually increases. Finally, the lacustrine zone exhibits lacustrine characteristics with low sedimentation rates, and deeper light penetration promotes autochthonous primary production; thermal stratification may occur during the summer.

Incoming river water forms a plunge point were the water does not mix immediately, but often sinks to a depth where its density is approximately similar to the reservoir water (Carmack 1979). From the plunge point, inflowing water may be integrated into reservoir waters as overflow, interflow or underflow currents (Ford 1990). Nutrients, organisms, and sediments travel within these currents and can be deposited within the reservoir. In an unstratified reservoir, outflow waters represent a composite from all depths, but in a stratified reservoir vertical mixing is inhibited and outflow waters are restricted to a particular stratum (Ford 1990). Most reservoirs discharge water through a subsurface outflow, which under stratified conditions leads to a restricted hypolimnion withdrawal zone, a deeper epilimnion, and increased heat storage (Ford 1999, Martin 1978). Hypolimnetic-discharge reservoirs tends to exhibit higher nutrient concentrations in outflowing waters compared to epilimnetic outflowing waters (Martin et al. 1978). Changes in water elevation associated with dam operations can enhance nutrient exchange between littoral and pelagic zones.

Sedimentation acts as nutrient sink in reservoirs, while sediment-water exchange of solutes can release nutrients in a reservoir. Most of the sedimentation typically occurs near the inflow with minimal sediment deposits at the dam. James et al. (1987) noted significant losses of phosphorus, nitrogen and carbon in DeGray Lake inflow water resulting from sedimentation. Sediment accumulation varied depending on the season, with higher deposition during the spring compared to summer. However, sediment retention depends on water velocity and less may be retained if flushing rates are high (Jossette et al. 1990). Clay and silt sedimentation in the transition and lacustrine zones removes associated trace metals and nutrients from the overlying waters. Anoxic conditions in the waters overlying sediments during summer stratification can cause the release of trace metals, phosphorus and ammonium from sediment into the overlying waters. Reservoir sediments can be either a net sink or source of nitrogen (Sherman 2001). Transition and lacustrine zones are the main zones of nutrient release from sediments in reservoirs; advective forces in the transition zone distribute released nutrients within the reservoir (Kennedy and Walker 1990).

Reservoirs are divided into three classes based on residence time (Straskraba 1999). The first class is the through-flowing reservoir with residence times less than two weeks. The intermediate-residence time reservoir class has residence times between two weeks and one year. The long-residence time reservoir class has residence times greater than one year. Long residence time reservoirs behave much like a stratified lake. Nutrient availability is affected by reservoir residence time. Reservoirs with residence times greater than 120 days retain much of total phosphorus in inflowing waters, whereas at short residence times (less than 10 days) there may be no phosphorus retention due to the high flushing rates (Soballe 1987, Straskraba 1999). However, nitrogen retention is not affected as much by reservoir retention time, but more by reservoir morphology. More nitrogen is retained in shallow reservoirs where sediment-water interactions (including dentrification) have more influence on overlying waters, compared with deep reservoir systems (Howarth 1995, Straskraba 1999, Scheffer, 1998). Silica is replenished in short-residence time reservoirs by river inputs, whereas systems with long residence times serve as a sink for silica, especially when they have high nitrogen and phosphorus inputs (Conley, 1993).

A shift from allochthonous to autochthonous energy sources supporting food webs is common in reservoir systems. Phytoplankton are able to flourish in reservoir systems with sufficiently long enough residence times due to constant inputs of riverine nutrients, increased light penetration and warming water temperatures. The longitudinal gradient establishes primary production in the lacustrine zone. Phytoplankton concentrations peak with a reduction in turbidity and velocity but where nutrient availability is still high (Gloss et al. 1980, Kennedy et al. 1982). During the summer, reservoirs usually increase in water temperature relative to inflowing river waters, promoting biological activity (Carmack 1979). Internal recycling of nutrients by phytoplankton partially controls the amount of nutrients available in a reservoir. Jossette et al. (1990) concluded from a biogeochemical mass balance that 60% of phosphorus inputs either were lost by sedimentation or retained by algae, and that silica was deposited in reservoirs as a result of diatom uptake. Total nitrogen and phosphorus budgets in Sulejow Reservoir indicated that these nutrients were assimilated by phytoplankton (Galicka and Penczak 1989).

Primary production affects calcium carbonate ($CaCO_3$) formation in reservoirs by algae for growth, and by regulating dissolved carbon dioxide concentrations through photosynthesis. High algal photosynthetic rates, deplete dissolved $CO_2$ and raise pH; as a result, $CaCO_3$ may precipitate in alkaline waters. Increased water temperature also contributes to $CaCO_3$ supersaturation. $CaCO_3$ precipitation decreases calcium and alkalinity concentrations (Schlesinger 1997) and can remove available phosphorus through sorption (Otsuki and Wetzel 1972, Bostrom et al. 1988).

Denitrification is a microbial respiratory process that reduces nitrate to nitrogen gas ($N_2$). Denitrification occurs in aquatic sediments under hypoxic or anoxic conditions, is favored by warm temperatures, and may be limited either by nitrate or labile organic carbon (Seitzinger 1988). A correlation exists between nitrogen inputs and nitrogen retention in reservoirs, yet nitrogen retention can depend on changes in residence time and water volume (sediment-water interaction) (Tomaszek and Koszelnik, 2003). Nitrate inputs via river flow into reservoirs form a longitudinal gradient with high nitrate concentrations at the riverine end and lower concentrations at the dam end; denitrification may increase towards the dam as temperatures increase and oxygen concentrations in water overlying the sediments decrease (Wall 2005). The highest denitrification rates occur at the end of the spring or summer when oxygen concentrations are lowest (Tomaszek and Czerwieniec 2003, Wall 2005). Nitrogen retention gradually declines in autumn (Tomaszek and Koszelnik, 2003, Wall 2005) reaching the lowest retention in the winter when low temperatures limit denitrification rates (Wall 2005).

Rooted macrophytes and periphyton often have limited primary production in reservoirs due to turbidity and water level fluctuations. However, if water levels are stable with clear water, macrophyte communities can establish (Barko 1981), and smaller shallow reservoirs can support abundant periphyton growth as well. Submerged vegetation serves as habitat for fish and provides a surface for periphyton growth (Kimmel et. al. 1990), and detrital inputs from vegetation represent a slow release nutrient source for the overlying waters (Miner 1974). Tropical and subtropical reservoirs often develop extensive stands of floating emergent plants (Thomas et al. 1999). Light penetration, nutrients, substratum composition and stability impact benthic algal community development (Stevenson 1996). These same factors also affect nutrient uptake by benthic algae. Phytoplankton have more ready access to water column nutrients than benthic algae. However, benthic algae have another nutrient source beside the overlying waters; benthic algae utilize nutrients within and released from the sediments and benthic algae can thereby restrict nutrient movement from the sediments into overlying waters (Hasson 1988). Benthic algae can be favored by shallow waters and short residence times that restrict the growth of phytoplankton.

*Study Site*

The Kalamazoo River watershed is located in the southwestern Michigan, with a watershed area of approximately 5,231 km$^2$. The Kalamazoo River runs 260 km through 10 counties of variety of land uses (developed areas, farmland and forest including the Allegan State Game Area) (Figure 1). Morrow Lake and Lake Allegan are shallow and non-stratifying run-of-the-river impoundments located on the Kalamazoo River. The water discharged at the dam is essentially drawn from the entire water column, with a spillway to accommodate excess discharge. Water levels are kept constant behind the impoundment wall. Morrow Lake is located 69 km upstream of Lake Allegan, and there are no major tributary inputs between the impoundments, although groundwater inputs are substantial. The morphometric features of both reservoirs are listed in Table 1.

Consumers Power Company created Morrow Lake in 1939 for the Bryce E. Morrow Power Plant in Comstock, Michigan. The plant was fueled by coal, which supplied energy to the boiler to produce steam. Morrow Lake's water was pumped through condensers, which condensed hot steam from the boilers to hot water, which was then pumped back into boilers. The two electric generators were powered by steam turbines, which produced 35,000 kilowatts each.

In 1969, the plant was converted to natural gas power, and in 1971 was rebuilt to use oil. Consumers Power closed Morrow Plant in July 1982 due to high operating costs and reduction in power consumption. STS Consultants Ltd. purchased about 1,400 acres surrounding Morrow Plant (excluding the building and equipment) to construct a new hydroelectric facility. The hydroelectric plant now generates about 1,000 kilowatts of electricity. Currently, Morrow Impoundment is owned by STS Hydropower and is not licensed by the Federal Energy Regulation Commission (FERC).

Calkins Dam was constructed by the city of Allegan from 1931-1936. The city's municipal utility operated the dam from 1936 to 1968. In 1968, Consumers Energy purchased the dam and to date operates the dam.

There are also several decommissioned hydropower dams and diversion dams for a mill race, all located between Morrow Lake and Lake Allegan. Chapter Two describes these dams in more detail.

*Total Maximum Daily Load (TMDL) for Lake Allegan*

The United States Environmental Protection Agency conducted a National Eutrophication Survey in 1972 and classified Lake Allegan as hypereutrophic (USEPA 1975). The source of Lake Allegan's hypereutrophication was deemed to be phosphorus based on the well-documented tendency for other Michigan lakes to be phosphorus limited. The Michigan Department of Environmental Quality (MDEQ) monitored Lake Allegan from April through September of the years 1988, 1994, 1996 and 1997, and determined that total phosphorus concentrations in Lake Allegan averaged 96 μg/L and ranged from 69 to 125 μg/L (Heaton 2001). In 1998, Lake Allegan remained classified as hypereutrophic, exhibiting high nutrient and chlorophyll *a* concentrations (67 μg/L), excessive turbidity (0.6 m Secchi depth), low dissolved oxygen, and an unbalanced fish community dominated by carp and channel catfish (87% community average) (Heaton 2001).

In 1999, MDEQ developed a phosphorus Total Maximum Daily Load (TMDL) for Lake Allegan. A Total Maximum Daily Load (TMDL) is an estimate of the total daily input of a pollutant stressor (from point, non-point, and natural background sources) that may be allowed within a segment of receiving water without exceeding applicable water quality criteria.

A reduction of total phosphorus in Lake Allegan should improve water quality conditions if it is indeed the main factor controlling algal growth. Morrow Lake, an impoundment located upstream, served as a reference in setting Lake Allegan TMDL parameter goals. Morrow Lake has morphometry similar to Lake Allegan, but with better water quality: no nuisance algae blooms, lower chlorophyll *a* (23 μg/L), higher transparency (Secchi depth average 1.0 m), a balanced non-carp-dominated fish community (39% carp and catfish by number), and 58 μg/L total phosphorus. Morrow Lake's water quality characteristics were considered a realistic and desirable target Lake Allegan. Therefore, the Lake Allegan total phosphorus TMDL goal was set at 60 μg/L for the inflow in the expectation that Lake Allegan would become more like Morrow Lake with this lower phosphorus load.

Considering their spatial proximity and the fact that Lake Allegan and Morrow Lake are both shallow lakes located on the Kalamazoo River without any major tributary inputs directly into or between them, the question arises as to why there are major differences in the total phosphorus concentration and in algal blooms and fish communities between the reservoirs.

*Objective and Hypotheses*

The objective of this research was to conduct a comprehensive biogeochemical analysis of inflow and outflow waters of Morrow Lake and Lake Allegan. The analysis will help develop an understanding of the differences and similarities between Morrow Lake and Lake Allegan and to explain why only Lake Allegan has reported problems with excessive algal growth and poor water quality.

I hypothesized that the following critical biogeochemical processes may alter elemental fluxes and influence algal growth in Morrow Lake and Lake Allegan:

- Residence time limits the time for algal growth within the reservoirs.
- Phosphorus forms change within the reservoirs by phytoplankton uptake/release and sediment/water exchanges.
- Algal uptake and denitrification remove nitrate within the reservoirs.
- Calcium carbonate precipitation decreases concentrations of calcium and alkalinity within the reservoir.
- Diatoms measurably reduce available silica concentrations during the spring.
- Nutrient ratios (N:P and Si:N) shift seasonally in the reservoirs during periods when residence time is long enough for biological uptake to impact concentrations, resulting in shifts in the potentially limiting nutrient for algal growth.

## Methods

### *Field Sampling*

The Lake Allegan inflow sampling location was the historical downtown bridge on Bridge Road, and the outflow site location is just below the Caulkins Dam on Lake Allegan Dam Road; both sites are located in Allegan County, Michigan. The Morrow Lake inflow sampling location was where E. Michigan Avenue crosses the Kalamazoo River in Galesburg; the outflow sampling location is Merrill Park in Comstock about 2 km below the dam. Morrow Lake is in Kalamazoo County, Michigan.

In 2003, samples of inflow and outflow waters were collected in early spring (13 March 2003) and weekly during summer (14 May-19 August 2003). In 2004, inflow and outflow waters were sampled once during ice–cover in early spring (10 Feb 2004) and monthly during summer (26 May-20 September 2004). The right and left banks were sampled periodically for differences in nutrient concentrations, since the Morrow Lake outflow was sampled from left bank. Lake Allegan inflow and outflow waters and Morrow Lake inflow waters were sampled with a Van Dorn Sampler and Morrow Lake outflow waters by an extendable hand-held dipper. Temperature, pH, conductivity, and dissolved oxygen were measured at each sampling site with a Hydrolab Sonde.

One diel cycle of temperature, oxygen, pH and conductance was recorded with a YSI multiparameter sonde for Lake Allegan on 19-20 August 2003 and Morrow Lake on 23-24 August 2003. In Lake Allegan the sonde sensor probe was suspended from the impoundment wall between two intake gates; in Morrow Lake the sonde was positioned in water of 0.7m depths off an island in the center. Both locations represent the surface mixed layers, although persistent thermal stratification has not been documented in these reservoirs.

In late summer 2004, vertical profiles were measured from a boat in each reservoir near the impoundment wall, at the deepest point. At that time when maximum vertical differences would have existed. Depths were determined with Hummingbird sonar depth finder. The Morrow Lake vertical profile was measured on 27 August 2004, taking 7 samples at 1-meter depth intervals. The Lake Allegan vertical profile was measured on 20 September 2004, taking 10 samples at 1-meter depth intervals. Secchi depths were recorded in each reservoir. Temperature, pH, conductivity, dissolved oxygen were measured in each vertical profiles at 1-meter intervals with the Hydrolab Sonde.

*Laboratory Analyses*

Water samples were filtered through 0.45µm membrane filters and refrigerated (nutrients, anions) or acidified with 8 N $HNO_3$ (cations). Ammonium was analyzed colorimetrically by the phenylhypochlorite method (Aminot et al 1997). Soluble reactive phosphorus (SRP) was measured colorimetrically by the acid molybdate method; silica was analyzed colorimetrically by the ammonium molybdate method (Wetzel and Likens 2001). Total soluble phosphorus (in filtered water) and total phosphorus (unfiltered water) were determined after persulfate digestion in a pressure steam sterilizer by colorimetric analysis of the resultant orthophosphate (Valderrama 1981, Langner and Hendrix 1982). The sterilizer was operated at 20 psi for two hours followed by a gradual cool down period. Standards included ATP to ensure efficient oxidation of organic matter. Reagent and water contributions to the analytical blank were determined by varying the reagent amount and only the reagent contribution was subtracted from sample absorbances (this was also routinely done for ammonium analyses). Nitrate, sulfate, and chloride were measured with an ion chromatograph. Calcium, magnesium, sodium and potassium were measured with a flame atomic absorption spectrophotometer. Alkalinity was determined by Gran titration with 0.3 N HCl. Sestonic chlorophyll a was filtered onto Type A/E glass fiber filters and frozen. The filters were later halved and one half was extracted with 95% ethanol, and chlorophyll a was measured by fluorometry (Welschmeyer 1994).

Data from inflow and outflow waters were analyzed by linear and multiple regression using SYSTAT 9.0

Water residence time was calculated from USGS discharge records and reservoir volumes. For Morrow Lake the gauging station was Comstock and for Lake Allegan the gauging station was Trowbridge. Lake Allegan and Morrow Lake volume and area were recorded from critical infrastructure information provided by the Federal Energy Regulatory Commission. The maximum depth was recorded from the vertical profiles. A time-integrated residence time was calculated as follows, to reflect short-term changes in river discharge. First, the daily residence time for each sampling day was calculated from the daily discharge and reservoir volume. Once the daily residence time was determined for that sampling day, I started with that sampling day and counted back the number of days equal to the residence time estimate. I then calculated the mean daily discharge residence time over that preceding interval.

## Results

*Climate and River Hydrology*

Discharge varied throughout the season with the highest discharge during February through May and the lowest discharge during June through September. The river at Lake Allegan had higher discharge than at Morrow Lake (Figure 2). Discharge was higher overall in 2004 than in 2003. The mean annual discharge for March through September over 72 years (1931-2003) was 26.38 $m^3$/sec. The mean for March through September 2003 was 20.6 $m^3$/sec and for March through September 2004 it was 29.72 $m^3$/sec.

Residence times in the two reservoirs varied seasonally and were shorter during February through May than in June through August. Beginning in June residence times increased. Residence time varied inversely with discharge and thus was longer in 2003 than in 2004 (volumes of each reservoir were constant). Lake Allegan had a longer residence time than Morrow Lake (Figure 3).

The climate of the region is humid and temperate. Air temperatures in 2003 and 2004 were low during January through April and started gradually increasing in May. The highest temperatures occurred in July and August (Figure 4).

*Statistical predictors of algal growth in the reservoirs*

Simple linear and multiple regression analyses were used to determine what factors predict algal growth. In 2003 (Table 2), residence time was a good predictor of algal growth in Morrow Lake ($p < 0.05$) and Lake Allegan ($p < 0.05$). Outflow total phosphorus predicted algal growth only in Morrow Lake ($p < 0.05$), and was not a significant predictor in Lake Allegan ($p=0.061$). However, combining the residence time and outflow total phosphorus yielded better prediction of algal growth in Morrow Lake ($p < 0.05$) and Lake Allegan ($p < 0.05$). In 2004, when residence times were shorter (Table 3), p-values were not significant for either of these factors predicting algal growth. Combining the 2003 and 2004 data (Table 4), residence time predicted algal growth in Morrow Lake ($p < 0.05$) and Lake Allegan ($p < 0.05$). Addition of the total phosphorus concentrations yielded a better prediction in Morrow Lake ($R^2=0.62$, $p < 0.05$), but did not improve the prediction in Lake Allegan ($R^2=0.37$, $p < 0.05$).

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*Lake Allegan*

The residence time of water in Lake Allegan was relatively long during March 2003, then became shorter as discharge increased in April and May. Beginning in July residence time gradually increased (Figure 5A). However, in 2004 the residence time did not increase seasonally, but remained short all summer (Figure 5B). Residence time was longer in 2003 than in 2004, reflecting the discharge in those years.

Chlorophyll *a* concentrations were variable during March and in early July 2003 and 2004, but were usually higher in the outflow. In July, there was a steady increase in the outflow chlorophyll *a* concentrations. Also in mid July the inflow chlorophyll *a* concentrations increased above the outflow, then declined sharply below the outflow (Figure 6A and 6B). Chapter 2 examines patterns in chlorophyll in the river between the two reservoirs and investigates the origin of the high chlorophyll concentrations in the Lake Allegan inflow waters.

The outflow concentrations of total soluble phosphorus were usually lower than the inflow concentrations during April through July 2003and 2004. Starting in mid-July the inflow concentrations fluctuated (Figures 7A and 7B).

The outflow concentrations of total phosphorus were usually lower than the inflow concentrations during April through mid July in 2003 and 2004, but in August outflow concentrations exceeded the inflow concentrations (Figures 8A and 8B). Soluble reactive phosphorus concentrations in 2003 and 2004 remained low in the outflow, but fluctuated in the inflow (Figures 9A and 9B).

Concentrations of soluble organic phosphorus (measured as the difference between total soluble phosphorus and soluble reactive phosphorus) were usually higher in the outflow than in the inflow. In July 2003, the inflow concentrations fell below detection (Figure 10A). In 2004, the outflow concentrations were usually higher than the inflow, but the inflow did not reach zero during the summer (Figure 10B).

Ammonium concentrations were variable during March through July 2003. From July on there was an increase in the outflow ammonium concentrations relative to the inflow, peaking in August (figure 11A). However, March-June 2004 inflow and outflow concentrations were constant, there was a peak in outflow concentration in early July followed by a decline starting in late July (Figure 11B). Nitrate concentrations in the inflow and outflow were similar from March through May 2003, but after June there was a consistent decline in nitrate concentrations, almost reaching undetectable levels ($< 15$ μg N/L) at the outflow in late July through mid-August (figure 12A). The pattern was the similar in 2004, except that outflow concentration did not reach undetectable levels in July (Figure 12B).

From March through August 2003, outflow concentrations of silica were lower than in the inflow. The first marked decline was in April 2003 followed by a second decline in July, and the outflow concentrations fell to nearly undetectable levels in late July through mid August (Figure 13A). Outflow concentrations of silica declined in April and July 2004 (Figure 13B). The July 2004 outflow concentration decline was not as marked as it was in July 2003.

Redfield ratio is based on Liebig's law of the minimum, which states the smallest quantity of a nutrient relative to growth needs will become the limiting factor. The ratio for algal biomass is C:N:P = 106:16:1. In the case of diatoms Si:N = 1:1. From March through June 2003, ratios of available N:P (DIN:TP) indicated that the outflow waters shifted from potential phosphorus limitation to potential co-limitation between nitrogen and phosphorus, while inflow waters remained potentially phosphorus limited(Figure 14A). From July through August, the inflow remained potentially phosphorus limited, but the outflow became potentially nitrogen limited. The 2003 pattern was similar in 2004 except the outflow waters never show potential nitrogen limitation (Figure 14B). These ratios reflect potential nutrient limitation because in most samples the concentrations exceeded those known to be physiologically limiting to algal growth.

In April 2003, diatom growth in both inflow and outflow waters was potentially silica limited (Figure 15A). Beginning in May, inflow and outflow waters shifted to potential nitrogen limitation, and in July inflow and outflow waters were potentially silica limited and shifted back to potential nitrogen limitation during mid August. In contrast, the inflow waters were only potentially silica limited in April and remained potentially nitrogen limited for remaining months. The outflow pattern was similar in 2004 with potential silica limitation in June and August (Figure 15B).

In 2003, the inflow waters were mainly potentially phosphorus limited or silica-phosphorus limited, while the outflow waters were potentially phosphorus limited, co-limited between phosphorus and nitrogen, or silica-nitrogen limited (Figure 16A). In contrast, 2004 outflow waters were slightly potentially silica-nitrogen limited and there was no co-limitation between phosphorus and nitrogen.

In 2003 and 2004, water temperatures were similar between the inflow and outflow from March through June, but starting in July temperatures gradually increased in the outflow compared with the inflow (Figures 17A and 17B).

Transparency was not measured in this study. Secchi depth measured by the Michigan Department of Environmental Quality (MDEQ) from 1998-2003 averaged 0.68 m. The compensation point depth above which net algal photosynthesis could occur was thus approximately twice this, or 1.37 m. The mean depth of Lake Allegan is 1.80 m and the maximum depth is 7 m. Sufficient light to support algal growth could therefore penetrate 76 % of the water column.

The total suspended solid concentrations were generally higher in the outflow than the inflow (Figures 18A and 18 B). There was no consistent difference in 2004. The particulate matter usually appeared to be mostly algal biomass.

In 2003 and 2004, oxygen concentrations were usually higher in the outflow than in the inflow (Figures 19A and 19B). In 2003, The difference was greatest during May through July (Figure 19A), when the outflow concentrations noticeably increased, but then in August the inflow and outflow concentrations were similar. The outflow was generally supersaturated, especially during June through mid July 2003, and the inflow remained undersaturated (Figure 20A). However, in 2004 the inflow and outflow were undersaturated from March through June, but in mid-July the outflow shifted to supersaturation and inflow generally remained undersaturated (Figure 20B). Very high oxygen superatsauration occurred in the outflow on several dates during the summer, indicating intense algal photosynthesis.

A diel cycle of temperature and dissolved oxygen was measured off the dam on 19-20 August 2003 (Figure 21A) at the depth of 1 m. A vertical profile taken at the beginning showed the water column to be well-mixed. Temperature and oxygen concentrations paralleled each other with the lowest values recorded in the early morning hours, and a gradual increase followed by a peak in the late afternoon and a decline in the evening.

The pH did not change consistently from inflow to outflow but the outflow pH was most often slightly elevated in comparison to inflow pH (Figure 22A). Inflow and outflow pH were similar from March through July 2004 including one sampling date when maximal pH was observed, corresponding with very high oxygen supersaturation (Figure 22B).

Calcium concentrations were lower in the outflow than in the inflow, and from mid-May through August 2003 there was a gradual decline in the outflow calcium concentrations (Figure 23). Likewise, the alkalinity did not change until July 2003 after which a decline in the outflow was observed (Figure 24). The calcite saturation index suggested than calcite potentially precipitated in both the inflow and outflow waters, with calcite saturation in the outflow lower than in the inflow on most dates from June through August (Figure 25).

The reduction in calcium and alkalinity support the conclusion from the calcite saturation index that calcite precipitated as water resided in Lake Allegan

Magnesium (Figure 26), sodium (Figure 27), potassium (Figure 28), chloride (Figure 29), and sulfate (Figure 30) concentrations showed some changes detectably as water passed through Lake Allegan from March through August in both 2003, but these were not large and will not be dealt with in this study.

*Lake Allegan vertical profiles*

Lake Allegan had a well-mixed water column on one date in late summer when thermal stratification would have been maximal. Chlorophyll *a* and total phosphorus concentrations were high throughout the water column (Figure 31). Soluble reactive phosphorus and total soluble phosphorus concentrations were high at the surface, and then high declined throughout the water column (Figure 32). Ammonium and nitrate concentrations were increased slightly with depth in the water column (Figure 33). Concentrations of total soluble and soluble reactive phosphorus as well as ammonium in the reservoir were lower than in inflow waters. Temperatures were uniform from the surface to bottom. Oxygen decreased below 2m (Figure 34). Conductance increased slightly and pH decreased slightly with depth in the water column (Figure 35).

*Morrow Lake*

As in Lake Allegan, the residence time of water in Morrow Lake was long during March 2003, and shorter in April and May. Beginning in June residence time gradually increased (Figure 36A). However, in 2004 the residence time did not change seasonally, but remained low (Figure 36B). Residence time was longer in summer 2003 than in summer 2004.

In 2003 and 2004, chlorophyll *a* concentrations in the Morrow Lake outflow were generally much higher than in the inflow (Figures 37A and 37B).

In the Morrow Lake outflow, concentrations of total soluble phosphorus were usually lower than inflow concentrations during April through July 2003(Figure 38A). However, in 2004 the difference between inflow and was less consistent and a much higher outflow concentrations was recorded on one date in July (Figure 38B).

The total phosphorus concentrations did not change much as water passed through Morrow Lake during March through June 2003, but then after July total phosphorus increased in the outflow relative to the inflow (Figure 39A). In 2004 outflow total phosphorus was lower in concentration on 5 of 7 sampling dates, but much higher on one date in July (Figure 39B). This contrasts with the net phosphorus loss observed in both years in Lake Allegan (Figure 8A). The soluble reactive phosphorus concentrations were consistently lower in the outflow than the inflow in 2003, especially in late summer (Figure 40A). On one date in July 2004 a different pattern was observed with an increase in soluble reactive phosphorus concentrations in the outflow compared to the inflow (Figure 40B); this peak in outflow concentrations corresponded with exceptionally high total and total soluble phosphorus concentrations.

The soluble organic phosphorus concentrations did not change consistently from inflow to outflow in 2003 (Figure 41A). Starting in June 2003 the inflow and outflow concentrations gradually declined approaching zero in July. This pattern was not observed in 2004 when the outflow dissolved organic phosphorus concentrations were always higher than in the inflow (Figure 41B).

Ammonium concentrations were variable but were most often lower in the outflow (Figures 42A and B). From mid July through August 2003 and 2004 there was a larger and more consistent decline in ammonium concentrations. This decline in ammonium contrasts with the increase in ammonium observed in Lake Allegan (Figure 11A). Nitrate concentrations did not change as water passed through Morrow Lake from March through May 2003, but after June there was a consistent decline in nitrate concentrations, reaching nearly zero at the outflow in late July-mid August (Figure 43A). The similar pattern was observed in 2004 except the outflow nitrate concentrations did not reach nearly zero in July and August (Figure 43B).

Silica concentrations did not change from March through June in 2003 and 2004 (Figures 44A and 44B). Starting in July 2003 (Figure 44A) there was a consistent decline in the silica outflow concentrations relative to the inflow. In contrast to 2003, in

2004 outflow concentrations of silica only slightly declined in late summer relative to inflow (Figure 44B).

From March through July of 2003, ratios of available N:P (DIN:TP) indicated that inflow and outflow waters were both potentially phosphorus limited. From mid-July through August 2003 the inflow remained phosphorus limited but the outflow became potentially nitrogen limited (Figure 45A). The pattern was similar in 2004 except the outflow waters were only potentially phosphorus limited in early July and shifted back to potential co-limitation in August (Figure 45B).

In March 2003 diatom growth in both the inflow and outflow waters was potentially silica-limited. Beginning in April, the inflow and outflow waters were potentially nitrogen limited (Figure 46A). In contrast, inflow and outflow waters in 2004 did not showed potential silica limitation only nitrogen limitation (Figure 46B).

In 2003 and 2004, Morrow Lake inflow and outflow waters were mainly potentially phosphorus limited or nitrogen limited (Figures 47A and B). This contrast with Lake Allegan where the waters were potentially silica-phosphorus limited and outflow waters were silica-nitrogen limited (Figure 16A).

In 2003 and 2004, water temperatures did not vary from March through June, but starting in July the outflow temperatures increased compared with the inflow (Figures 48A and 48B).

Transparency was not measured in this study. Secchi depth measured by the Michigan Department of Environmental Quality (MDEQ) from 1998-2003 averaged 0.97 m. The compensation point depth was thus approximately twice this, or 1.9 m. The mean depth of Morrow Lake is 1.66 m and the maximum depth is 5 m. Therefore, sufficient light to support algal could penetrate the entire water column.

In 2003, outflow concentrations of total suspended solids were generally higher than the inflow concentrations (Figure 49A). However, in 2004 inflow concentrations were more often higher than in the outflow (Figure 49B).

Oxygen concentrations in 2003 and 2004 were generally higher in the outflow than in the inflow, except early in the Spring (Figures 50A and 50B). Oxygen concentrations started gradually increasing in July 2003 (Figure 50A) and in May 2004 (figure 50B) relative to the inflow. Also in 2003 and 2004, the outflow waters were mainly supersaturated while the inflow waters were undersaturated (Figures 51A and 51B).

A diel cycle of temperature and dissolved oxygen was measured on 23-24 August 2003 along the Indian mound island (located south of the DNR launch site) at the depth of 0.39 m. The surface waters were well-mixed. Temperature and oxygen concentrations parallel each other with the lowest values recorded in the early morning hours, a gradual increase followed by a peak in the late afternoon and a decline in the evening (Figure 52). Oxygen was supersaturated throughout the diel cycle.

The outflow pH was almost always higher than inflow pH in 2003 and 2004 (Figures 53A and 53B), Starting in July 2003, pH gradually increased in the outflow relative to the inflow (Figure 53A). This contrasts with the decrease in outflow pH during the summer of 2003 in Lake Allegan (Figure 22A).

Calcium concentrations did not change as the water passed through Morrow Lake from March through July 2003, but after mid-July there was a decline in the outflow concentrations relative to the inflow (Figure 54). Like calcium, alkalinity did not change until July 2003, after which there was a decline in the outflow (Figure 55). The saturation index suggested that calcite potentially precipitated in the inflow and outflow, with calcite supersaturation in the outflow higher than inflow starting in late May 2003 (Figure 56). In contrast, Lake Allegan had a higher calcite saturation index in the inflow (Figure 25).

Magnesium (Figure 57), sodium (Figure 58) potassium (Figure 59), chloride (Figure 60), and sulfate (Figure 61) concentrations change little as water passed through Morrow Lake from March through August in 2003 and 2004.

*Morrow Pond Vertical Profile*

Morrow Lake had a well-mixed water column on one date in late summer when thermal stratification would have been maximal. Chlorophyll *a* and total phosphorus concentrations were high from the surface to the bottom but were lower than in Lake Allegan (Figure 62). Total soluble phosphorus concentrations were uniform throughout the water column, while soluble reactive phosphorus concentrations were lower at the surface (Figure 63). Ammonium concentrations gradually increased with depth and nitrate concentrations decreased slightly with depth (Figure 64). Compared to the inflow concentrations, the vertical profiles showed considerable production of ammonium and some loss of soluble phosphorus. Temperatures were uniform throughout the water column. Oxygen started to decrease slightly at 5-meter depth (Figure 65). Conductance was uniform and pH decreased with depth in the water column (Figure 66)

*Comparison of P forms above and below each reservoir*

The mean concentration of phosphorus during the 2003 and 2004 sampling periods in Lake Allegan and Morrow Lake inflow and outflow waters are summarized in Figure 67. Particulate phosphorus was calculated as the difference between total and total soluble phosphorus. Particulate phosphorus was the predominant form in all sites.
In 2003 Morrow Lake usually increased in particulate phosphorus from the inflow to the outflow, compared with no change or decrease in Lake Allegan (Figure 67 A). Soluble reactive phosphorus decreased from inflow to outflow in both reservoirs. Soluble organic phosphorus changed less from inflow to outflow. However, in 2004 (Figure 67 B), Morrow Lake did not show as large of an increase in particulate phosphorus from inflow to outflow, and soluble reactive phosphorus did not change from the inflow to the outflow. Lake Allegan decreased in particulate phosphorus and soluble reactive phosphorus from the inflow to the outflow.

**Discussion**

Morrow Lake and Lake Allegan are shallow, well-mixed (non-stratifying), eutrophic reservoirs, with short residence times (less than 11 days for both). Temperatures increased over the summer with the outflow temperature generally slightly warmer than inflow (Figures 17 and 48). Net oxygen production was apparent during the summer, and there is no evidence for persistent thermal stratification or anoxic bottom waters. In the 2004 season (March-September) discharge was higher, and in the 2003 season discharge was lower, than the 72-year annual season mean of 26.3 $m^3$/sec at the Trowbridge gauge (above Lake Allegan) (Figure 2). Lake Allegan always had a higher discharge than Morrow Lake. Due to its larger volume, however, Lake Allegan had a longer residence time than Morrow Lake (Figure 3). My sampling period for both years spanned the typical seasonal variation in discharge and residence time (Figures 2 and 3).

The nutrient concentrations of the Kalamazoo River make these reservoirs eutrophic by Midwestern United States lake standards. There are two substantial wastewater treatment plants that influence my sampling reach. The Battle Creek wastewater plant is 23 km upstream of the Morrow Lake inflow sampling location and the Kalamazoo wastewater treatment plant is 10 km downstream of the Morrow Lake outflow sampling location and 63 km above Lake Allegan. These effluents together with a number of industrial effluents that are discharged directly into the main channel likely explain the fairly high concentrations of soluble reactive phosphorus concentrations in the river (Figures 9 and 40).

*Comparisons between reservoirs*

During the two summers of sampling, Morrow Lake was a source, while Lake Allegan was a sink, for total phosphorus (Figure 67). In 2003 there consistently tended to be an increase in particulate phosphorus from the inflow to the outflow in Morrow Lake (Figure 67A). The highest total phosphorus concentrations occurred during summer and corresponded with the highest chlorophyll *a* concentrations. Lake Allegan was a sink for total phosphorus mainly during the summer when chlorophyll *a* concentrations were high, perhaps due to phytoplankton sedimentation. Referring to the regression statistics (Table 2), both residence time and total phosphorus are a significant predictors of algal growth in Morrow Lake. It is notable that more light reaches the bottom in Morrow Lake, which could promote the growth of benthic algae. Benthic algal mats uplifted from the bottom were observed during the summer and may be a major source of particulate phosphorus leaving Morrow Lake. During the spring and summer these benthic algal mats grow and once a maximum biomass is achieved, sloughing and lift off can occur (Stevenson 1996). Thus the apparent production of phosphorus in Morrow Lake could actually reflect seasonal uptake followed by release.

Residence time was the only predictor of algal growth in Lake Allegan; total phosphorus was not significant. Lake Allegan's residence time ranged from 3 to 11 days in 2003 (Figure 5A) and 3 to 8 days in 2004 (Figure 5B), depending directly on discharge, since the volume did not change. Chlorophyll *a* concentrations were the highest when residence time was the longest. The 2003 sampling season had higher chlorophyll *a* concentrations compared with 2004 probably because during 2003 discharge was lower and residence time was longer (Figures 6A and B). In 2004, the longest residence time in Lake Allegan was eight days, compared with 11 days in 2003. Residence times of around seven days or less limit phytoplankton production and species composition (Thornton 1980). Dickman's 1969 study of Marion Lake concluded that short residence times (less than 2.5 days) greatly reduced phytoplankton by flushing them via an outlet. Morrow Lake's residence time ranged from 2-7 days in 2003 (Figure 37A) and 2-5 days in 2004 (Figure 37B). Phytoplankton growth was thus likely to always be restricted by residence time. Compared to Lake Allegan, phytoplankton in Morrow Lake was more often flushed from the system before populations could accumulate. Benthic algal growth is not dependent upon residence time, but is controlled by light and nutrients. Since the phytoplankton is more often flushed from Morrow Lake perhaps, shading is prevented and more light is able to reach the lake bottom, allowing more benthic algal growth. In Lake Allegan phytoplankton may be the dominant form of algae, while in Morrow Lake benthic algae may be more important due to its shallower depth and higher flushing rate.

In the summer when algal growth was the highest in both reservoirs, nutrient concentrations changed from the inflow to the outflow. Morrow Lake was a variable either a sink or source for ammonium while Lake Allegan produced ammonium at least in the summer. Nitrate concentrations declined by the outflow in both reservoirs during the summer. However, in Morrow Lake nitrate concentrations approached zero in late summer (Figure 43), while in Lake Allegan they did not fall as far (Figure 12). Morrow Lake's very low summer nitrate concentrations may have resulted from benthic algal uptake as well as denitrification. Lake Allegan's ammonium source may be from sediment mineralization of organic nitrogen and its low nitrate concentrations may have resulted from phytoplankton uptake and well as denitrification.

Nutrient ratios show that both reservoirs are potentially nitrogen and phosphorus limited during the summer, but there was a difference in the degree of limitation (Figures 14 and 45). The greater degree of potential nitrogen limitation in Morrow Lake could have been caused by ammonium and nitrate uptake by benthic algae. The Morrow Lake vertical profile showed that ammonium production was greatest at deeper depths (Figure 64). Benthic algae are able to take up nutrients directly from the sediments and from overlying water (Hasson 1988). At the same time in Lake Allegan the potential nitrogen limitation was not as extreme due to ammonium production within the reservoir. Ammonium is preferred over nitrate as a nitrogen source for phytoplankton (Reynolds 1984). Based on N:P ratios, nitrogen was never potentially limiting in the inflow waters of either reservoir, although it was potentially limiting in the outflow waters during late summer.

Lake Allegan has an established phosphorus Total Maximum Daily Load to control algal growth. The undesirable algal blooms reportedly occur during the summer when residence time is longer, and at that time nitrogen limitation may be as or more important than phosphorus limitation. These environmental conditions can promote N-fixing cyanobacteria ("blue-green algae"), which are able to survive in nitrogen limited systems. Cyanobacteria fix atmospheric nitrogen when dissolved inorganic nitrogen concentrations are low, but phosphorus is available. Cyanobacteria take advantage of high phosphorus inputs through the ability to fix nitrogen from the atmosphere; (Schindler 1977). Eutrophic lakes tend to have low TN:TP ratios and are commonly dominated by N-fixing cyanobacteria (Downing 1992). Lake Allegan is classified as a hypereutrophic by USEPA and with average inflow total phosphorus concentrations of 84 μg/L in summer 2003 and 67 μg/L in summer 2004 (from my results).

During the summer, Lake Allegan produced ammonium as indicated by higher concentrations in the outflow than in the inflow. The ammonium is a source of dissolved inorganic nitrogen for algae. The vertical profile did not show an ammonium increase at deeper depths, in contrast to Morrow Lake (Figure 33). I am not aware of any quantitative information on the composition of the phytoplankton in these reservoirs. Lake Allegan's undesirable phytoplankton population could be composed of non N-fixing algae. Blomquist et. al. (1994) hypothesized that dominance by non-nitrogen fixing cyanobacteria depends on the form in which the inorganic nitrogen source is present; when ammonium is present or internally recycled at sufficient rates, phytoplankton growth favors the development of non-nitrogen fixing cyanobacteria. N-fixing cyanobacteria dominate only when both epilimnetic and benthic dissolved inorganic sources are inadequate to meet the demand (Feber 2004).

*The role of Silicon*

Silicon is another element that influences the nature and abundance of phytoplankton. In lakes, silicon concentrations are particularly important for spring diatom blooms. But how important is it for silicon to remain available throughout the summer?

Silicon uptake varied in each reservoir with Lake Allegan having the earliest and most persistent silicon uptake, approaching depletion (Figure 13). However, in Morrow Lake outflow waters silicon depletion did not occur until late summer (Figure 44). In Morrow Lake potential limitation by silicon occurred only in April, presumably when benthic diatom blooms occurred (Figure 46). However, in Lake Allegan silicon limitation occurred twice, first in April with spring diatom blooms and again in July when there were increased chlorophyll *a* concentrations (Figure 15). Diatoms can be silicon-limited when the available Si:N ratio falls below 1:1 (Turner 2003). In July 2003 in Lake Allegan, the Si:N ratio fell below 1:1 at the same time the chlorophyll *a* concentration peaked. One assumption from the silicon depletion hypothesis is that an increase in nutrient loading causes an increase in phytoplankton production, especially in diatoms (Conley 1993). Diatom growth depends on the presence of dissolved silica. When dissolved silica concentrations become limiting relative to N and P availability, other types of algae that do not require dissolved silicon can dominate the phytoplankton community and decrease diatom abundance, and these other algae include noxious bloom-forming species (Turner 2003).

*Ratios of N:TP and Si:N as indicators of potential nutrient limitation*

The N:TP and Si:N ratios are potential predictors of phytoplankton population shifts towards less desirable forms. By combining the two ratios one could predict which nutrients are potentially limiting in a system. Lake Allegan's outflow waters showed potential limitation of algal growth by phosphorus, nitrogen or silicon/nitrogen (Figure 16). Morrow Lake's outflow waters are potentially limited by only nitrogen or phosphorus (Figure 47). Morrow Lake's outflow was never potentially silicon-nitrogen limited. Silica-nitrogen limitation leads cyanobacterial dominance and hence to noxious phytoplankton development. Lake Allegan only showed potential silicon-nitrogen limitation during the summer (Figure 16). It is important to note that nutrients ratios only show the potential for limitation; concentrations may remain above limiting levels and this is often the case in the reservoirs under study here.

*Implications for the TMDL*

The Lake Allegan TMDL is based on the assumption that reducing point and non-point sources of phosphorus would impact the phytoplankton population and reduce harmful algal blooms. The TMDL goal for Lake Allegan is to attain a total phosphorus concentration of 60 μg/L in the inflowing river water. A main conclusion from this study is that Lake Allegan has a residence time that is marginally long enough to permit much algal growth. Nutrient concentrations within Lake Allegan are usually high enough to sustain high concentrations of phytoplankton, and phosphorus concentrations are not the most important factor regulating phytoplankton. Residence time is paramount in limiting phytoplankton biomass in Lake Allegan; nutrients are secondary importance and P, N and Si are each potentially significant. The same conclusion applies to Morrow Lake, where the residence time is even shorter, remaining below the threshold for substantial accumulation of algal biomass for more of the summer.

When residence time is long enough for significant algal growth, nutrients become potential limiting factors. The existing elevated total phosphorus concentrations cause the current low DIN:TP ratio, and by lowering the total phosphorus concentrations, the goal of the TMDL, Lake Allegan may shift toward greater phosphorus limitation. But this does not address the summertime ammonium production, which may be important as a nutrient supply along with total phosphorus for phytoplankton growth, and in turn may lead to silicon depletion. Ammonium and silicon could be important as total phosphorus for controlling Lake Allegan's phytoplankton population.

Morrow Lake and Lake Allegan are spatially separated reservoirs on the same river system. Morrow Lake is imperfect as a reference site to establish the Lake Allegan TMDL parameter goals. Morrow Lake's residence time (less than 8 days) is not sufficient for phytoplankton populations to establish, and benthic algae may be more important due to shallower depth and greater light penetration. The nutrient ratios of Morrow Lake are different during the summer, favoring nitrogen and phosphorus limitation and never silica limitation. Ultimately, residence time is allowing phytoplankton to build up to undesirable levels within Lake Allegan, but not in Morrow Lake. Ammonium, phosphorus and silicon all potentially influence algal abundance and species composition. The internal ammonium source possibly favors for non-N fixing algae and if so, reducing the total phosphorus concentration may not directly affect the trophic state until concentrations reach physiologically limiting levels.

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| | **Morrow Lake** | **Lake Allegan** |
|---|---|---|
| Reservoir Area ($km^2$) | 4.0 | 6.4 |
| Volume ($m^3$) | $7.4x10^6$ | $2.1x10^7$ |
| Mean Depth (m) | 1.85 | 3.3 |
| Maximum Depth (m) | 5.4 | 7 |

Table 1. Morphometric features of Morrow Lake and Lake Allegan.

| | Morrow Lake Outflow Chlorophyll *a* | Lake Allegan Outflow Chlorophyll *a* |
|---|---|---|
| RT | $R^2 = 0.59$<br>$p < 0.01$ | $R^2 = 0.59$<br>$p < 0.01$ |
| Outflow TP | $R^2 = 0.715$<br>$p < 0.01$ | $R^2 = 0.263$<br>$p = 0.061$ |
| RT &TP | $R^2 = 0.77$<br>$p < 0.01$ | $R^2 = 0.75$<br>$p < 0.01$ |

Table 2. Regression coefficients and p-values for residence time (RT) and/or outflow total phosphorus (TP) as predictors of outflow chlorophyll *a* for the spring and summer 2003 sampling period (15 weeks).

| | Morrow Lake Outflow Chlorophyll *a* | Lake Allegan Outflow Chlorophyll *a* |
|---|---|---|
| RT | $R^2 = 0.694$<br>$p = 0.20$ | $R^2 = 0.428$<br>$p = 0.111$ |
| Outflow TP | $R^2 = 0.152$<br>$p = 0.387$ | $R^2 = 0.064$<br>$p = 0.564$ |
| RT &TP | $R^2 = 0.705$<br>$p = 0.087$ | $R^2 = 0.428$<br>$p = 0.327$ |

Table 3. Regression coefficients and p-values for residence time (RT) and/or outflow total phosphorus (TP) as predictors of outflow chlorophyll *a* for the spring and summer 2004 sampling period (7 weeks).

| | Morrow Lake Outflow Chlorophyll *a* | Lake Allegan Outflow Chlorophyll *a* |
|---|---|---|
| RT | $R^2 = 0.533$<br>$p < 0.01$ | $R^2 = 0.602$<br>$p < 0.01$ |
| Outflow TP | $R^2 = 0.652$<br>$p < 0.01$ | $R^2 = 0.368$<br>$p < 0.01$ |
| RT &TP | $R^2 = 0.767$<br>$p < 0.01$ | $R^2 = 0.602$<br>$p < 0.01$ |

Table 4. Regression coefficients and p-values for residence time (RT) and/or outflow total phosphorus (TP) as predictors of outflow chlorophyll *a* for the combined spring and summer 2003 and 2004 sampling periods (22 weeks).

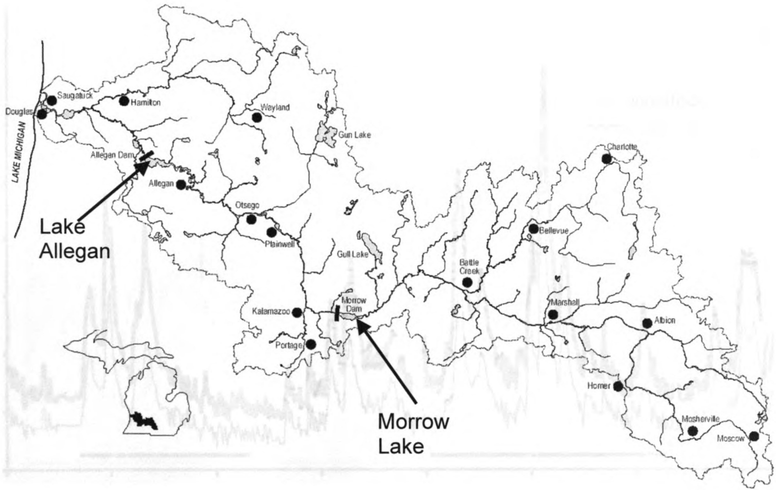



Figure 1. Kalamazoo River and Watershed

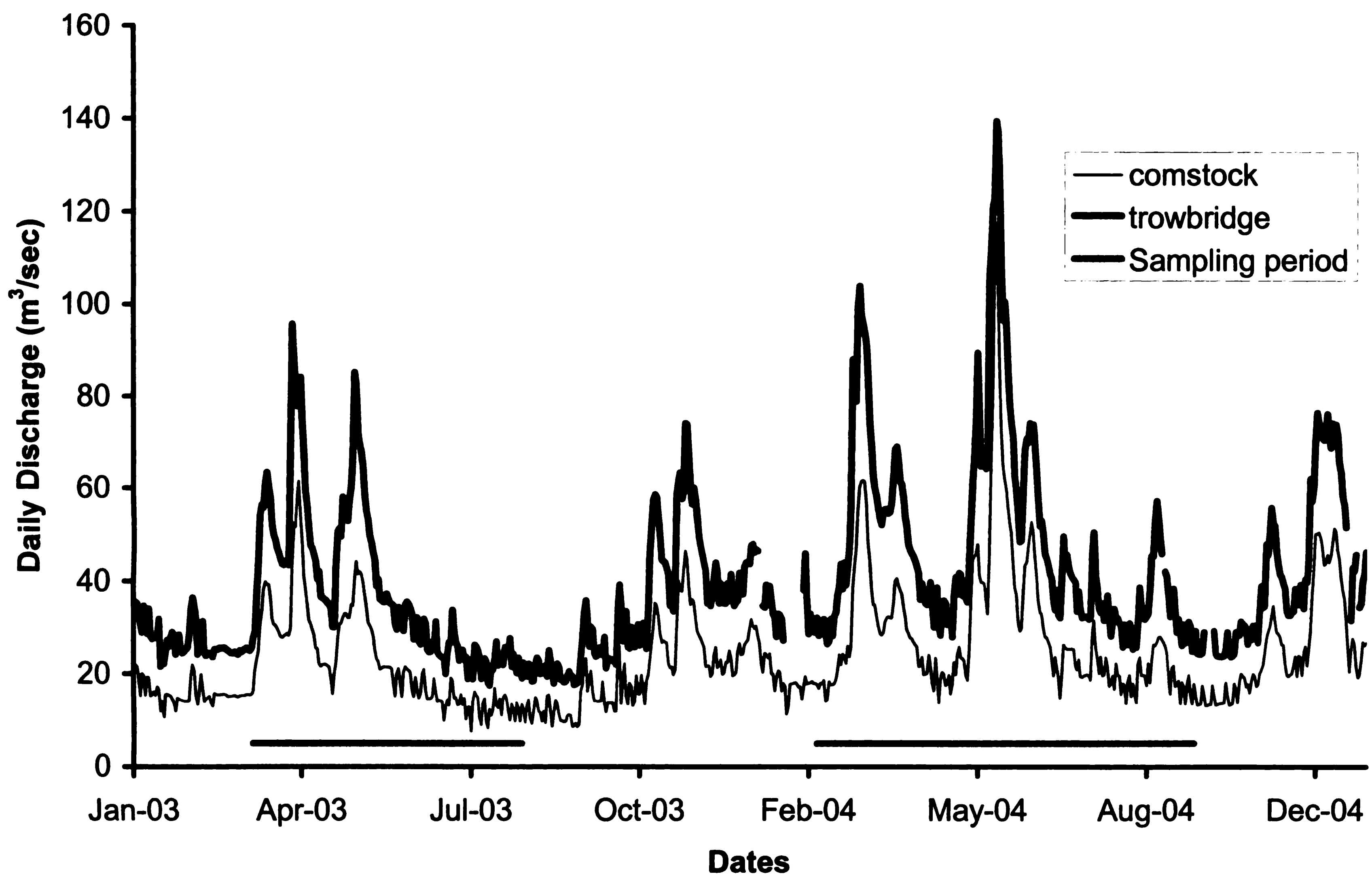



Figure 2. Mean discharge below Morrow Lake (Comstock gauge) and above Lake Allegan (Trowbridge gauge). Data from the U.S. Geological Survey

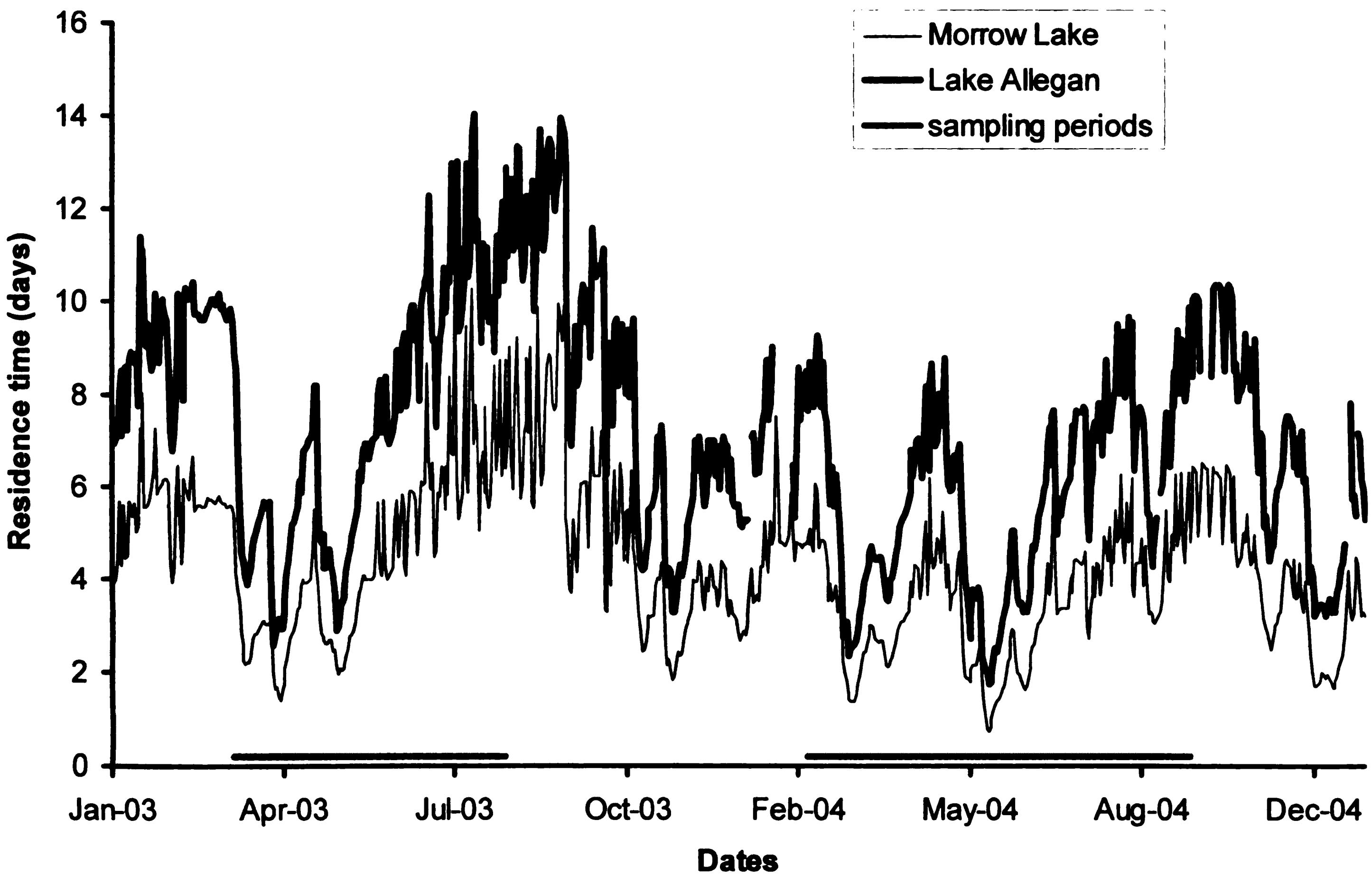



Figure 3. Hydraulic residence time for Morrow Lake and Lake Allegan. Sampling periods are marked along the abscissa.

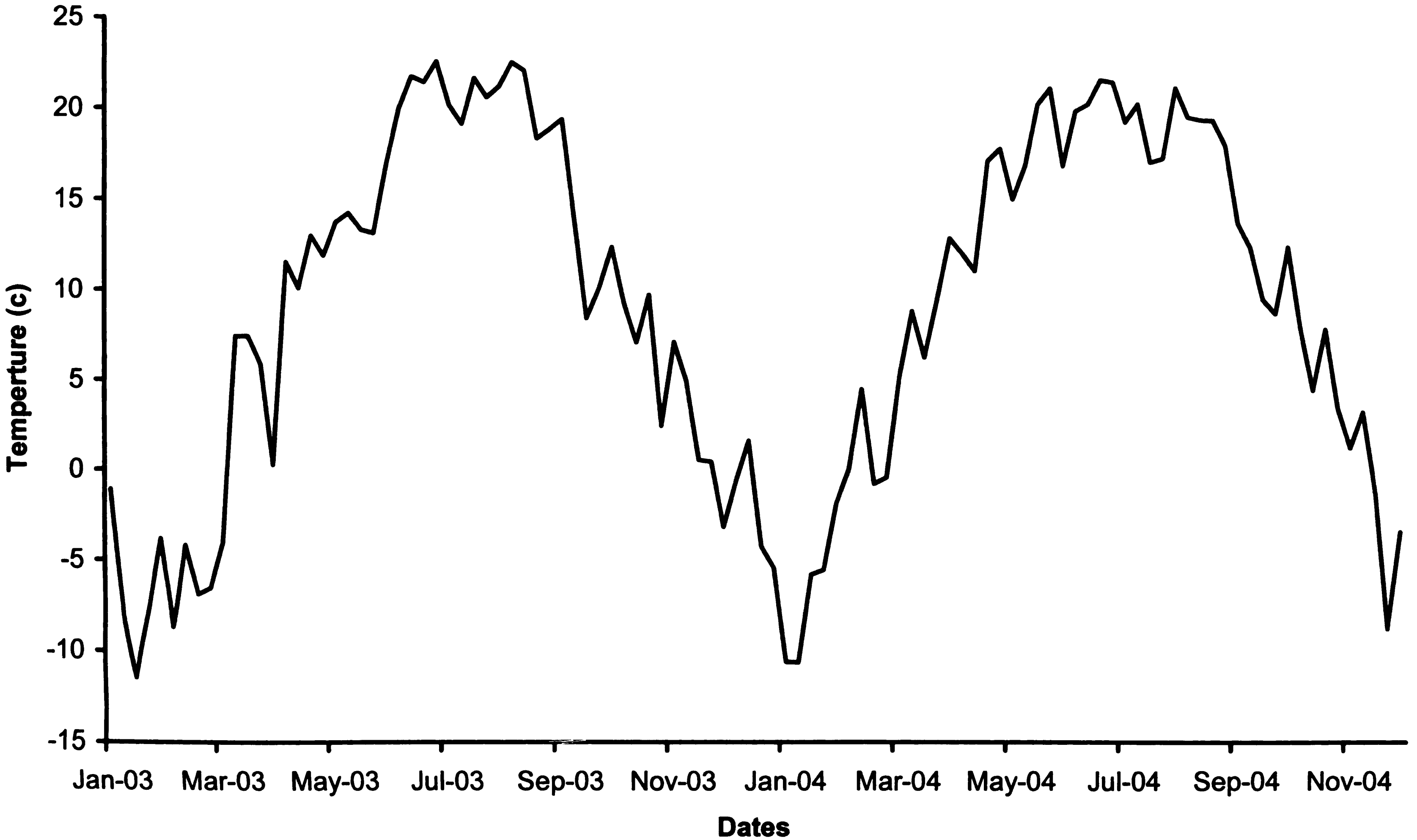
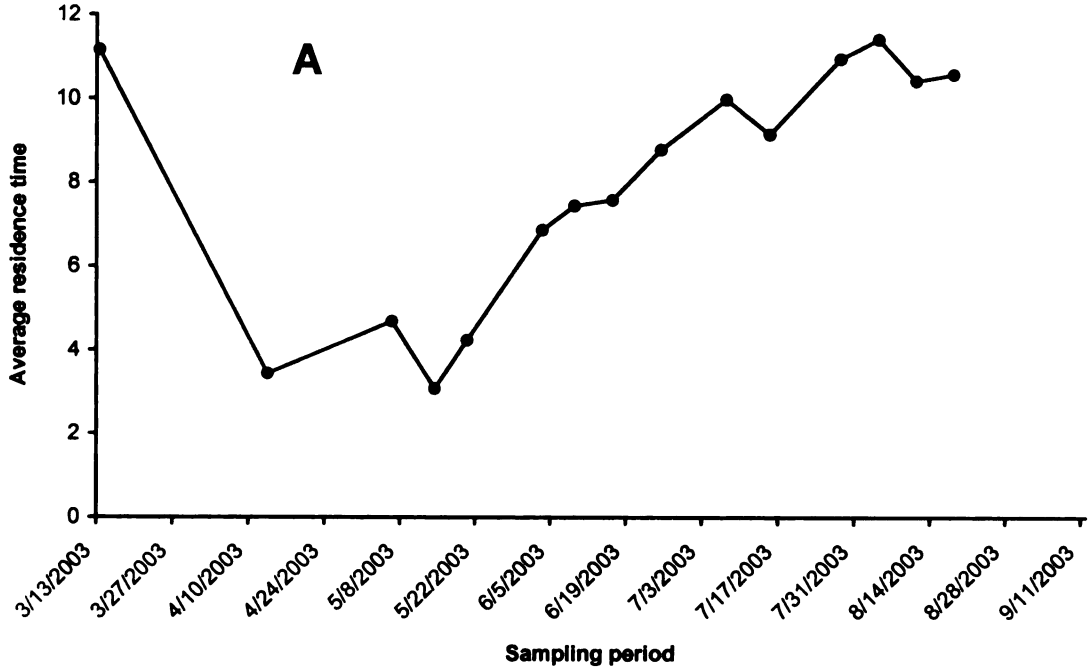



Figure 4. Mean air temperature for 2003 and 2004. Data from Kellogg Biological Station's Long Term Ecological Research Site



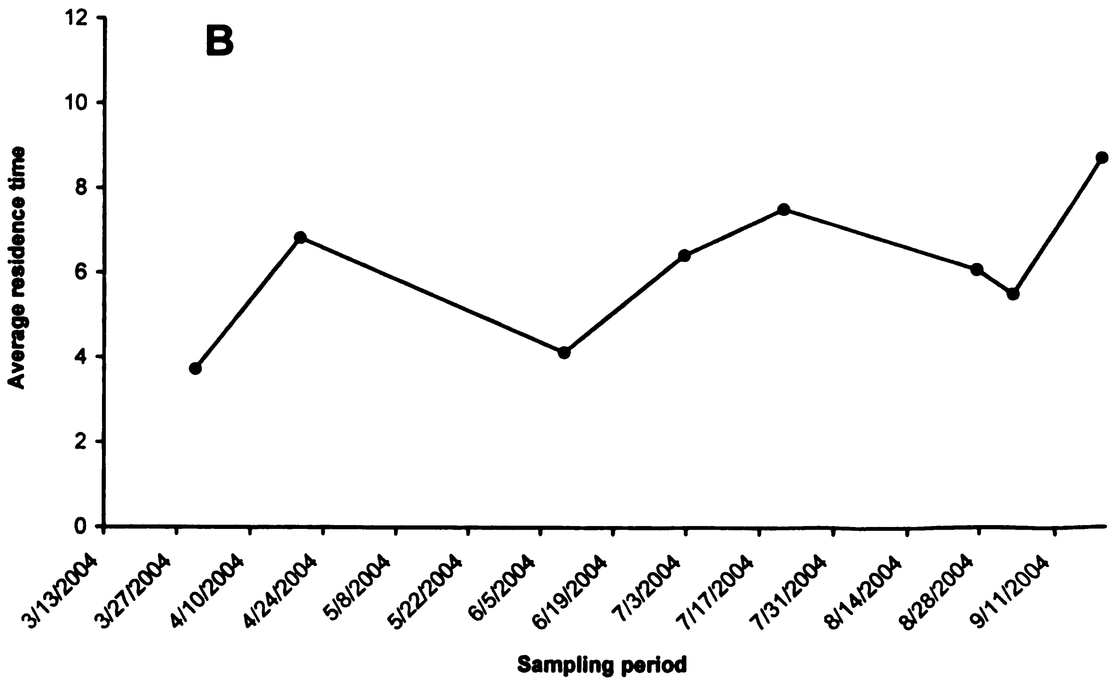




Figure 5. Lake Allegan residence time (days) preceding each sampling date in, A) 2003 and B) 2004.

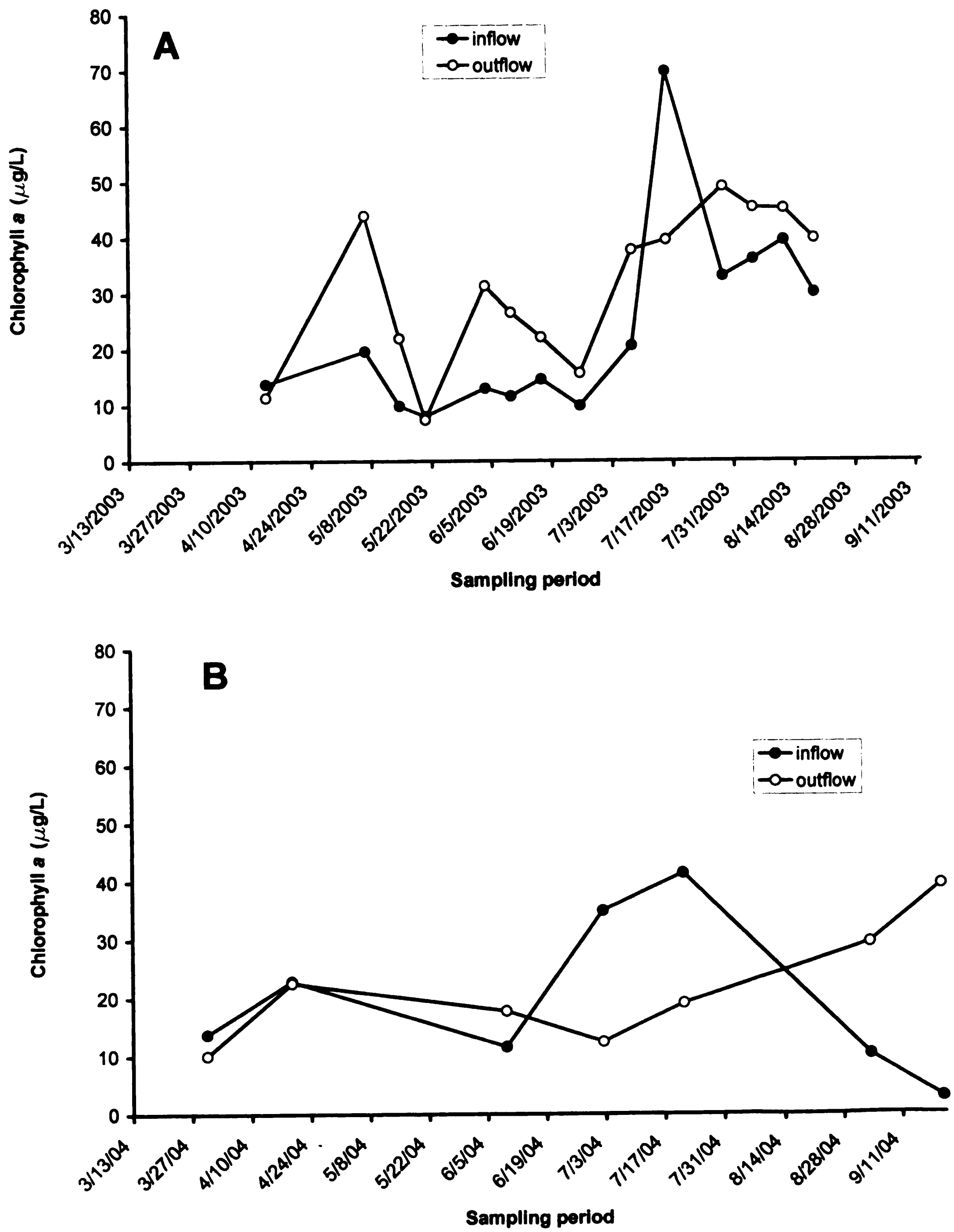
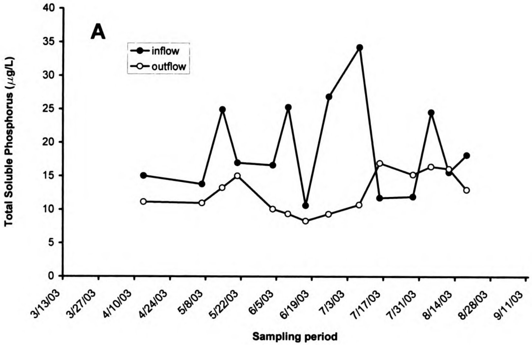



Figure 6. Lake Allegan inflow and outflow chlorophyll *a* concentrations, 2003 and B) 2004



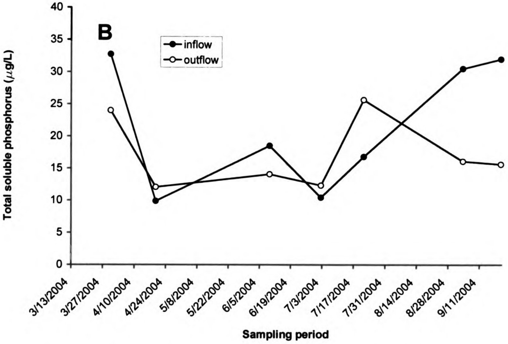
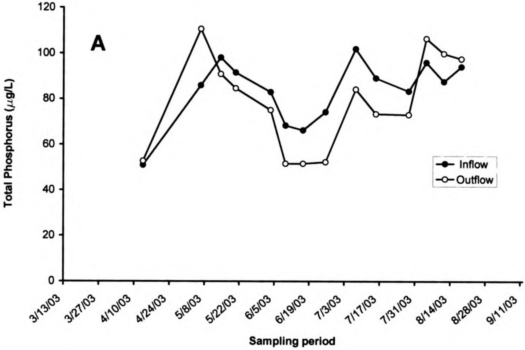




Figure 7. Lake Allegan inflow and outflow total soluble phosphorus concentrations, A) 2003 and B) 2004.



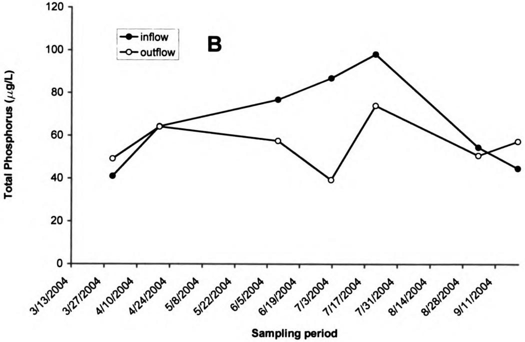




Figure 8. Lake Allegan inflow and outflow total phosphorus concentrations, A) 2003 and B) 2004.

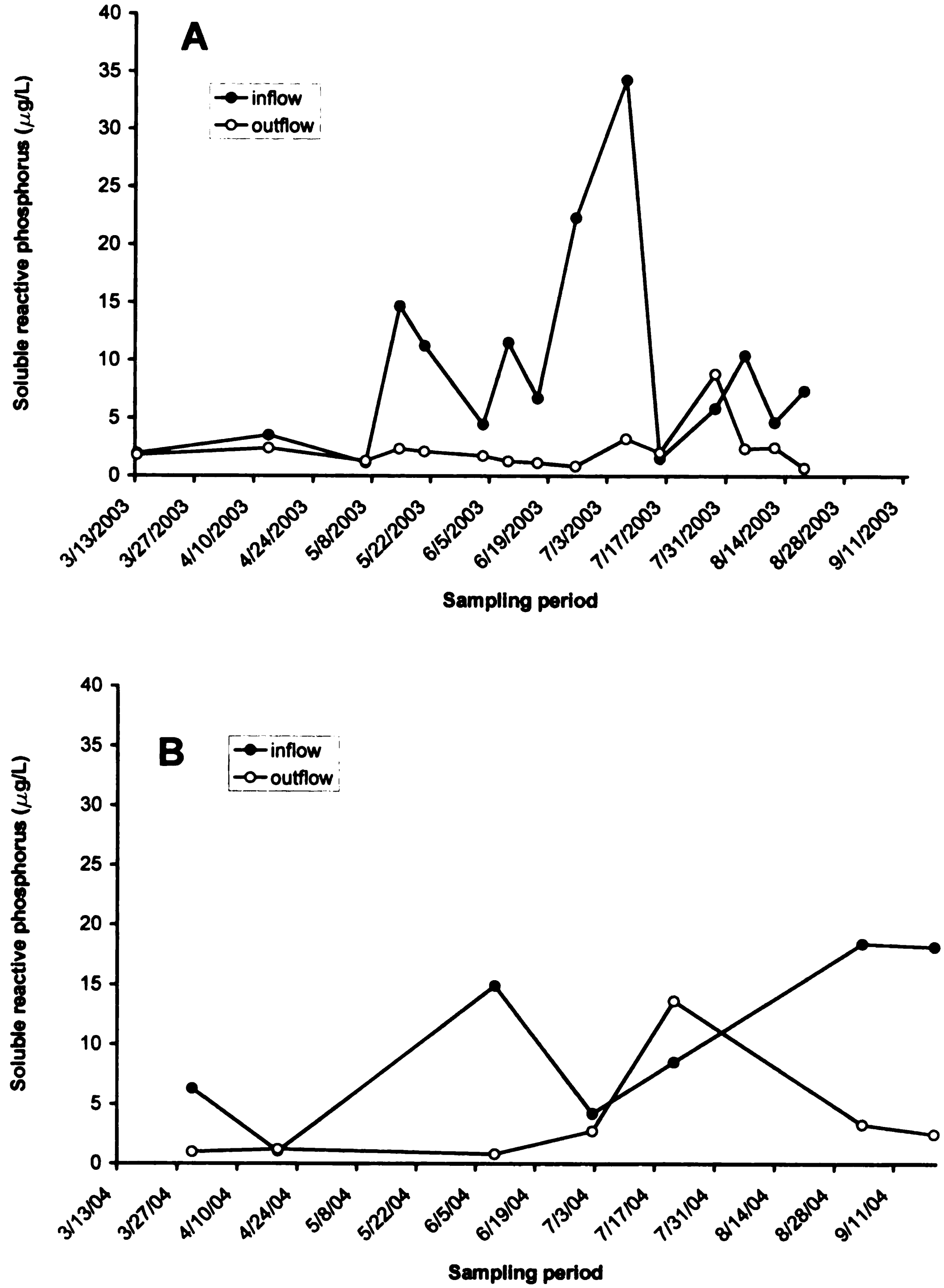



Figure 9. Lake Allegan inflow and outflow concentrations soluble reactive phosphorus, A) 2003 and B) 2004.

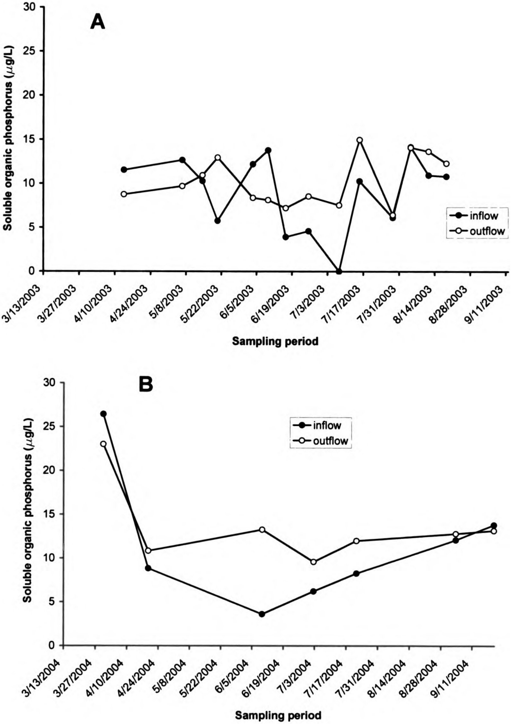
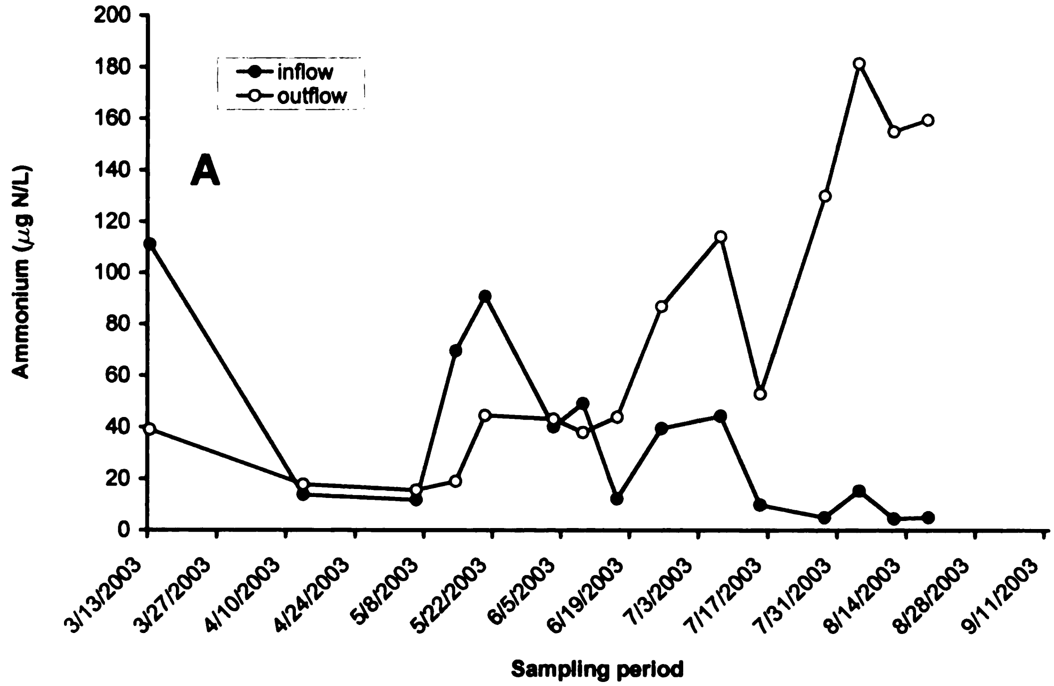



Figure 10. Lake Allegan inflow and outflow soluble organic phosphorus concentrations, A) 2003 and B) 2004.



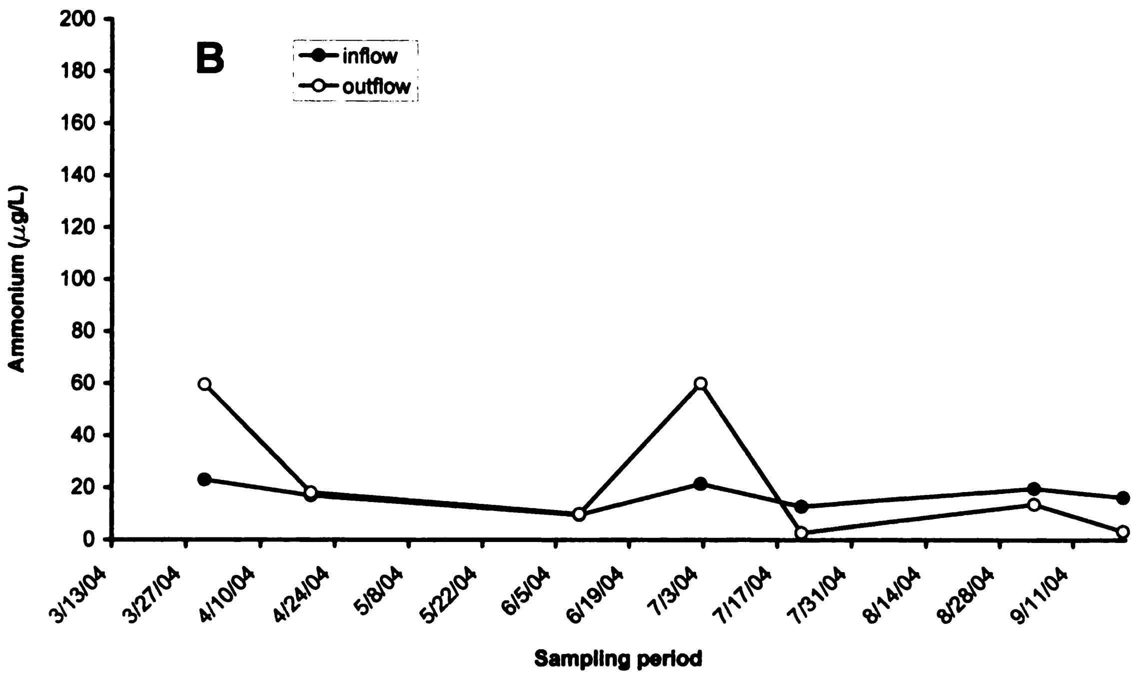
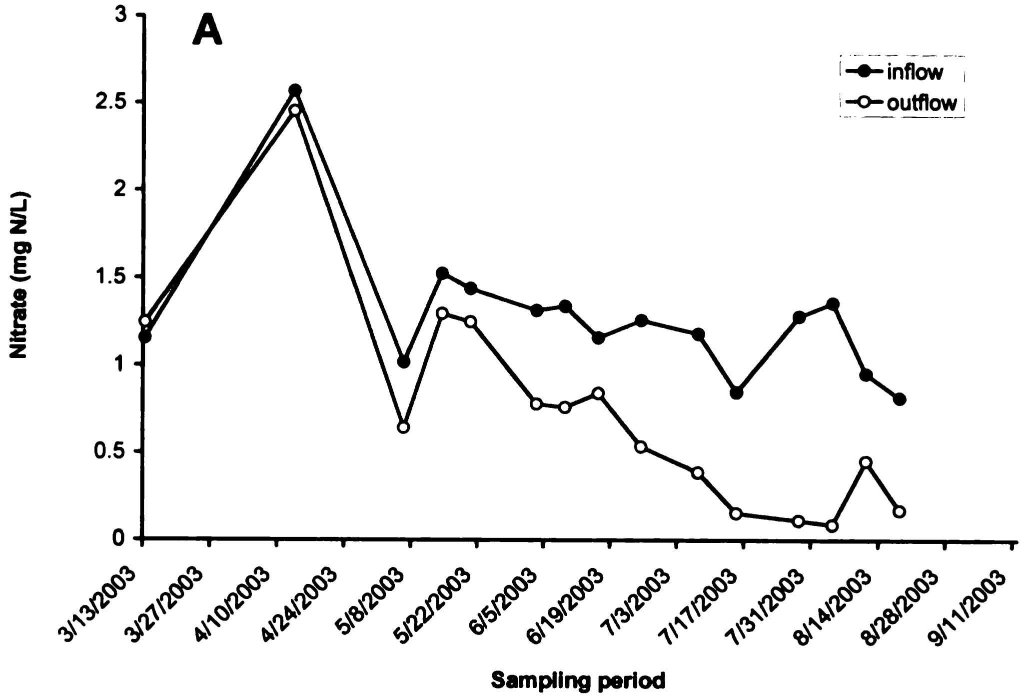




Figure 11. Lake Allegan inflow and outflow ammonium concentrations, A) 2003 and B) 2004.



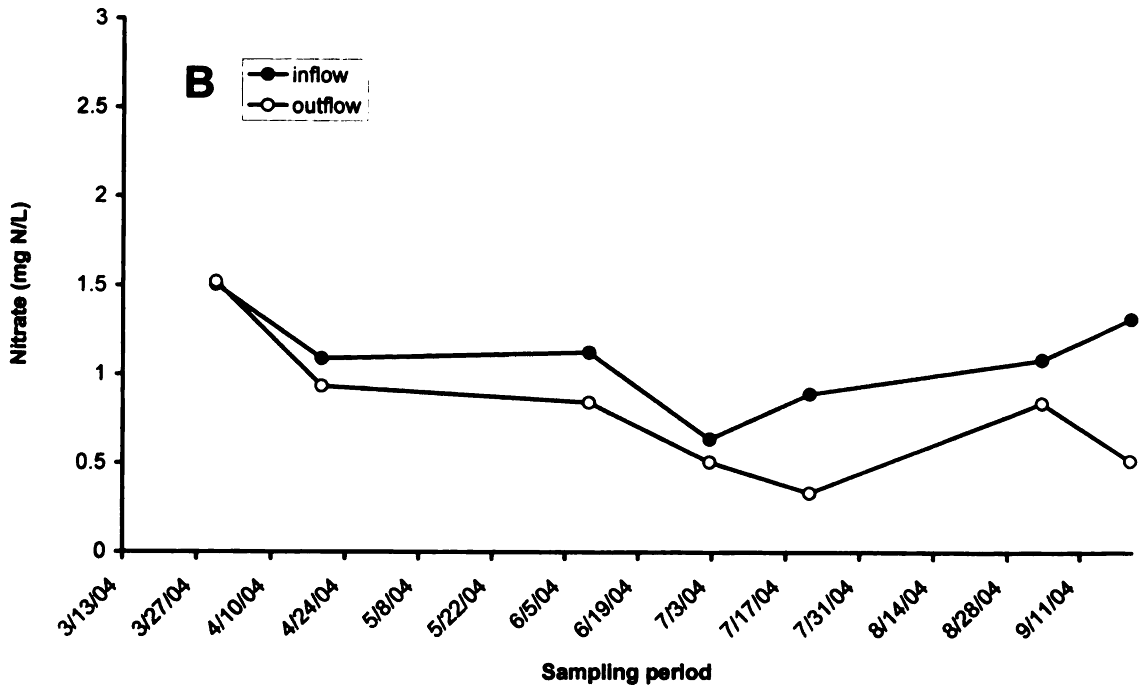
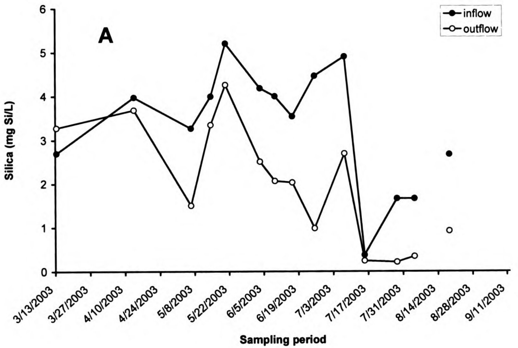




Figure 12. Lake Allegan inflow and outflow nitrate concentrations, A) 2003 and B) 2004.



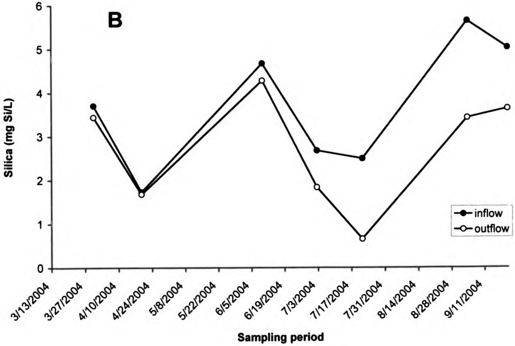




Figure 13. Lake Allegan inflow and outflow silica concentrations, A) 2003 and B) 2004.

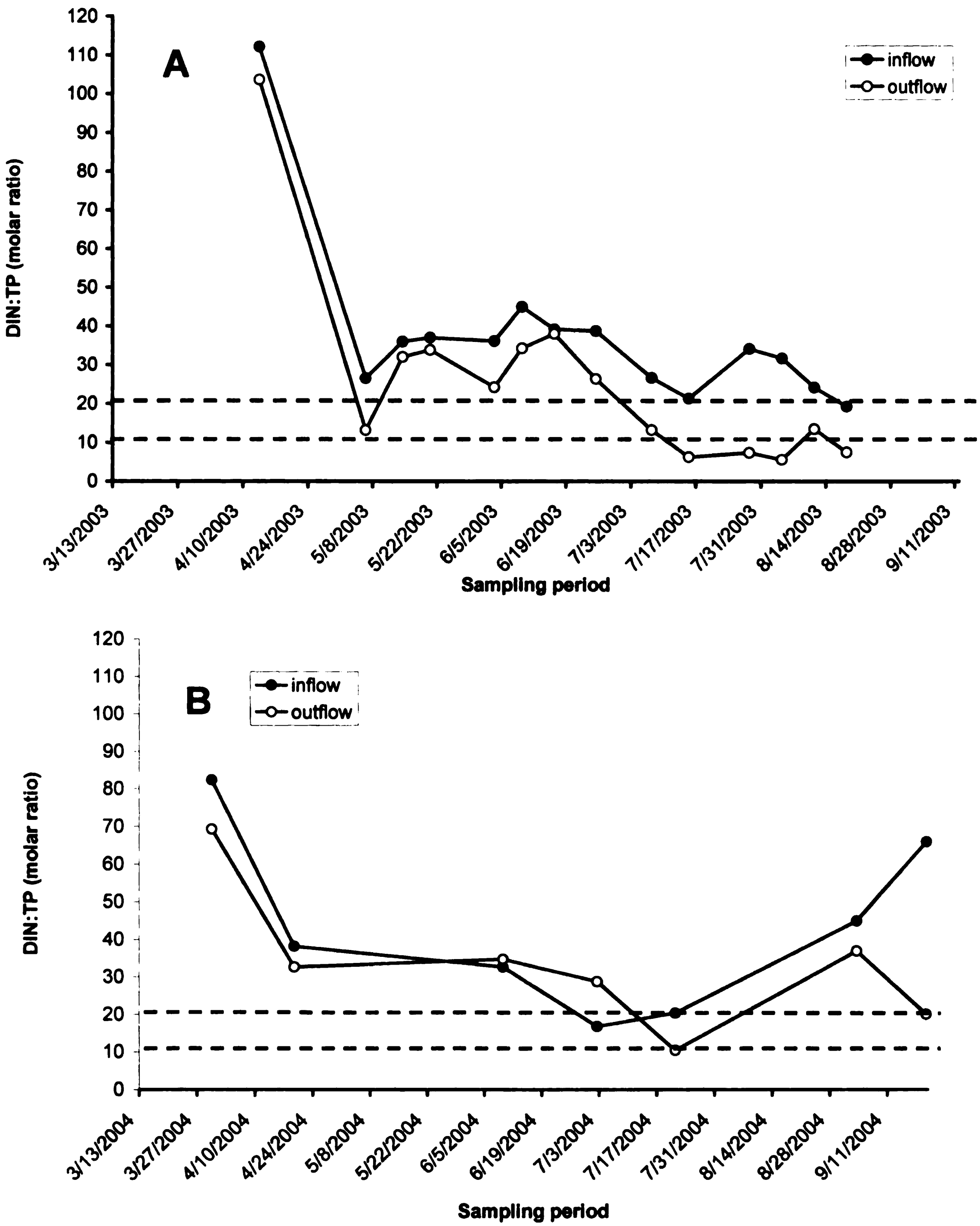
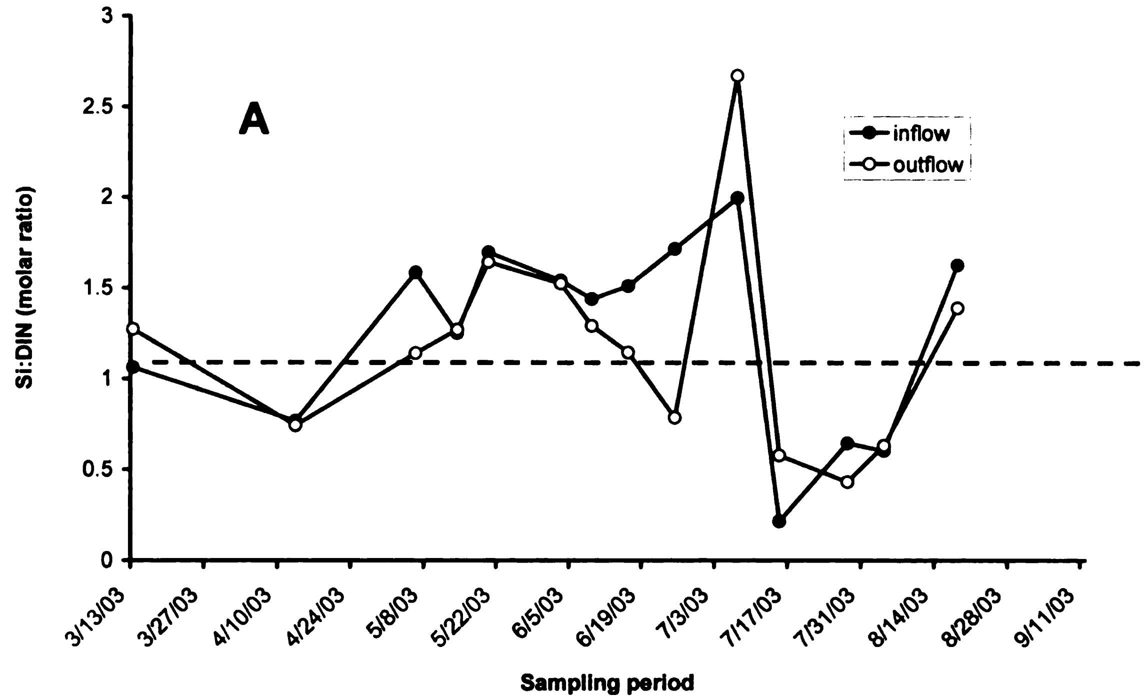



Figure 14. Lake Allegan inflow and outflow dissolved inorganic nitrogen (DIN) to total phosphorus (TP) ratio. Dashed lines show the thresholds of potential nitrogen limitation (DIN:TP less than 10) and phosphorus limitation ( DIN:TP greater than 20), A) 2003 and B) 2004.



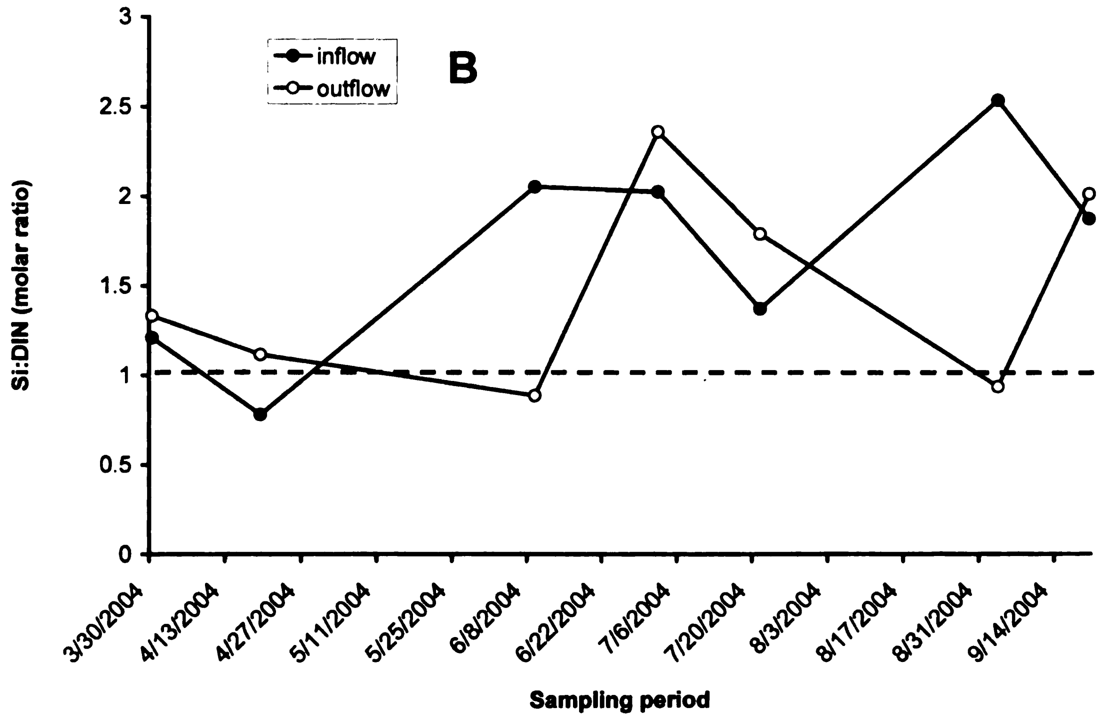




Figure 15. Lake Allegan inflow and outflow silica (Si) to dissolved inorganic nitrogen (DIN) ratio. Dashed line shows the threshold of potential silica limitation (less than 1), A) 2003 and B) 2004.

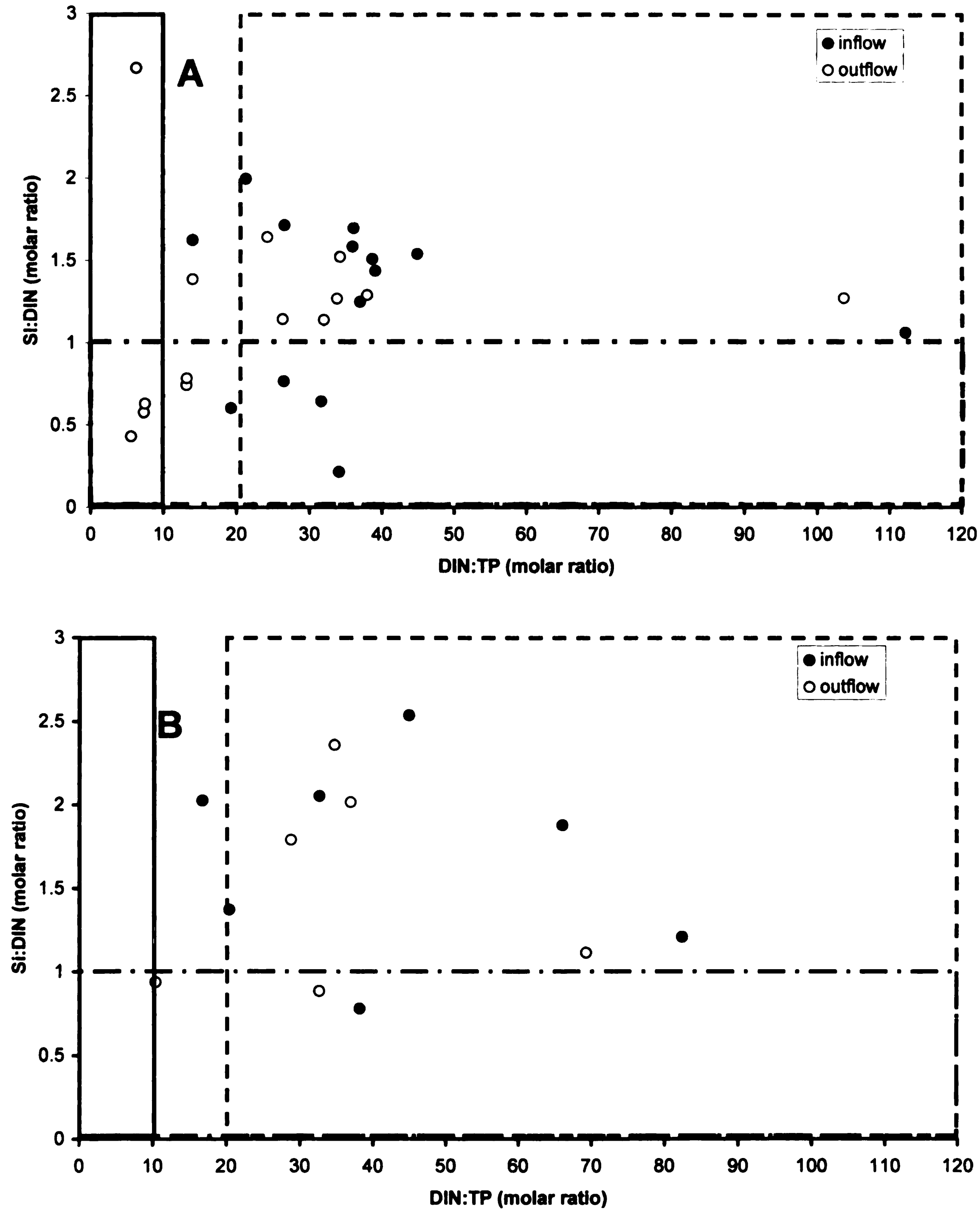
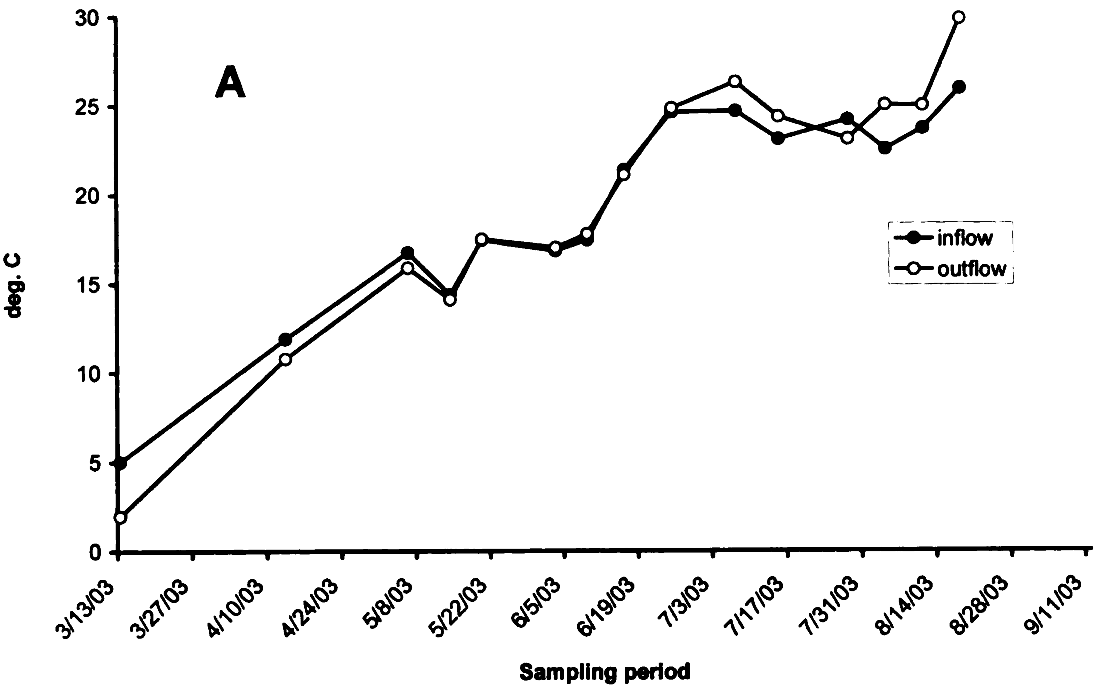



Figure 16. Lake Allegan inflow and outflow dissolved inorganic nitrogen (DIN) and Silica (Si) ratio versus dissolved inorganic nitrogen (DIN) to total phosphorus (TP) ratio. Nitrogen limitation is represented by the solid-line square, phosphorus limitation represented by dashed line, and silica limitation represented by dotted-dashed line, A) 2003 and B) 2004.



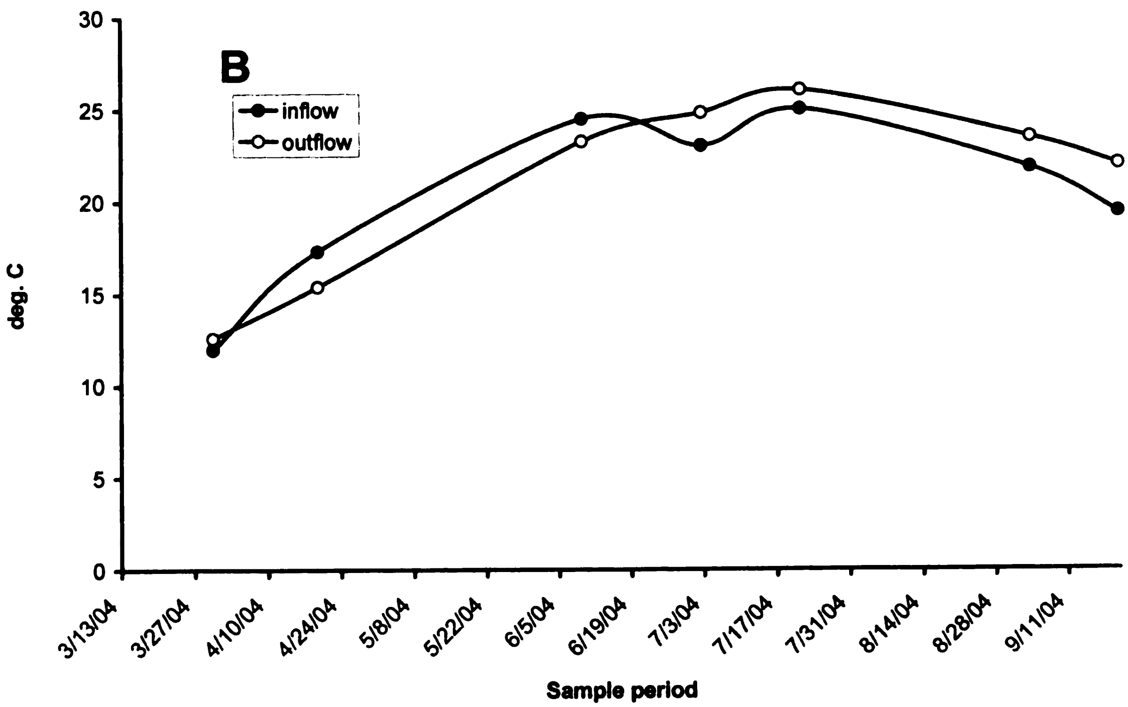
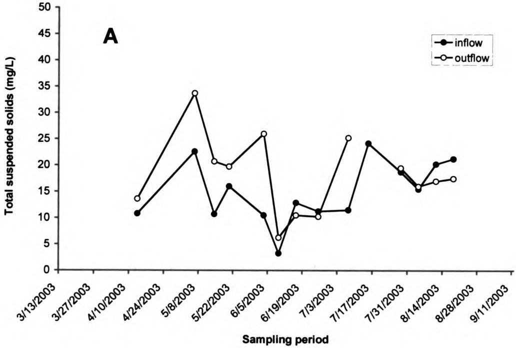




Figure 17. Lake Allegan inflow and outflow temperatures, A) 2003 and B) 2004.



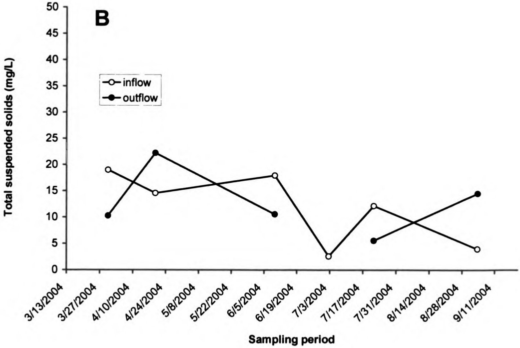
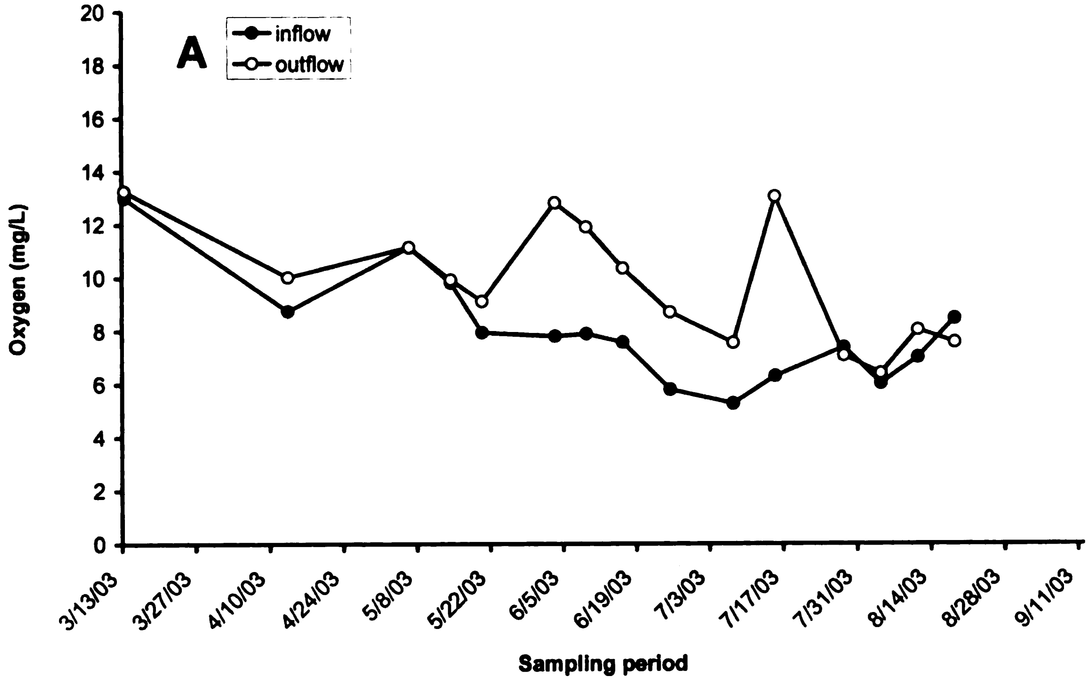




Figure 18. Lake Allegan inflow and outflow total suspended solids concentrations, A) 2003 and B) 2004.



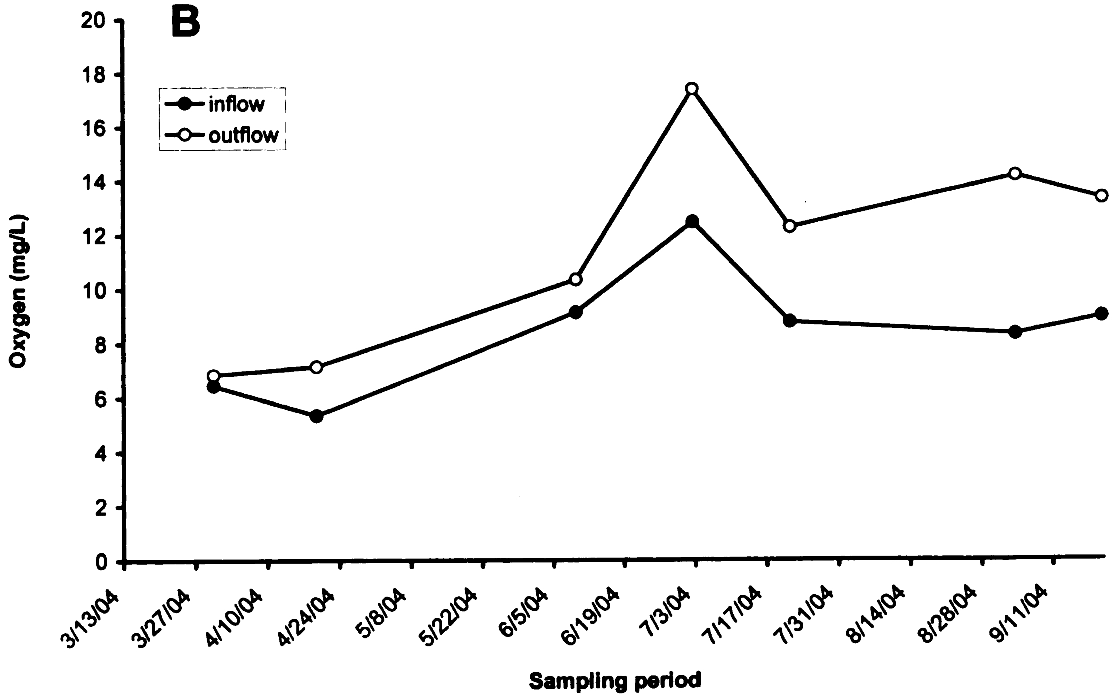
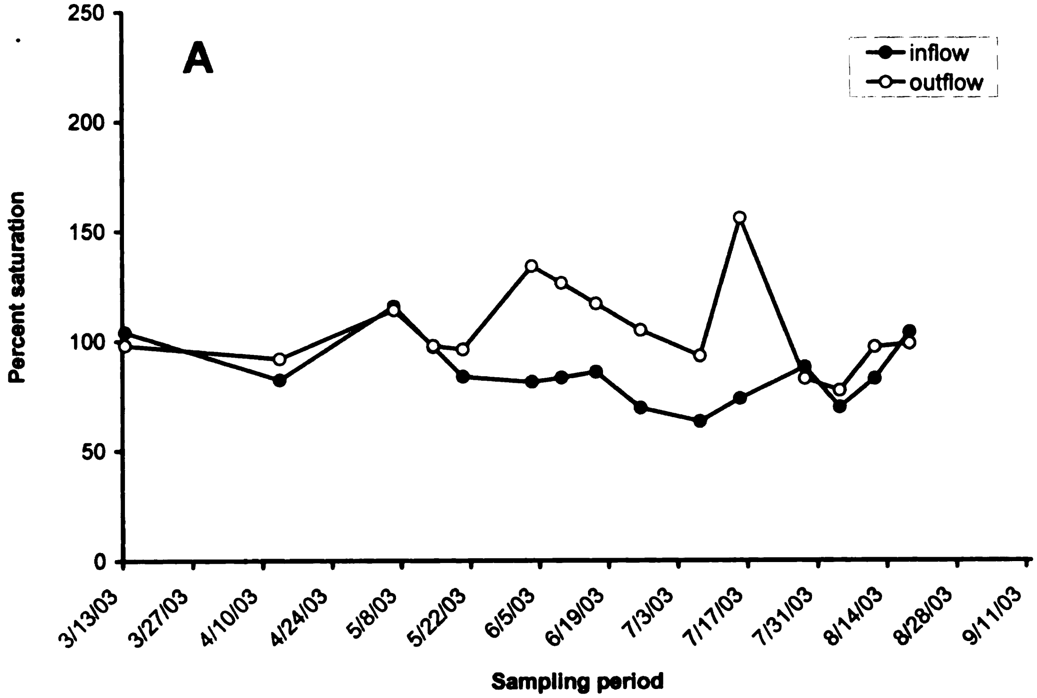
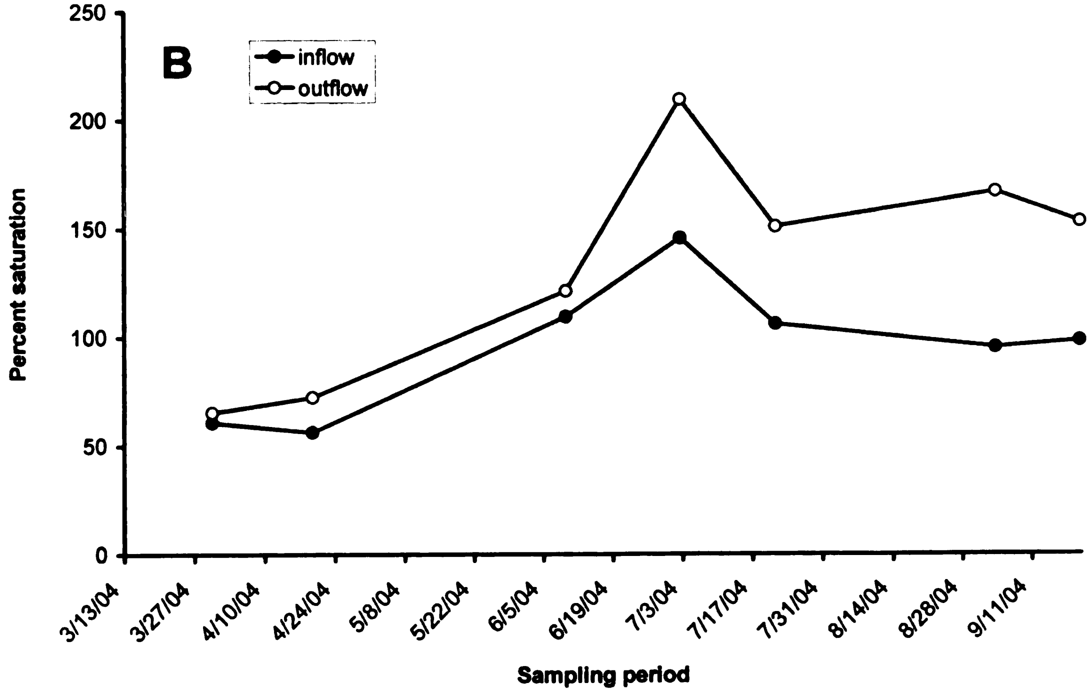




Figure 19 Lake Allegan inflow and outflow oxygen concentrations, A) 2003 and B) 2004.




A) Figure 20. Lake Allegan inflow and outflow percent oxygen saturation, A) 2003 and B) 2004.

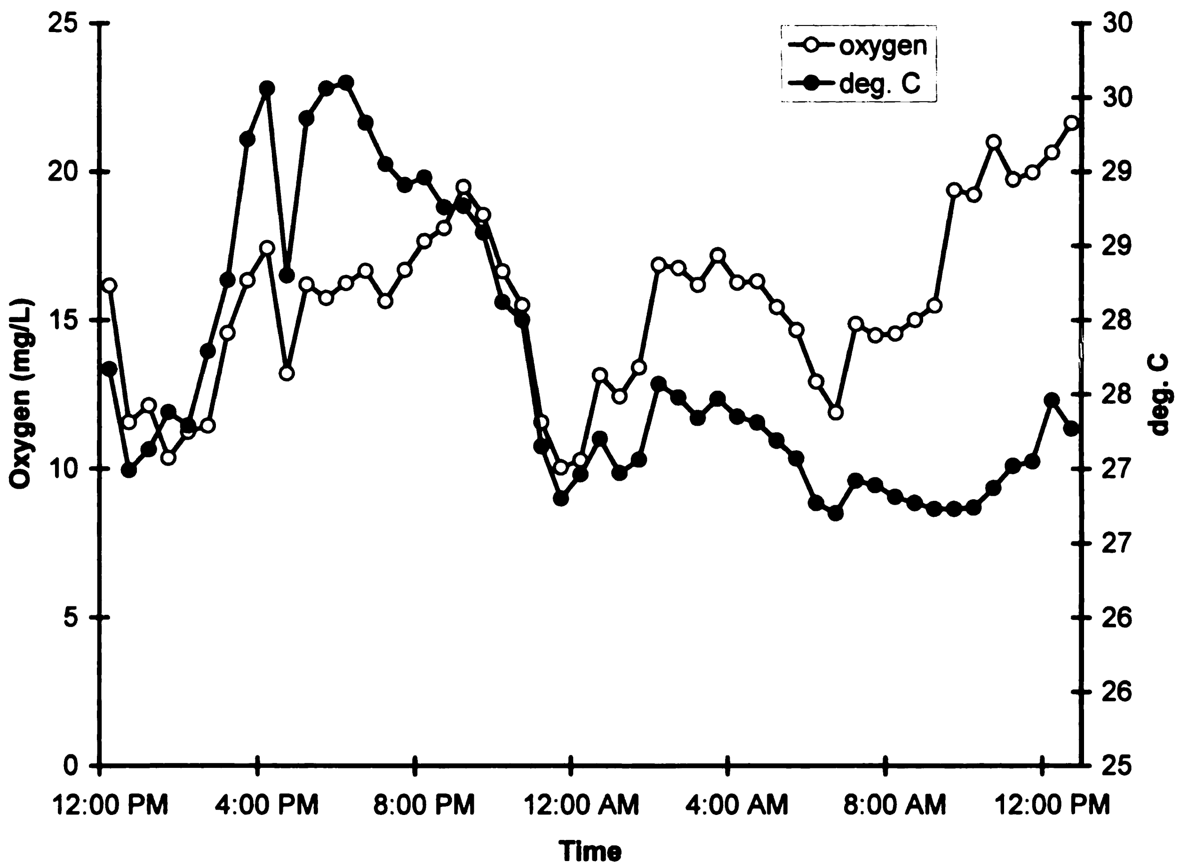
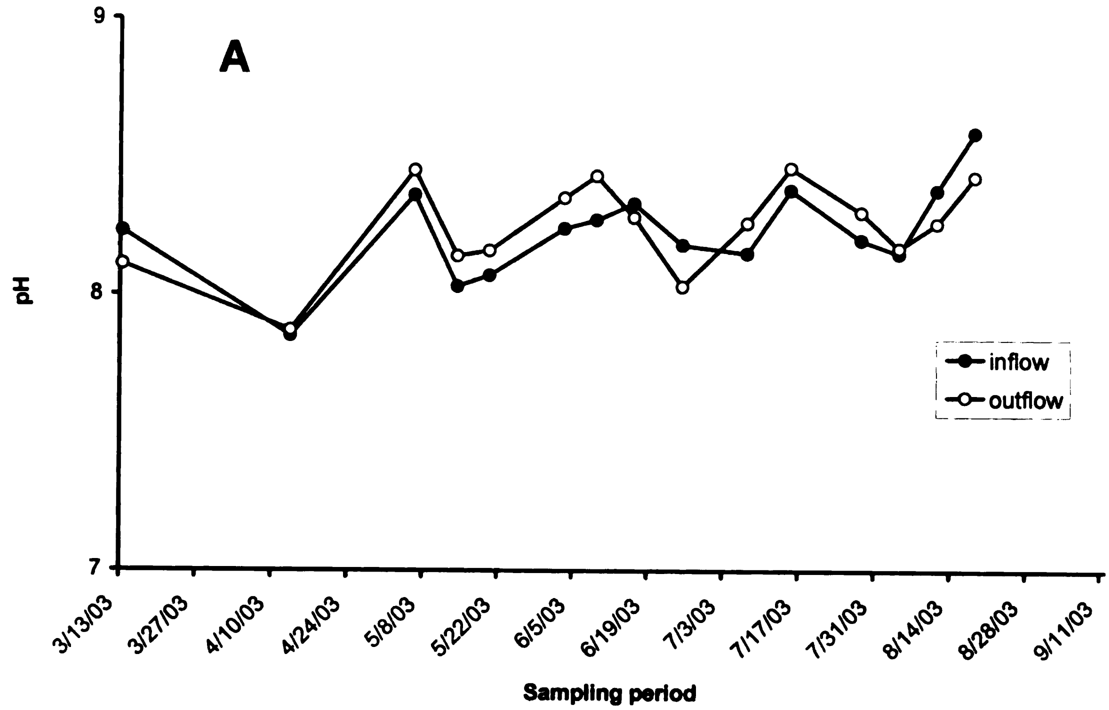



Figure 21. Lake Allegan diel cycle on 8-9 August 2003.



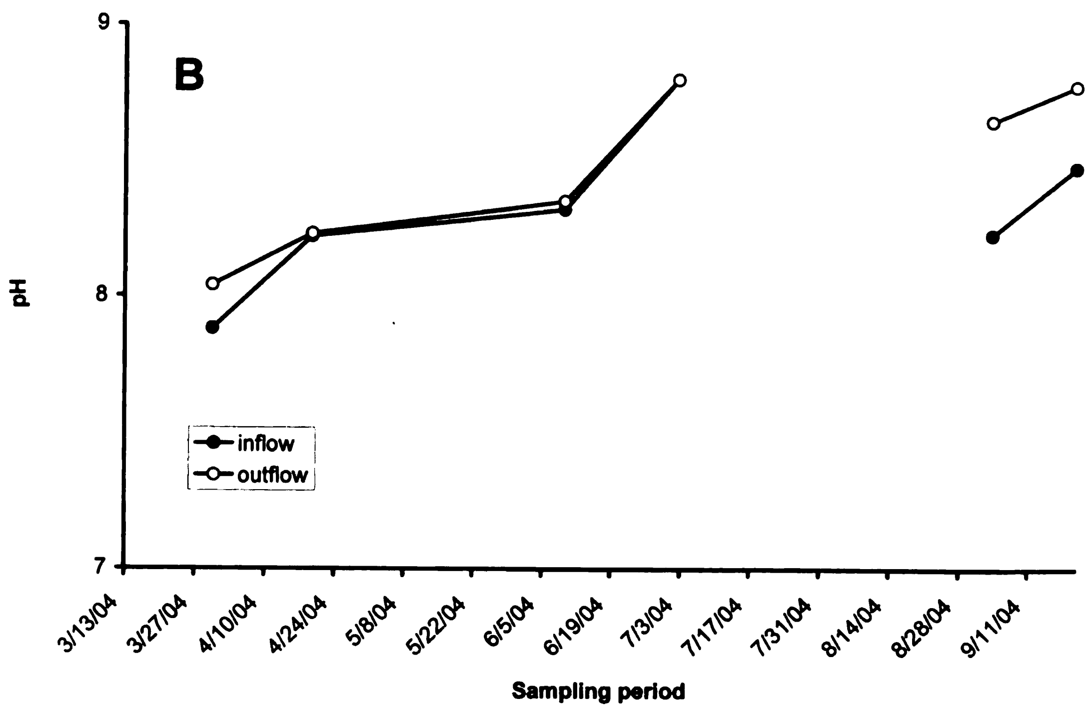




Figure 22. Lake Allegan inflow and outflow pH, A) 2003 and B) 2004.

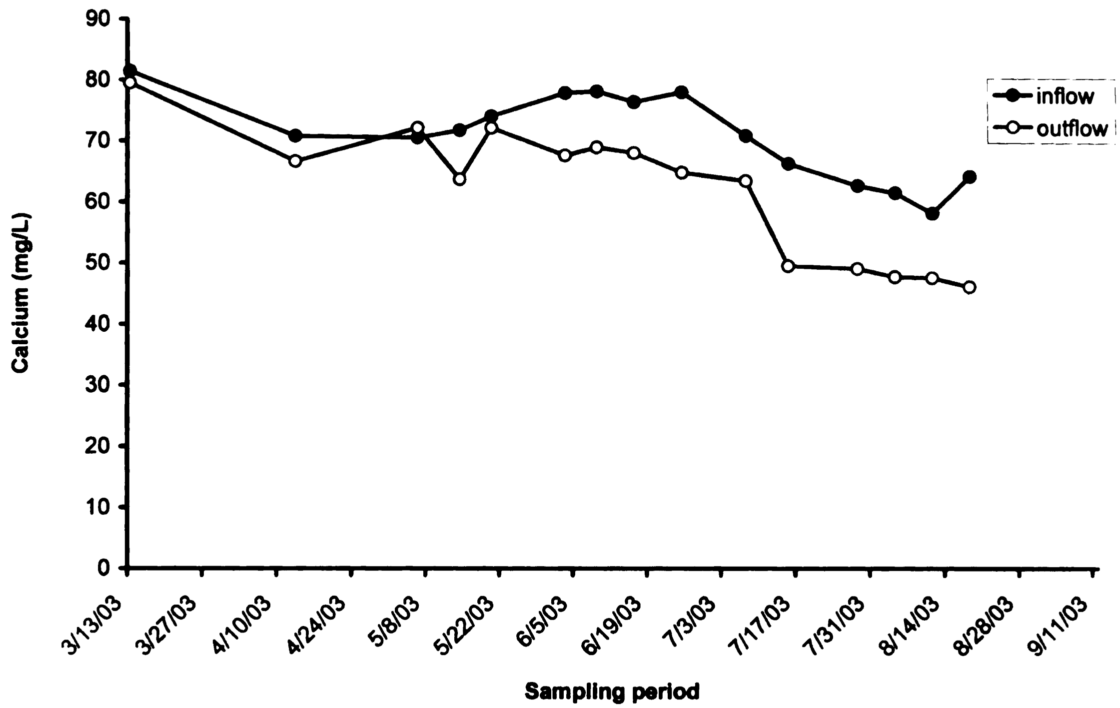



Figure 23. Lake Allegan inflow and outflow calcium concentrations for 2003.

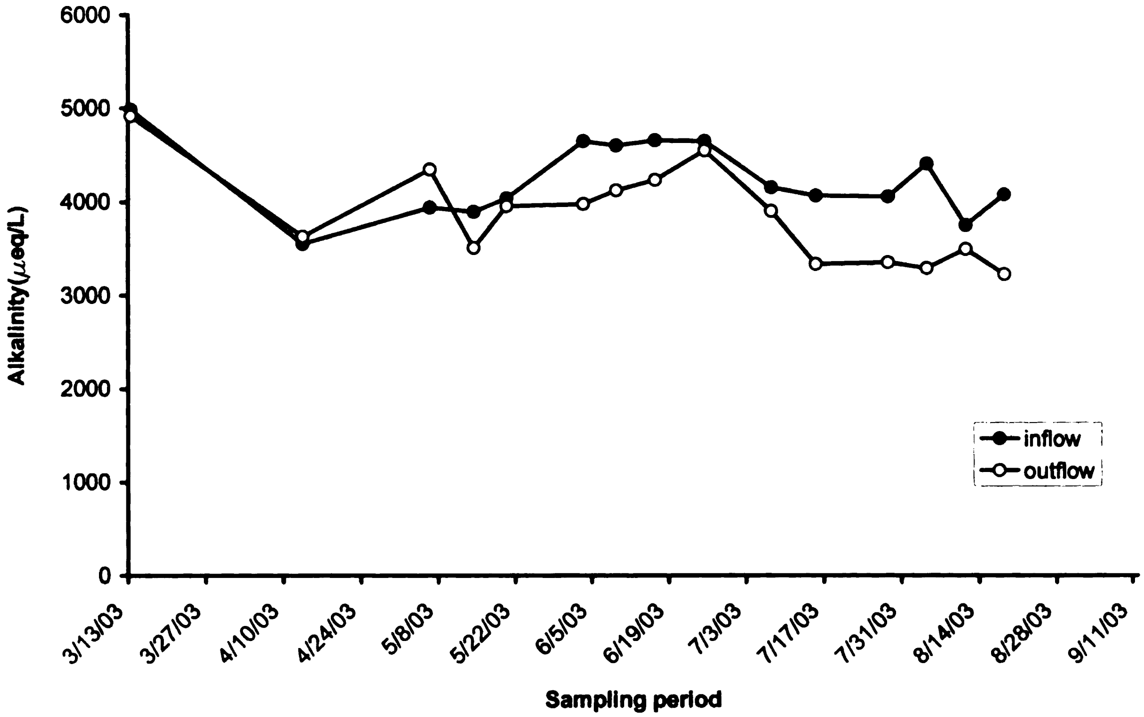



Figure 24. Lake Allegan inflow and outflow alkalinity concentrations for 2003.

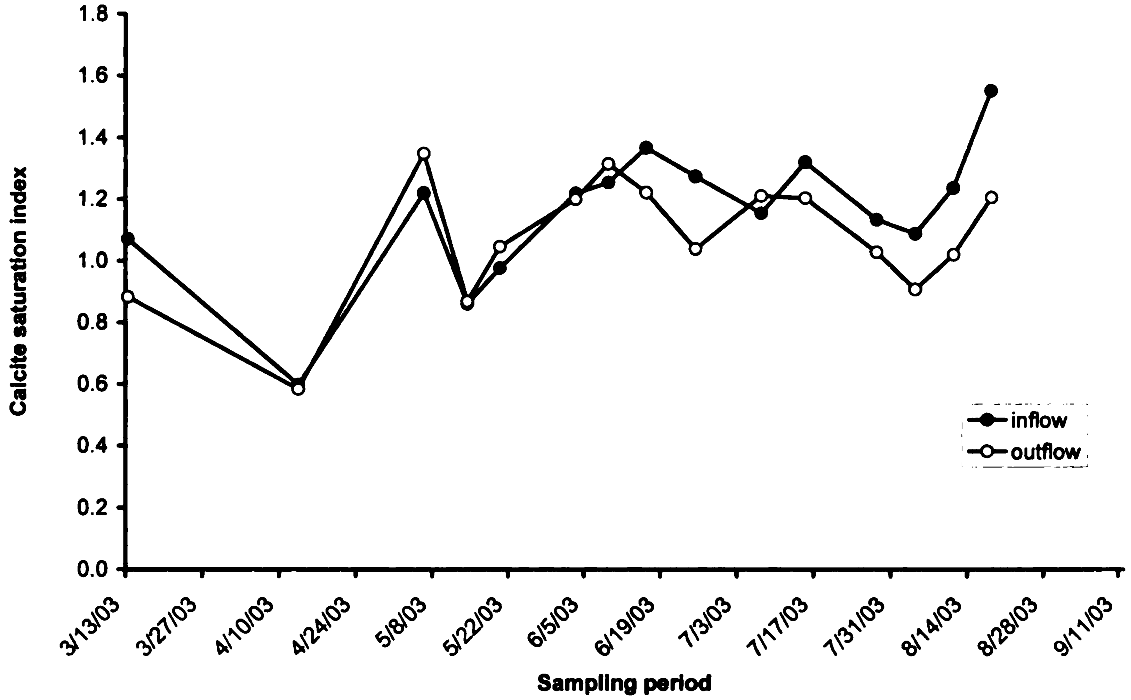



Figure 25. Lake Allegan inflow and outflow calcite saturation index for 2003

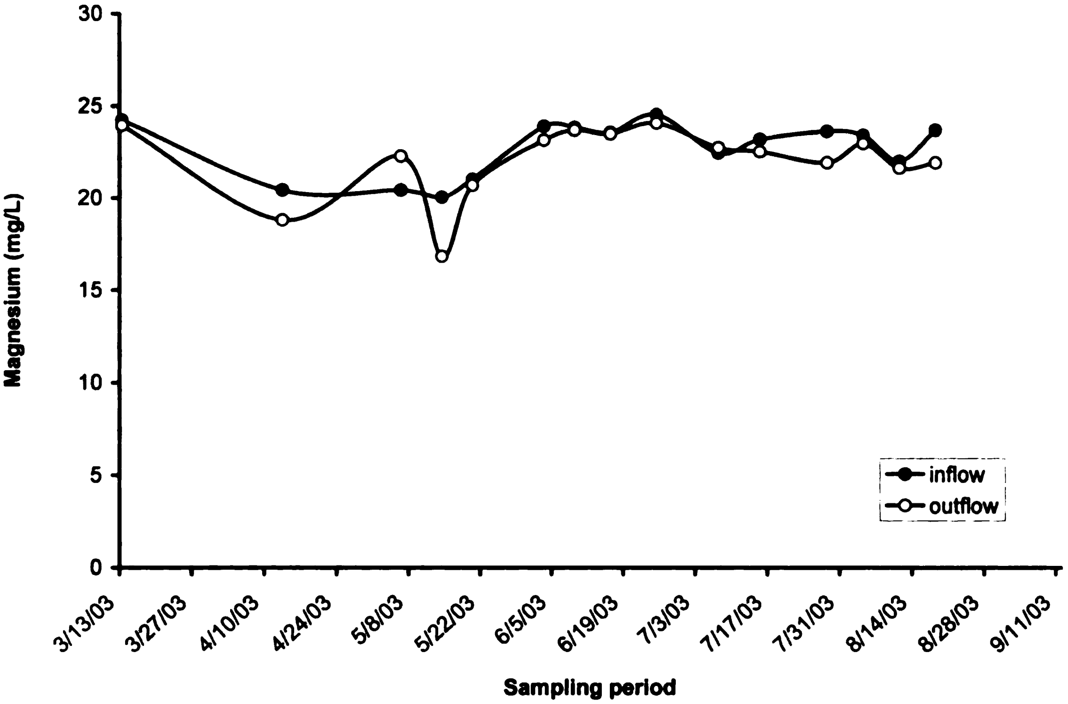



Figure 26. Lake Allegan inflow and outflow magnesium concentrations for 2003.

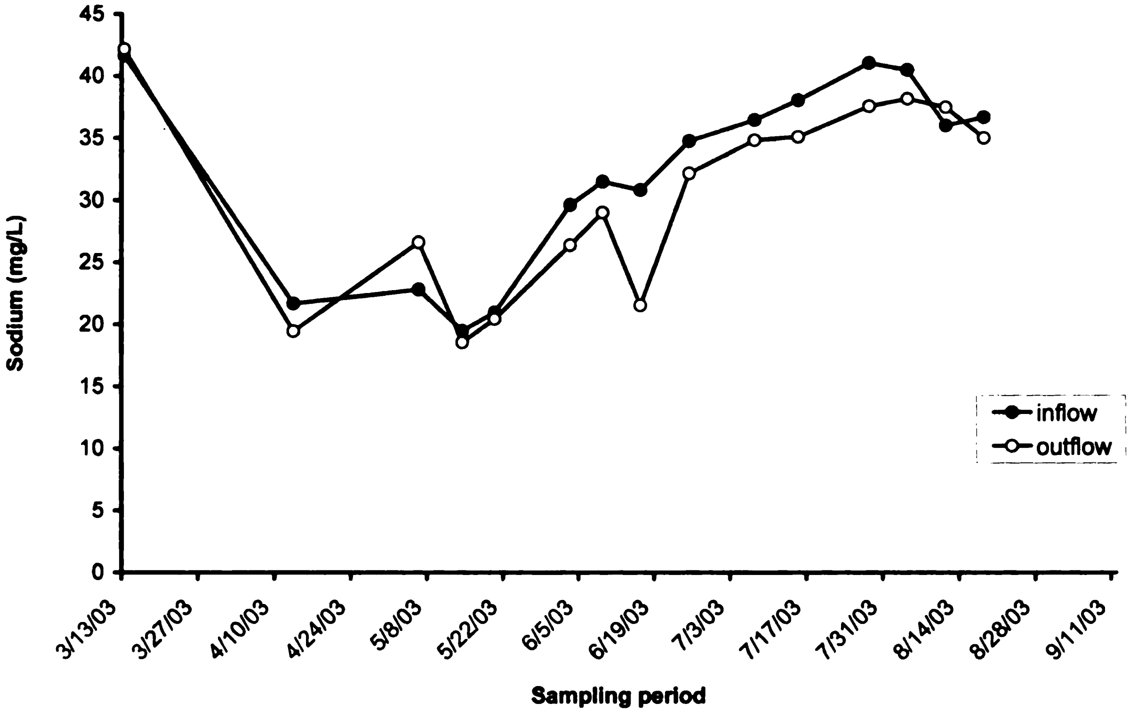



Figure 27. Lake Allegan inflow and outflow sodium concentrations for 2003

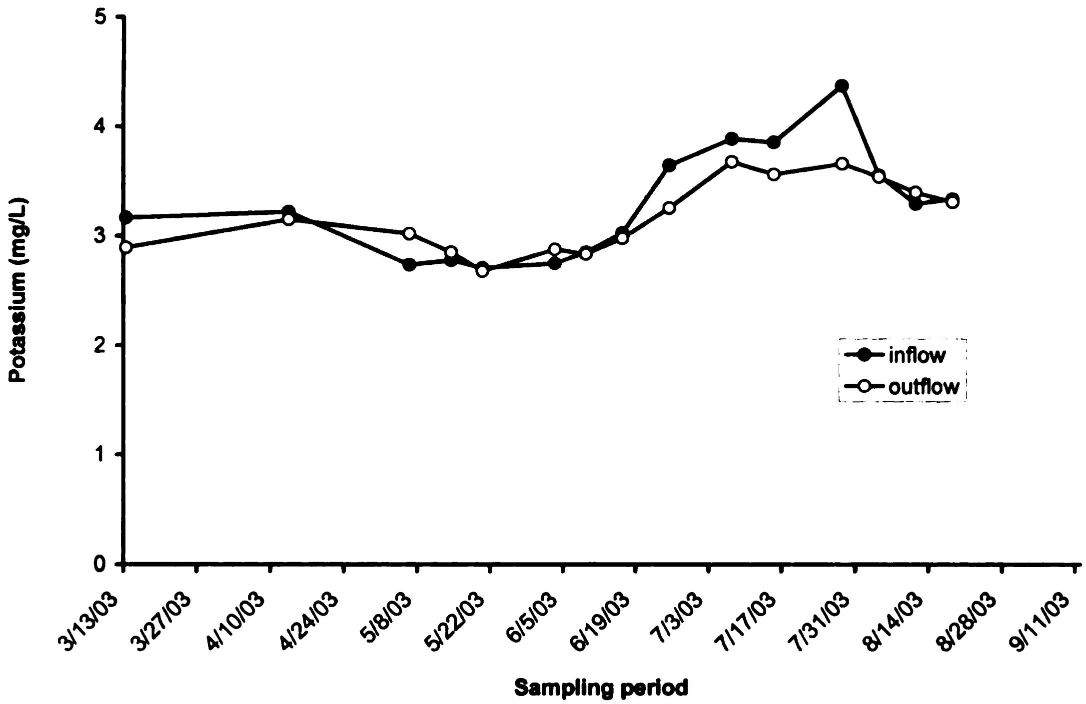



Figure 28. Lake Allegan inflow and outflow potassium concentrations for 2003.

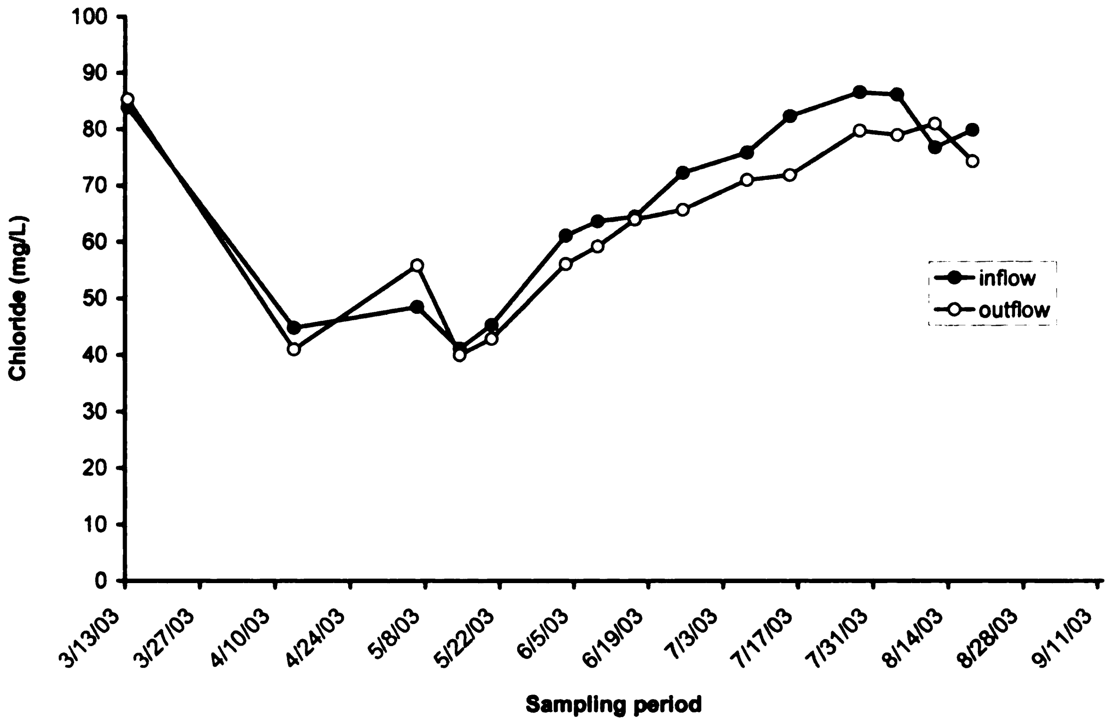



Figure 29. Lake Allegan inflow and outflow chloride concentrations for 2003.

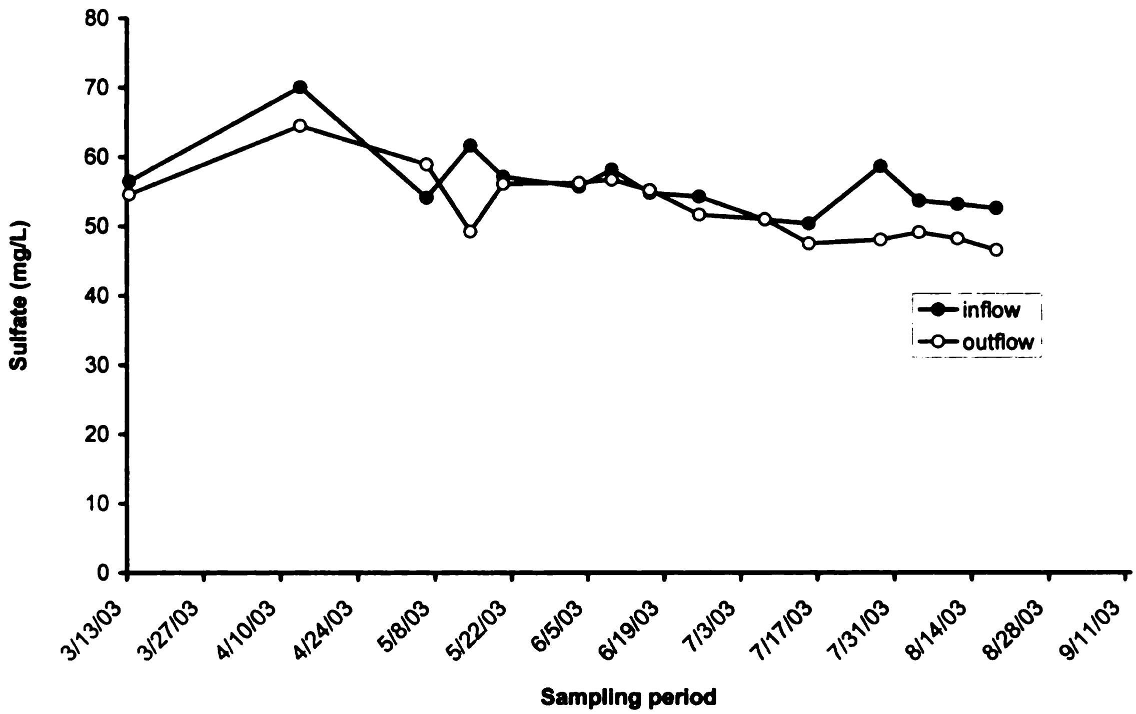



Figure 30. Lake Allegan inflow and outflow sulfate concentrations for 2003.

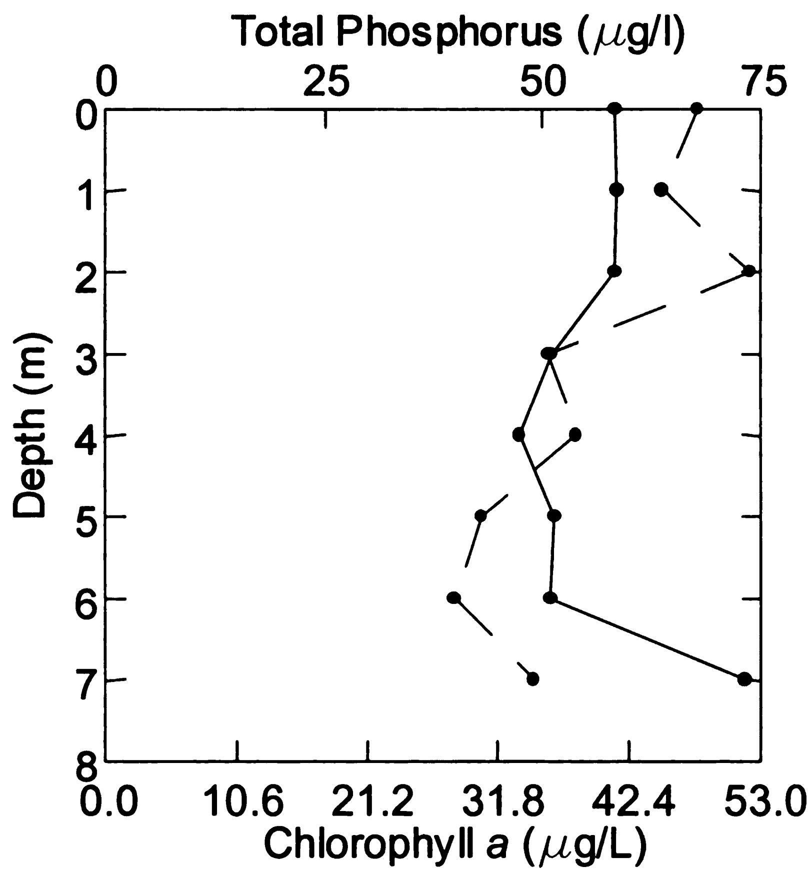



Figure 31. Lake Allegan vertical profile concentrations of total phosphorus (solid line) and chlorophyll *a* (dashed line). The inflow total phosphorus concentration for the day 44.8 µg/L was and the inflow chlorophyll *a* concentration was 2.8 µg/L.

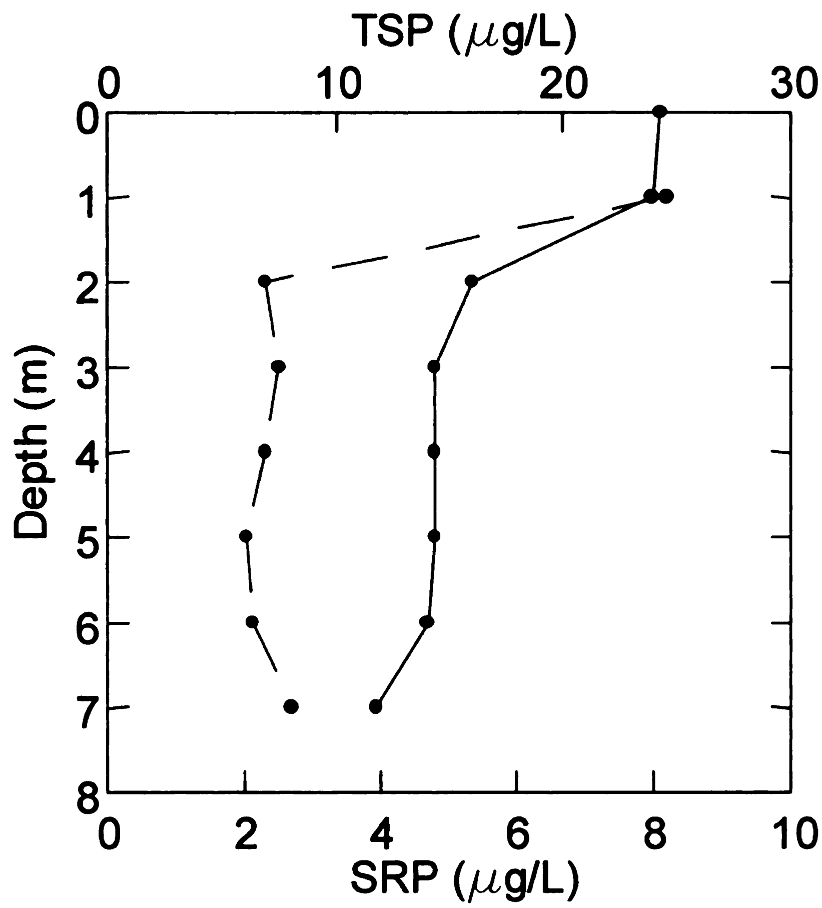



Figure 32. Lake Allegan vertical profile concentrations of total soluble phosphorus (TSP) (solid line) and soluble reactive phosphorus (SRP) (dashed line). The inflow total soluble phosphorus concentration for the day was 32 µg/L and the inflow soluble reactive phosphorus concentration was18.2 µg/L.

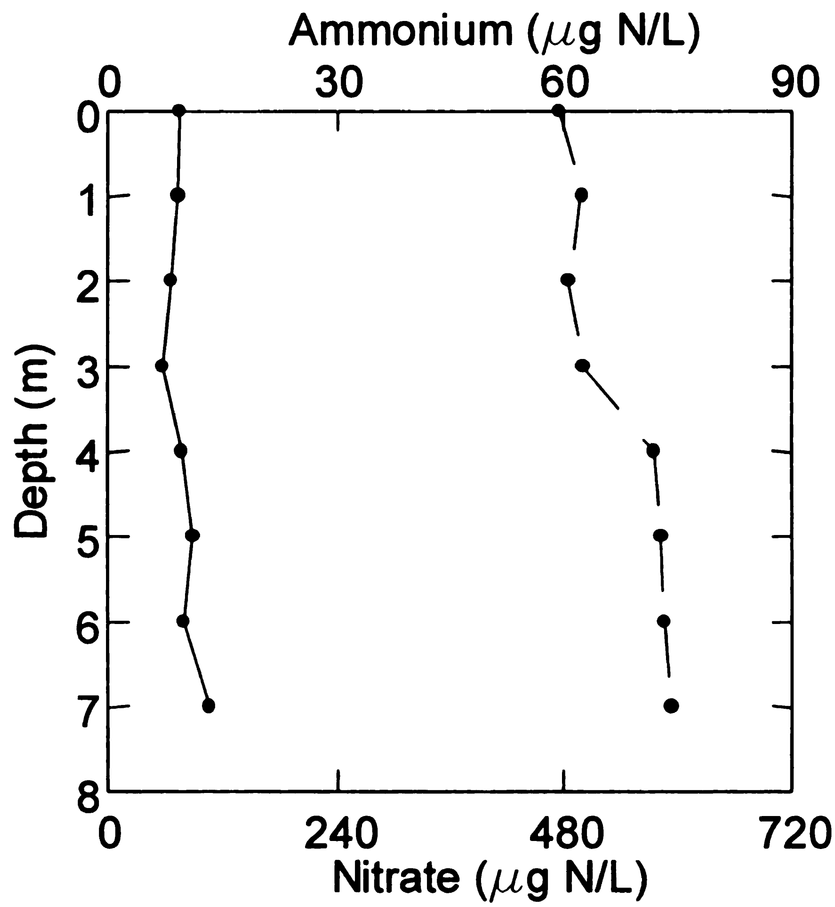



Figure 33. Lake Allegan vertical profile concentrations of ammonium (solid line) and nitrate (dashed line). The inflow ammonium concentration on the sampling day was 16 μg N/L and the inflow nitrate concentration was 1320 μg N/L.

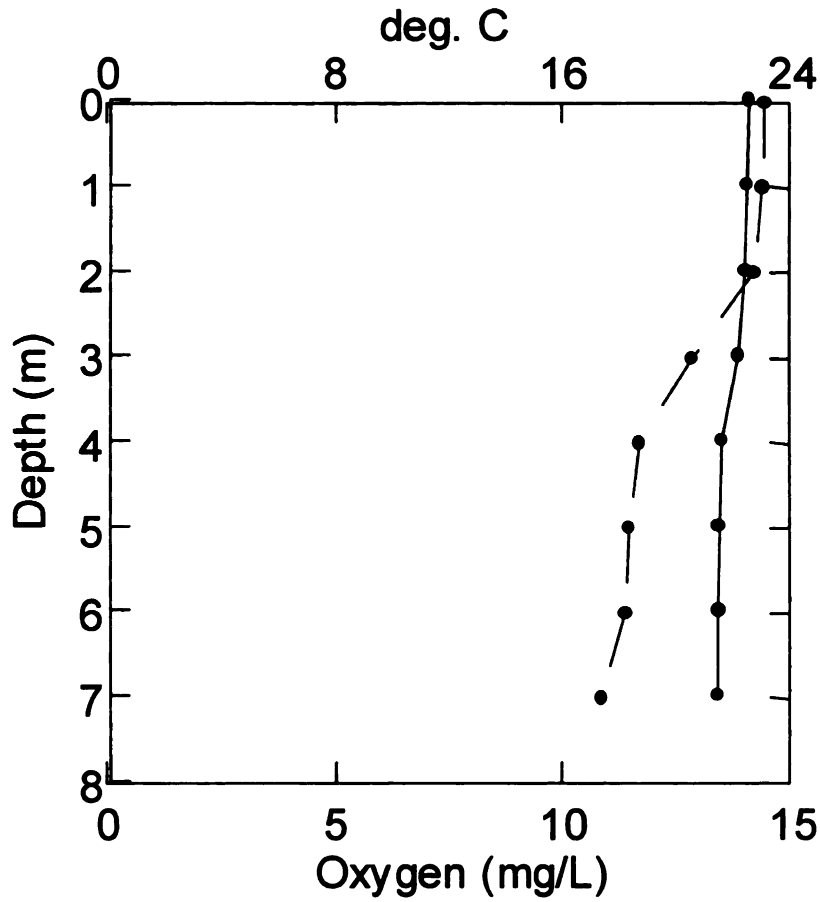



Figure 34. Lake Allegan vertical profile of temperature (solid line) and oxygen (dashed line). The inflow temperature for the day was 19.5 C and the inflow oxygen concentration was 9 mg/L.

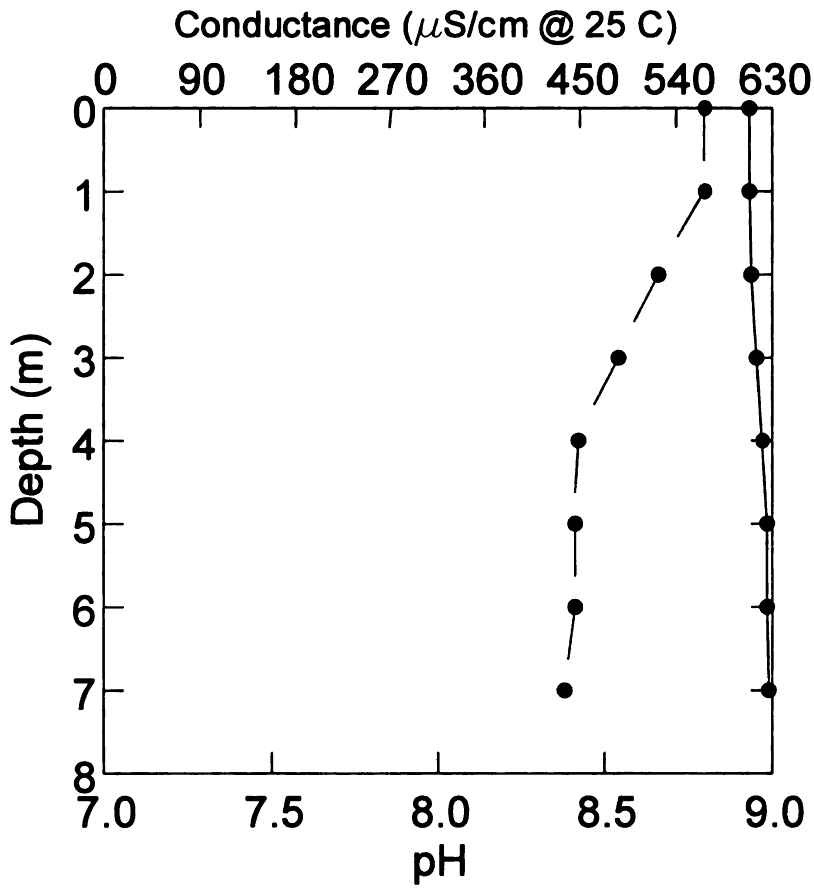



Figure 35. Lake Allegan vertical profile of conductance (solid line) and pH (dashed line). The inflow conductance for the day was 689 μS/cm and the inflow pH was 8.4.

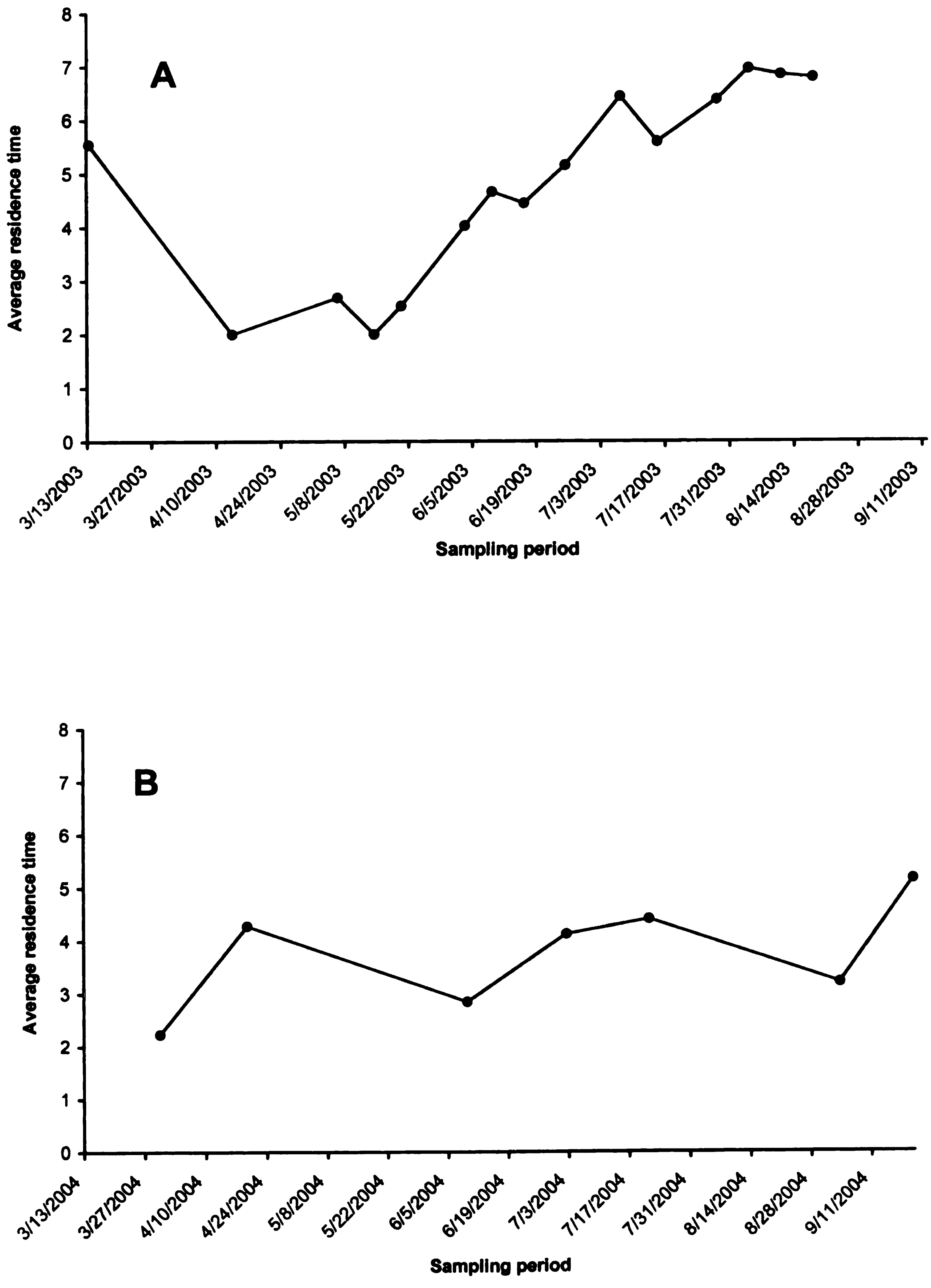



Figure 36. Morrow Lake residence time (days) preceding each sampling date in,
A) 2003 and B) 2004.

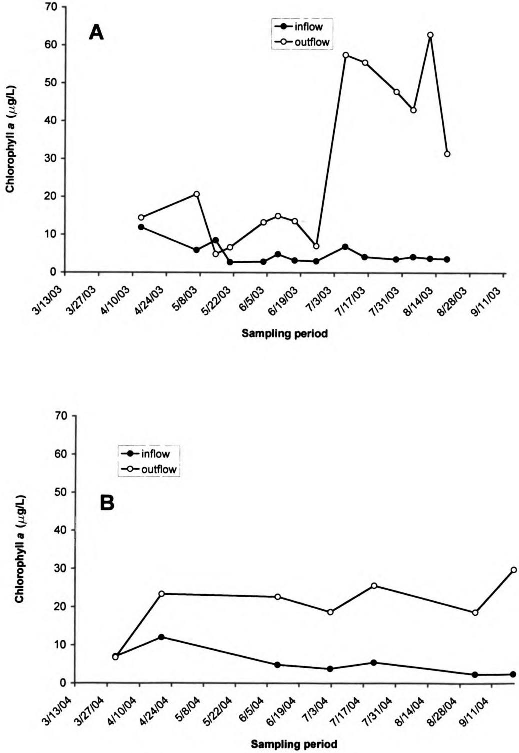



Figure 37. Morrow Lake inflow and outflow chlorophyll *a* concentrations, A) 2003 and B) 2004.

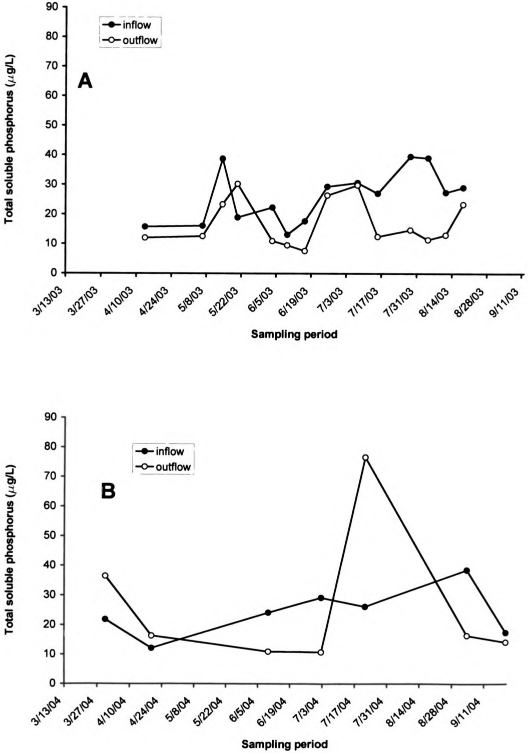



Figure 38. Morrow Lake inflow and outflow total soluble phosphorus concentrations, A) 2003 and B) 2004.

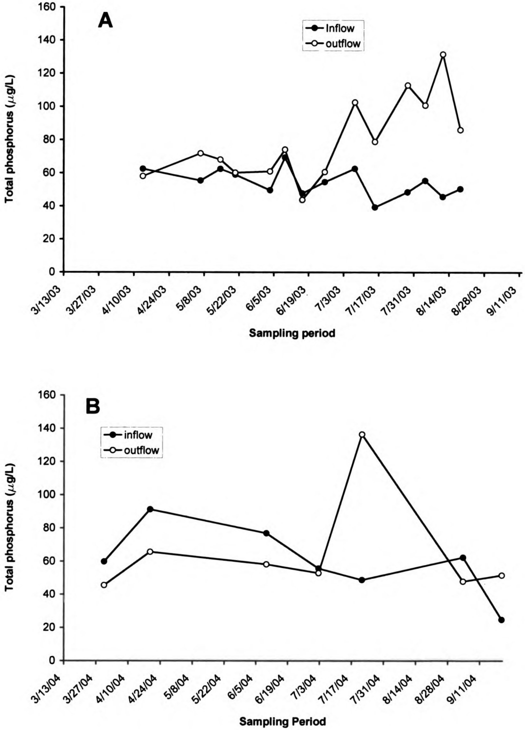
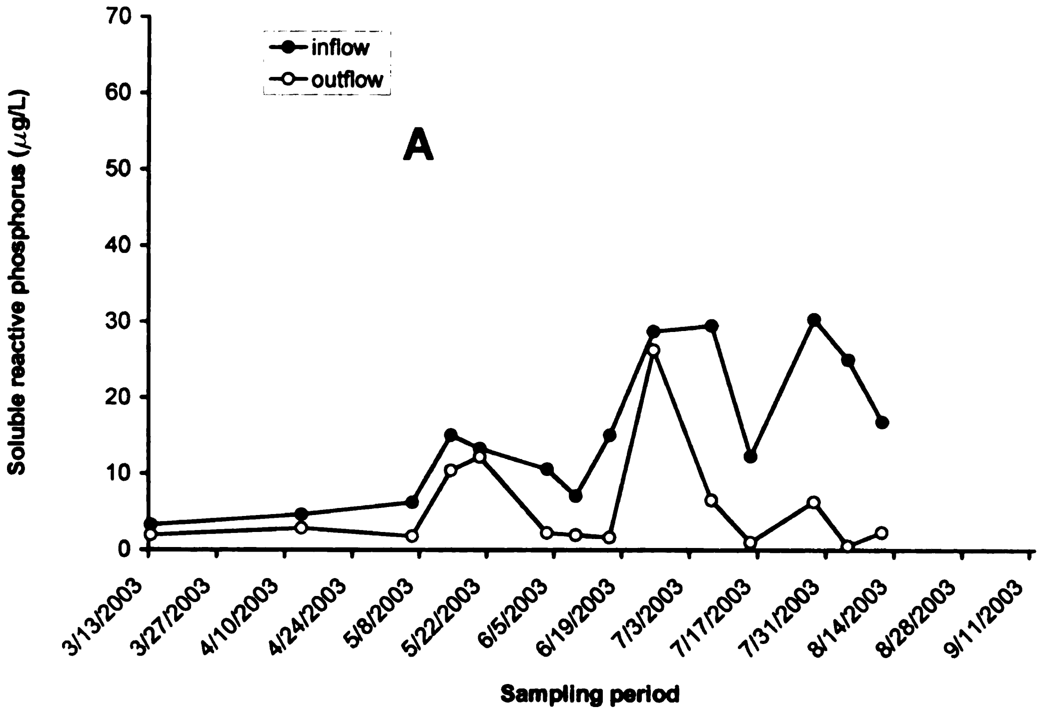



Figure 39. Morrow Lake inflow and outflow total phosphorus concentrations, A) 2003 and B) 2004.



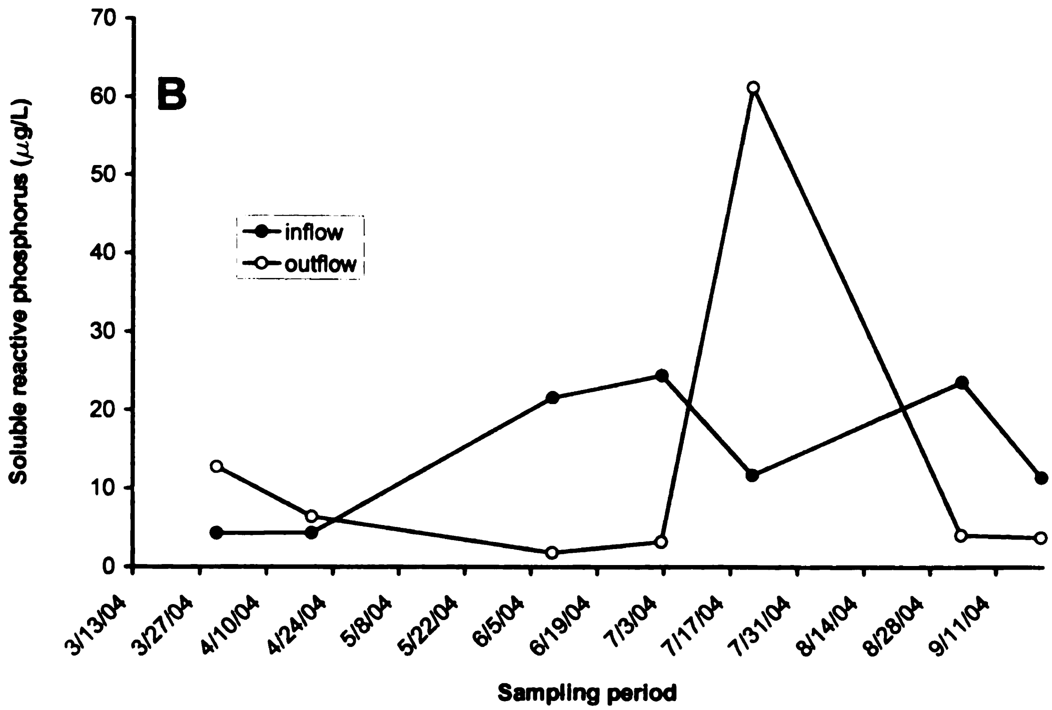




Figure 40. Morrow Lake inflow and outflow soluble reactive phosphorus concentrations, A) 2003 and B) 2004.

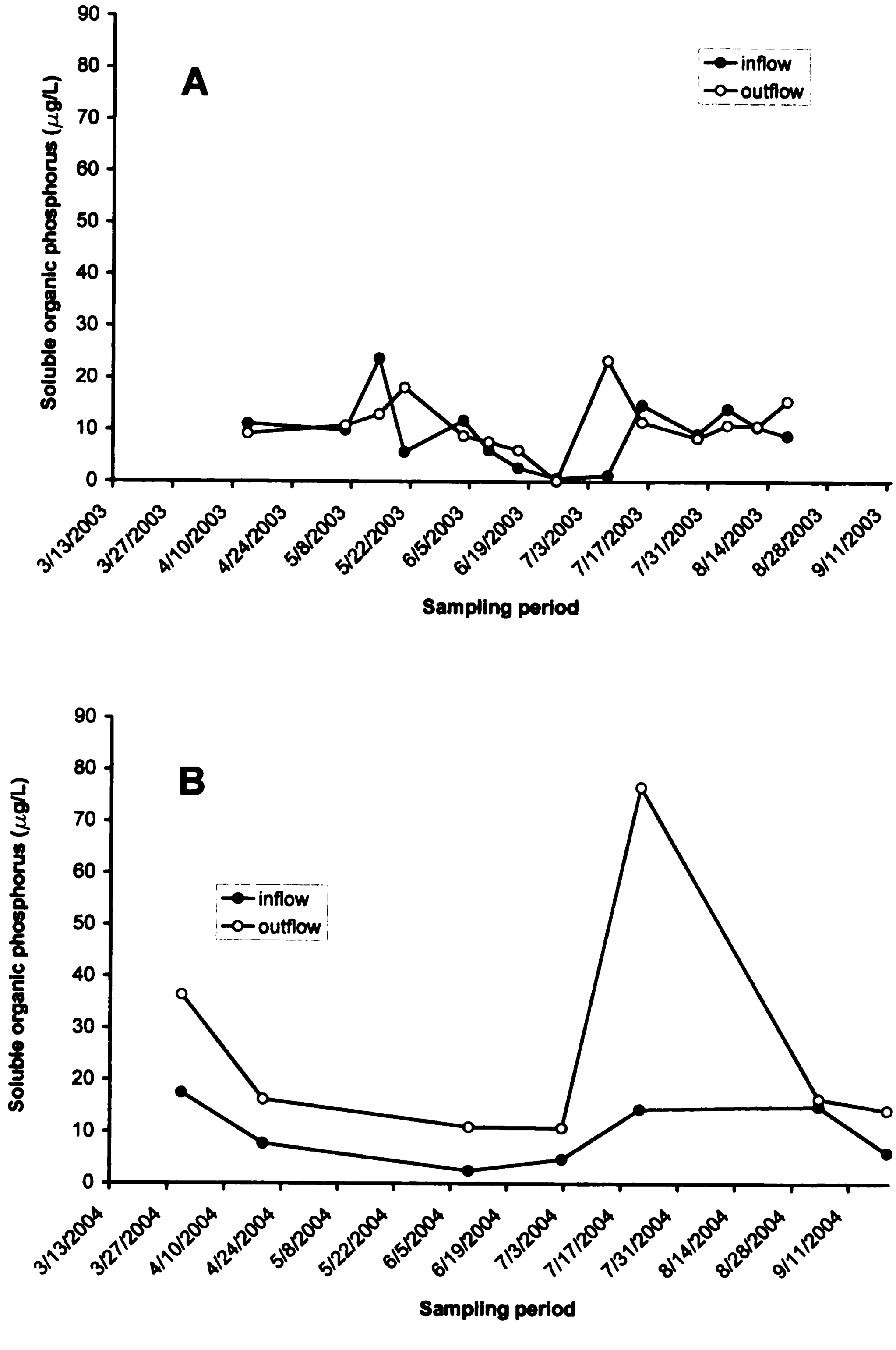



Figure 41. Morrow Lake inflow and outflow soluble organic phosphorus concentrations, A) 2003 and B) 2004.

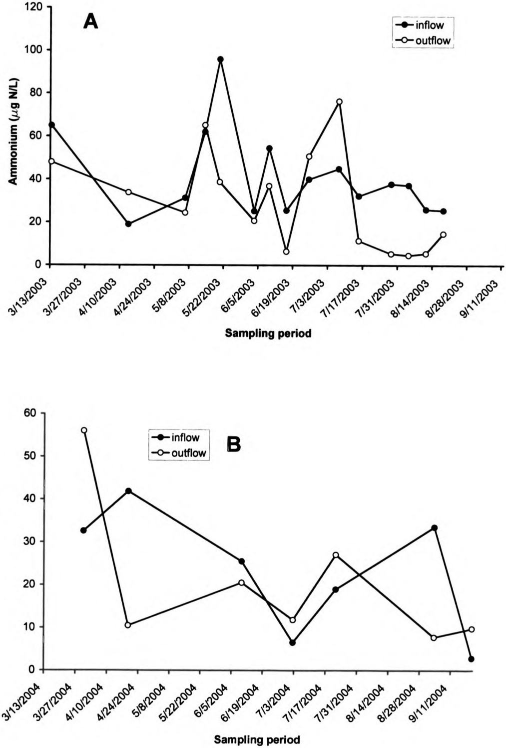



Figure 42. Morrow Lake inflow and outflow ammonium concentrations, A) 2003 and B) 2004.

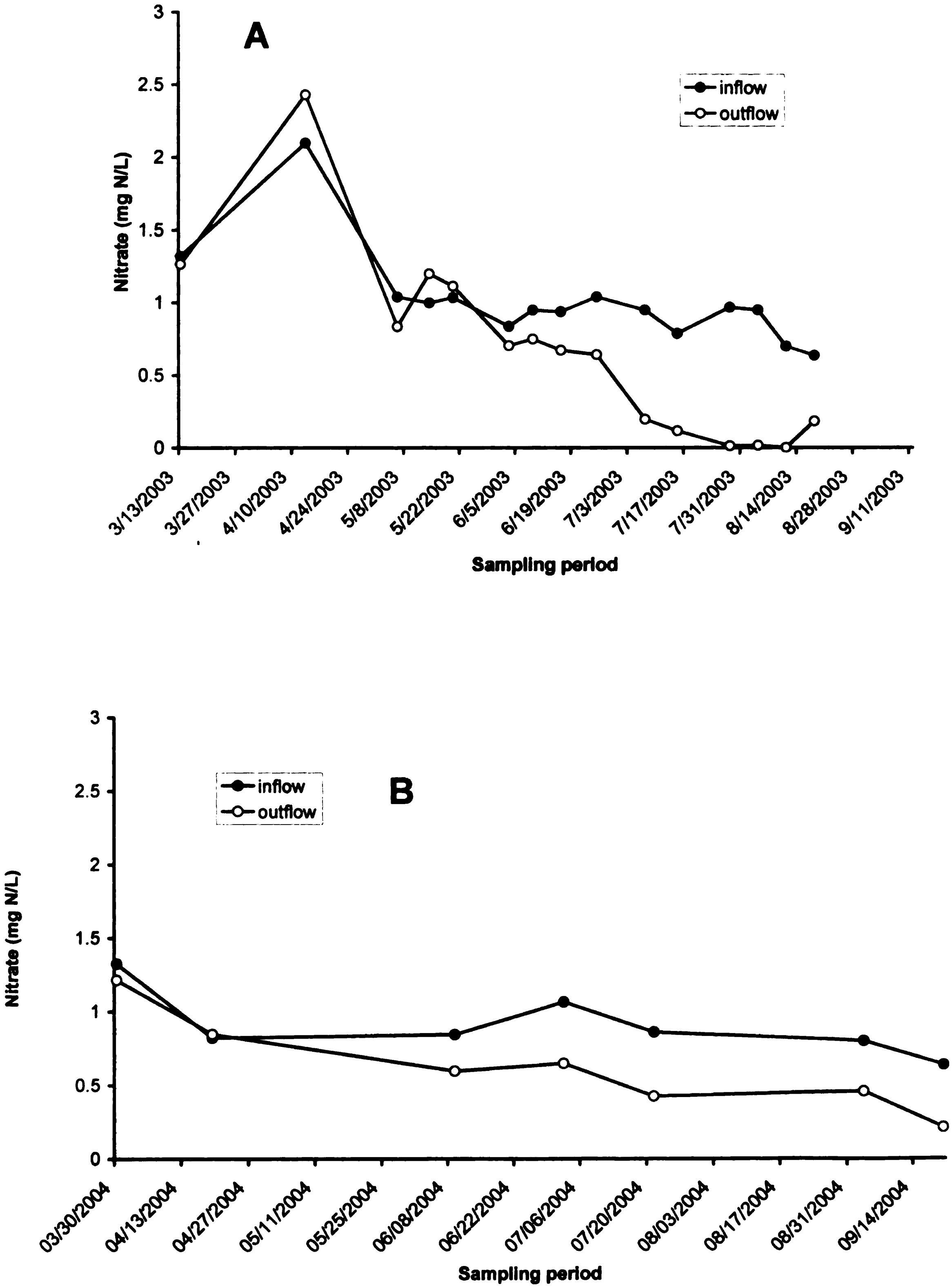



Figure 43. Morrow Lake inflow and outflow nitrate concentrations, A) 2003 and B) 2004.

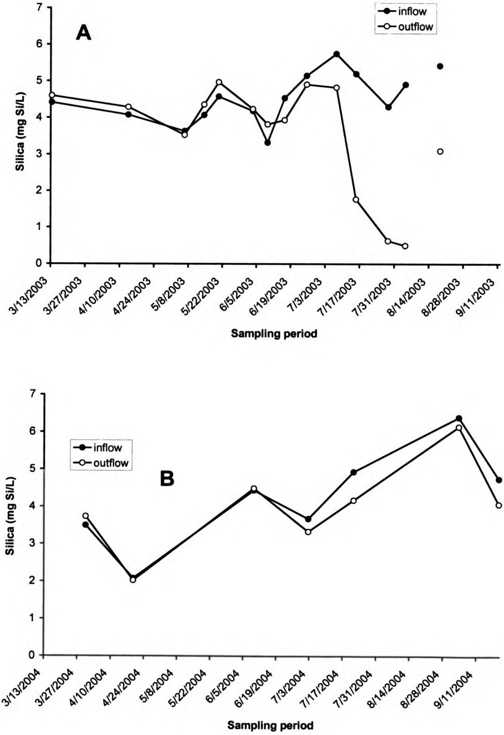
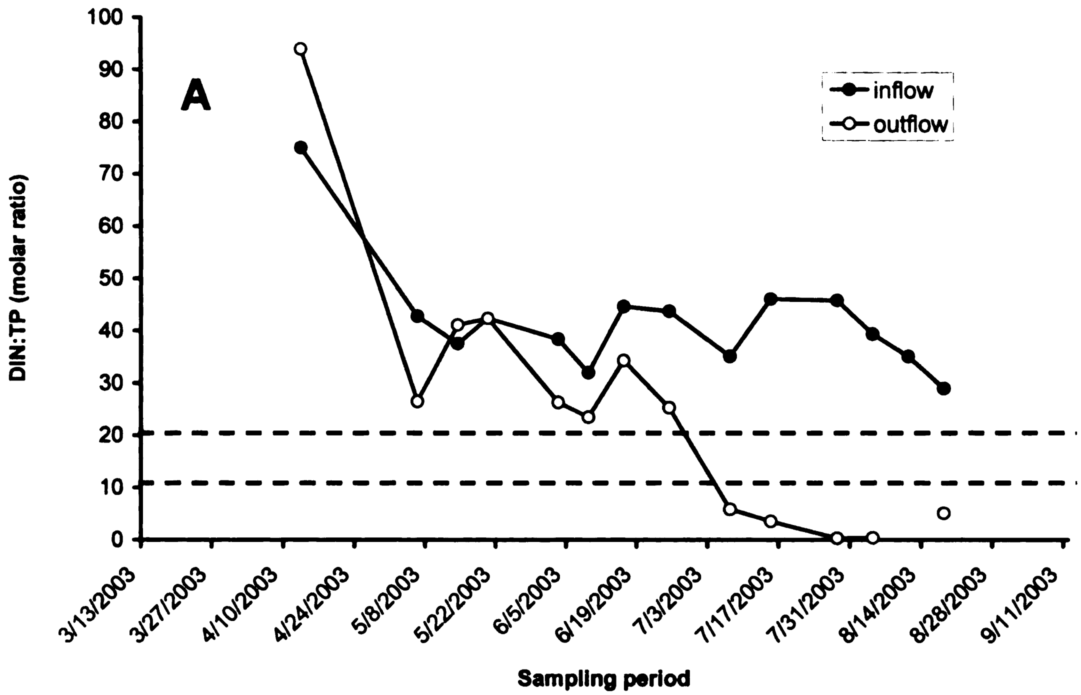



Figure 44. Morrow Lake inflow and outflow silica concentrations, A) 2003 and B) 2004.



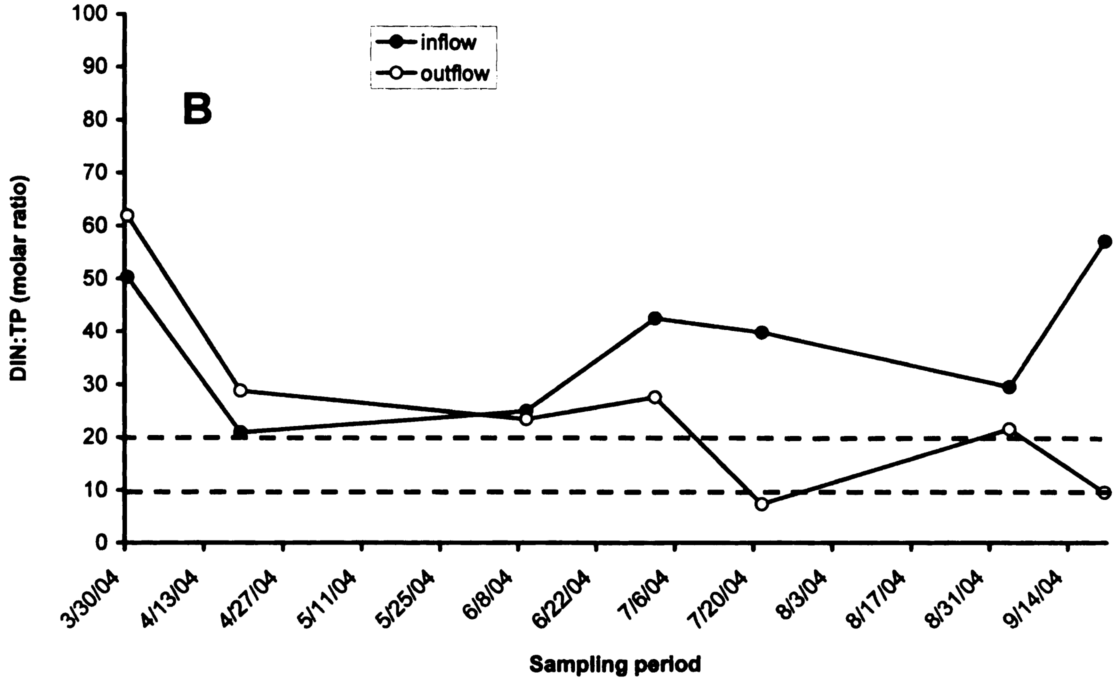
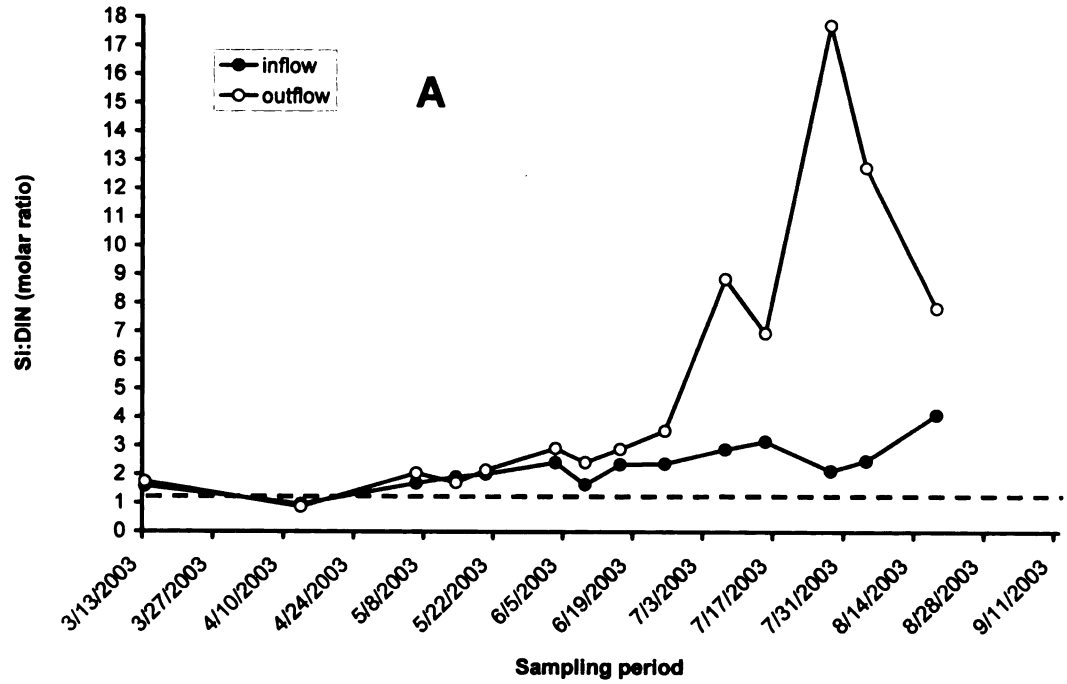




Figure 45. Morrow Lake inflow and outflow dissolved inorganic nitrogen (DIN) to total phosphorus (TP) ratio. Dashed line shows the thresholds of potential nitrogen limitation (less than 10) and phosphorus limitation (greater than 20), in A) 2003 and B) 2004.



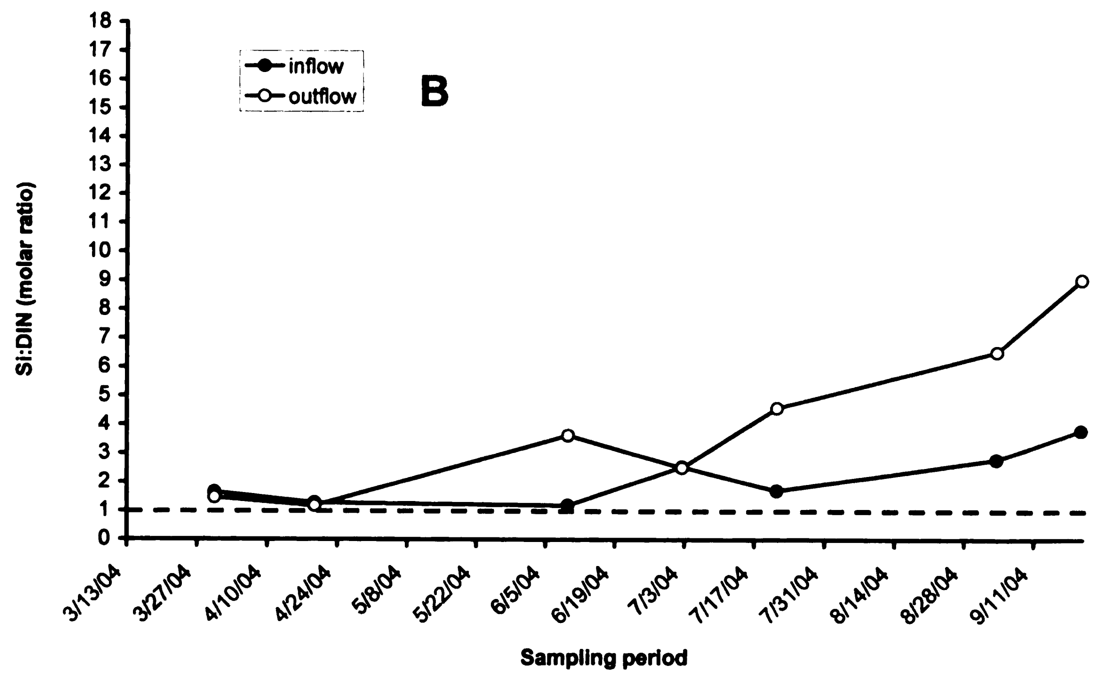
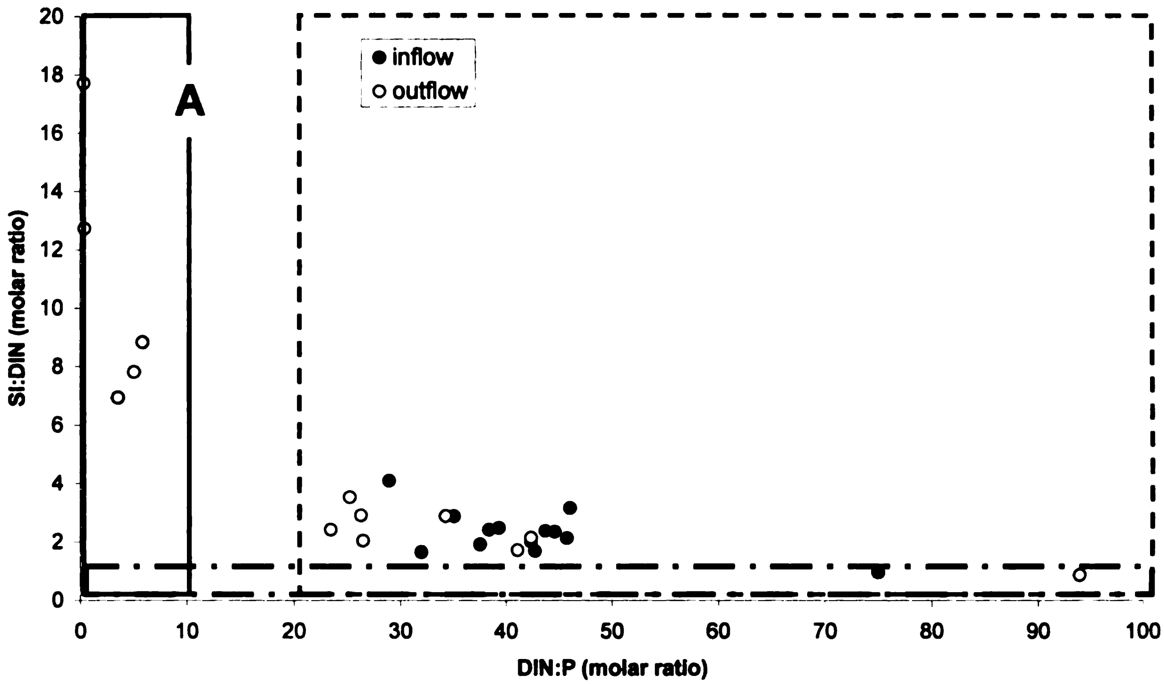




Figure 46. Morrow Lake inflow and outflow silica (Si) to dissolved inorganic nitrogen (DIN) molar ratio. Dashed line shows the threshold of potential silica limitation relative to nitrogen (less than 1), A) 2003 and B) 2004.



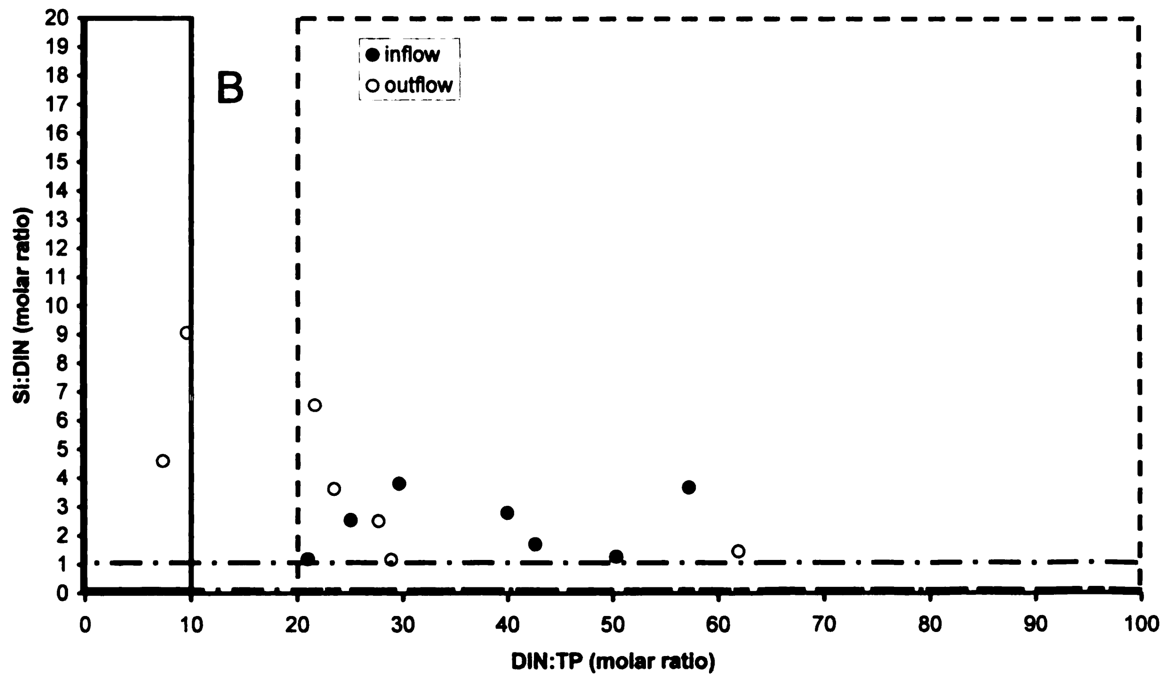




Figure 47. Morrow Lake inflow and outflow dissolved inorganic nitrogen (DIN) to Silica (Si) ratio versus dissolved inorganic nitrogen (DIN) to total phosphorus (TP) ratio. Potential Nitrogen limitation is represented by solid line square, phosphorus limitation represented by dashed line, and silica limitation represented by dotted-dashed line

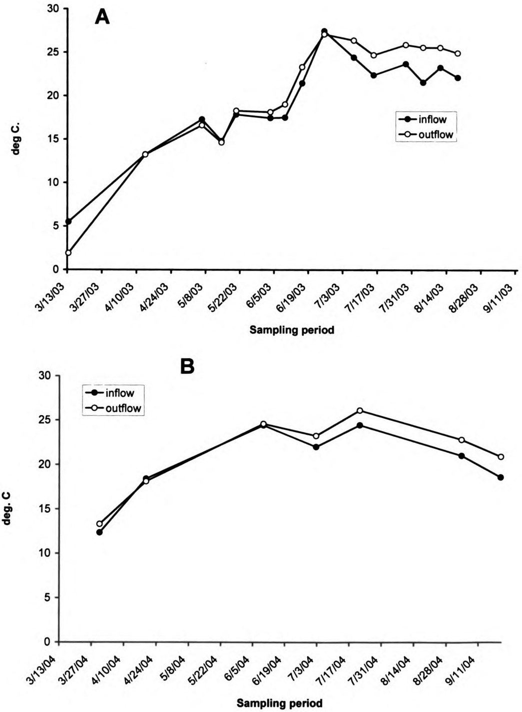



Figure 48. Morrow Lake inflow and outflow temperatures,
A) 2003 and B) 2004.

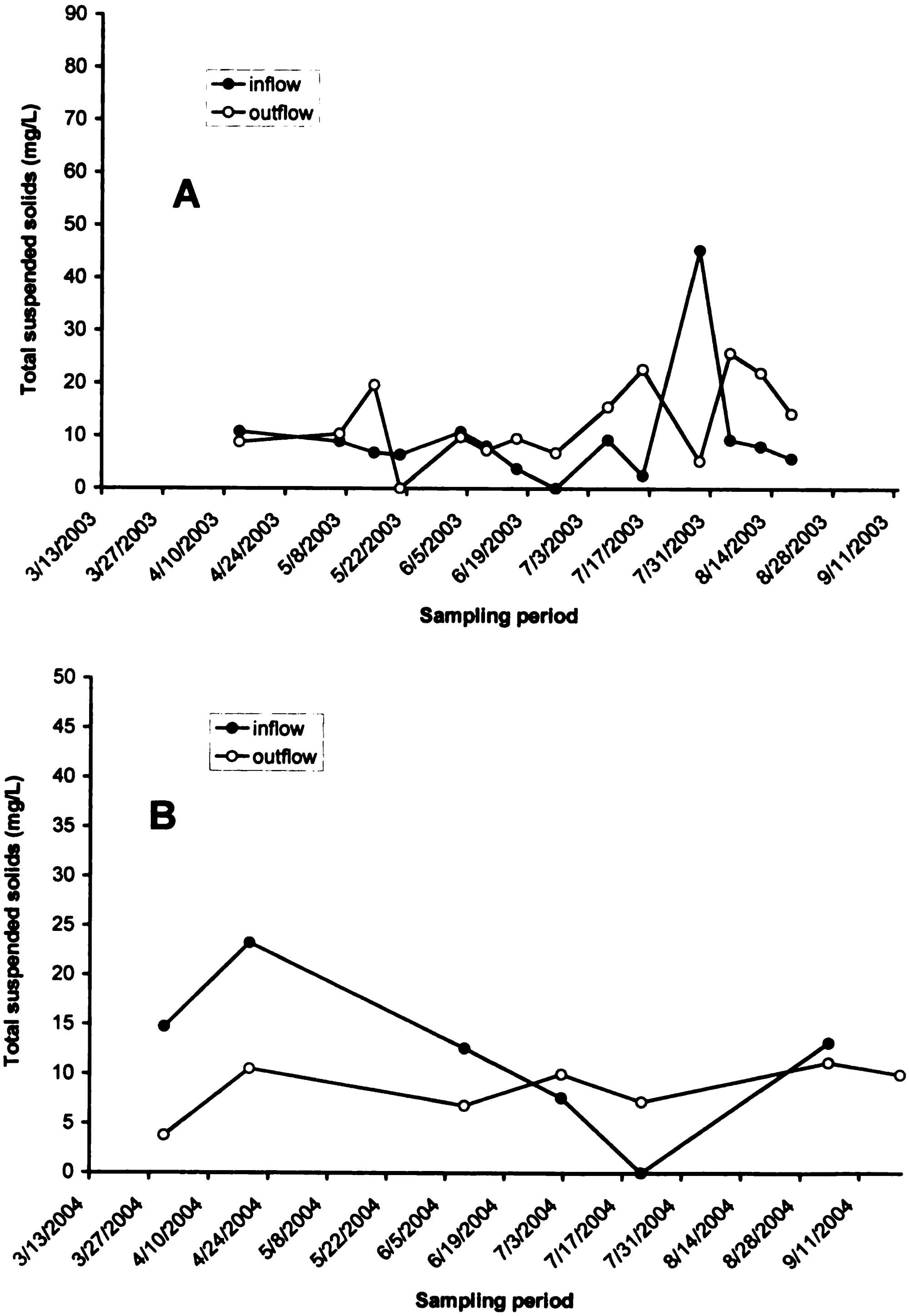
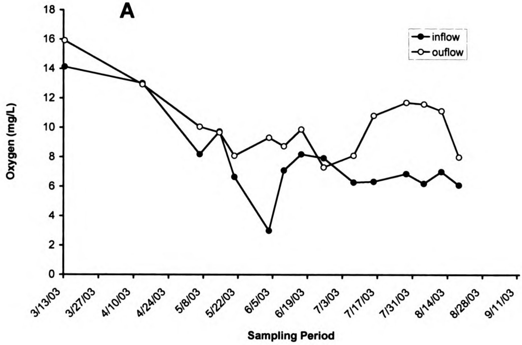



Figure 49. Morrow Lake inflow and outflow total suspended solids concentrations, A) 2003 and B) 2004.



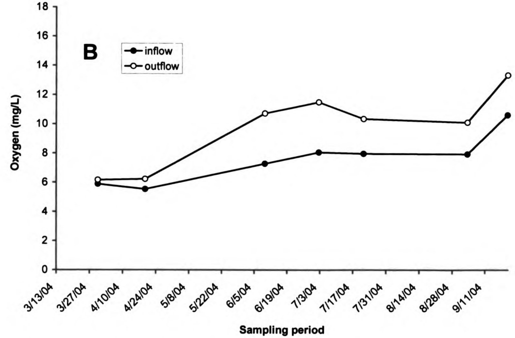




Figure 50. Morrow Lake inflow and outflow oxygen concentrations, A) 2003 and B) 2004.

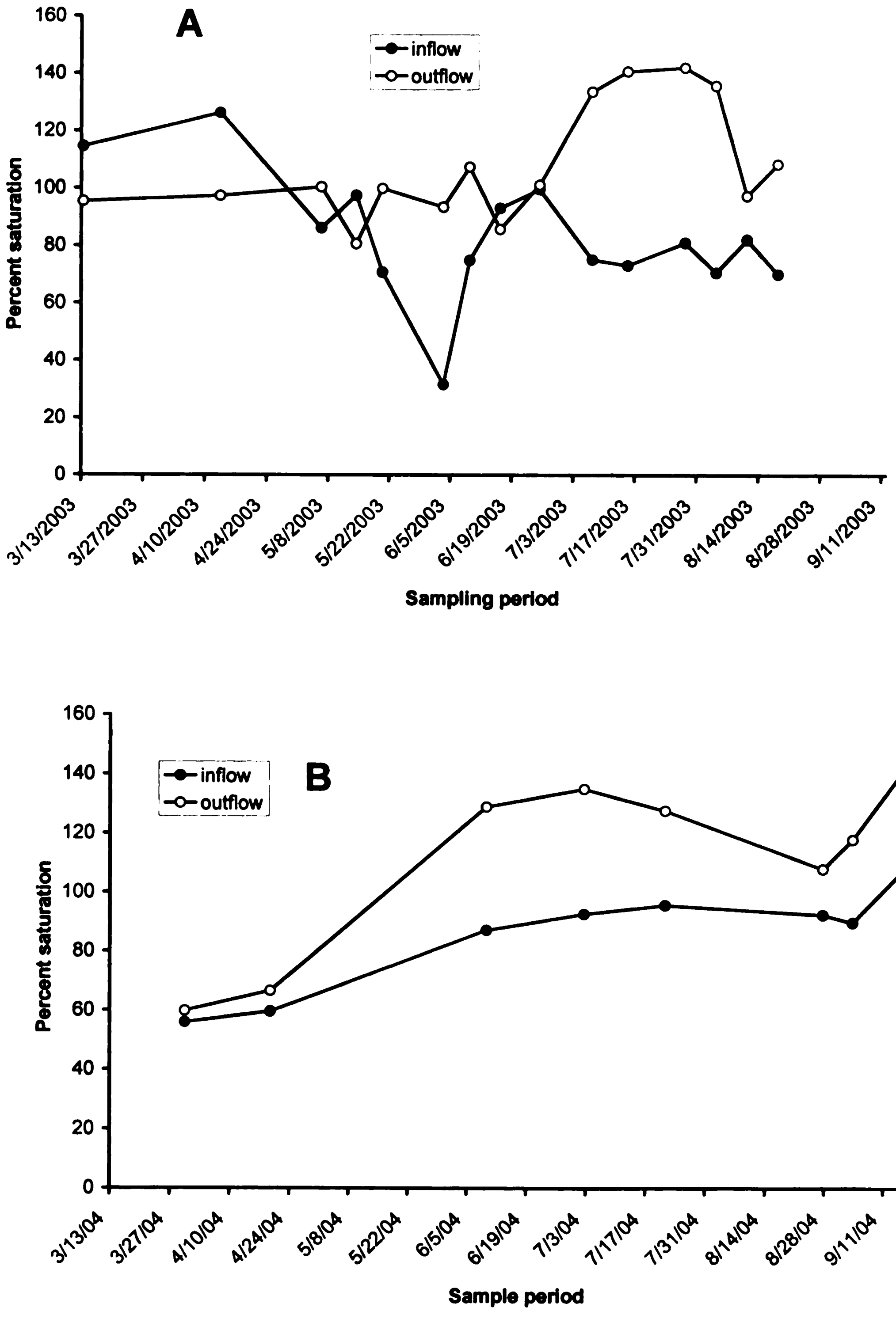



Figure 51. Morrow Lake inflow and outflow percent oxygen saturation concentrations, A) 2003 and B) 2004.

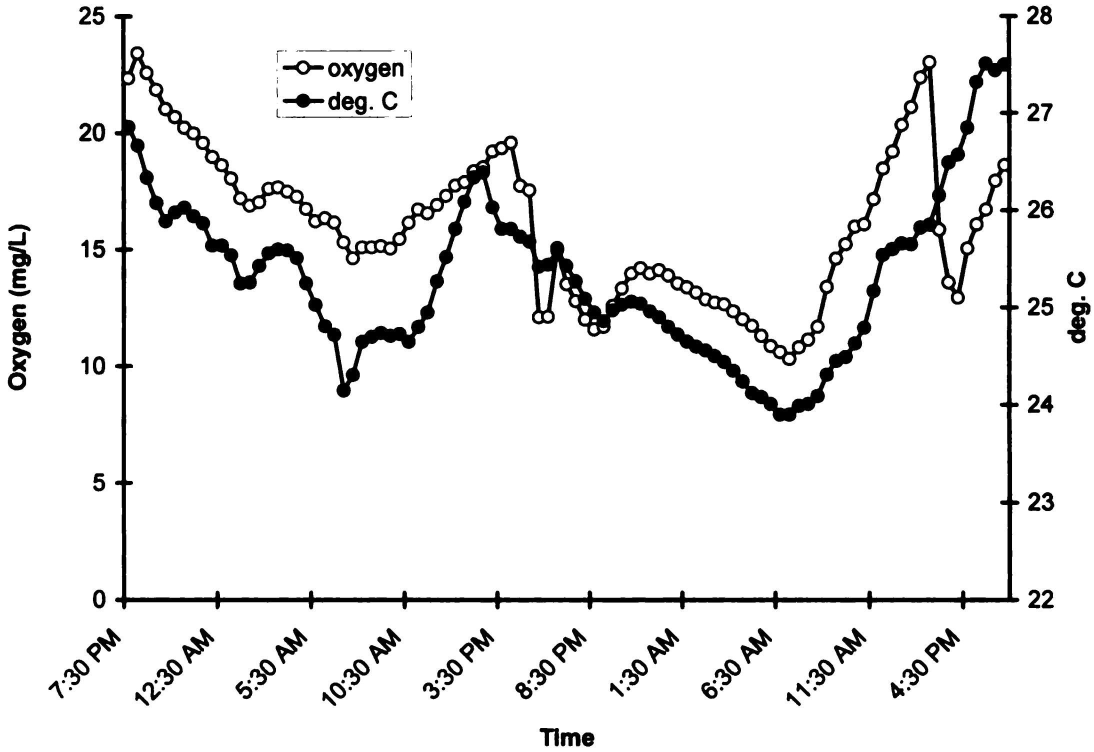
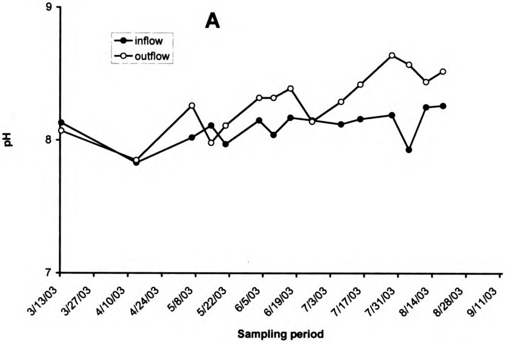



Figure 52. Morrow Lake oxygen and temperature diel cycle on 25-26 August 2003



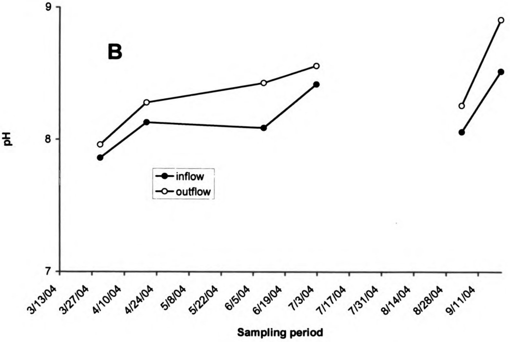




Figure 53. Morrow Lake inflow and outflow pH concentrations, A) 2003 and B) 2004.

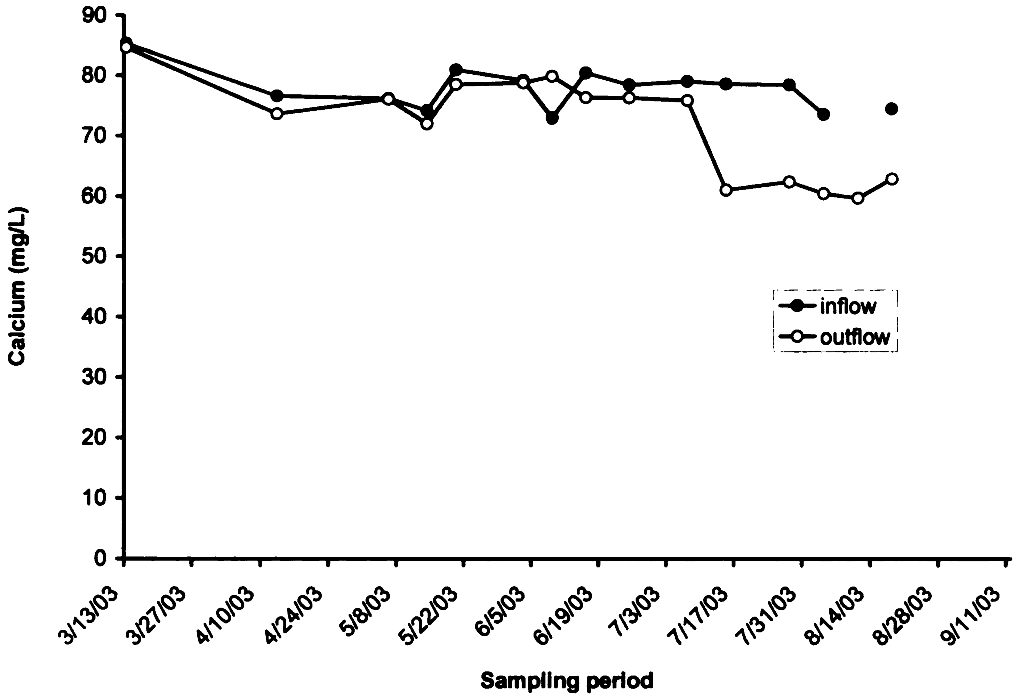



Figure 54. Morrow Lake inflow and outflow calcium concentrations for 2003.

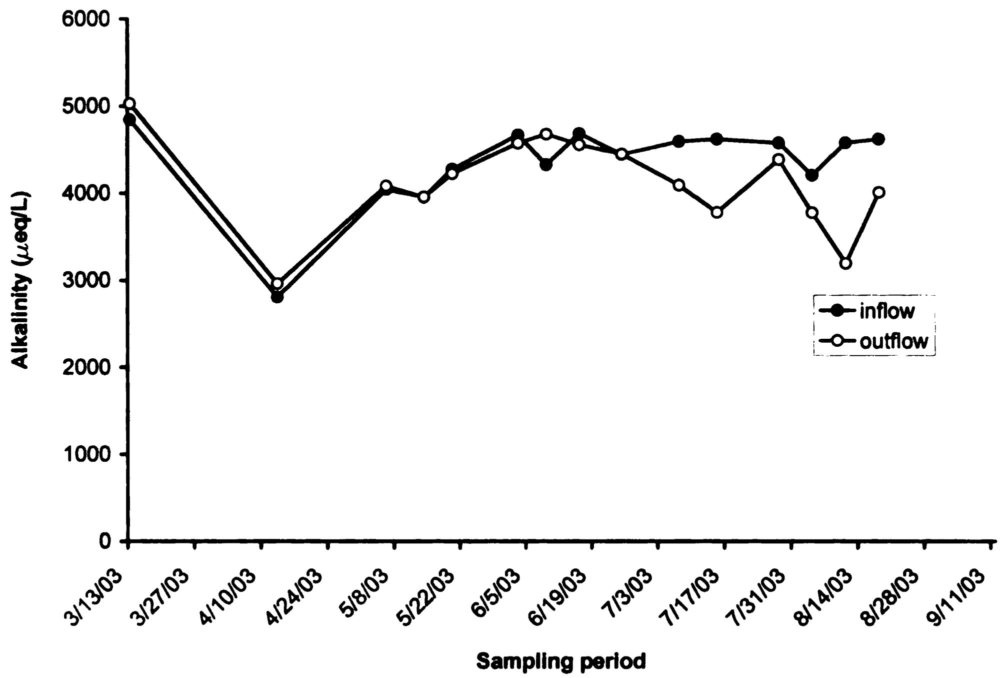



Figure 55. Morrow Lake inflow and outflow alkalinity concentrations for 2003.

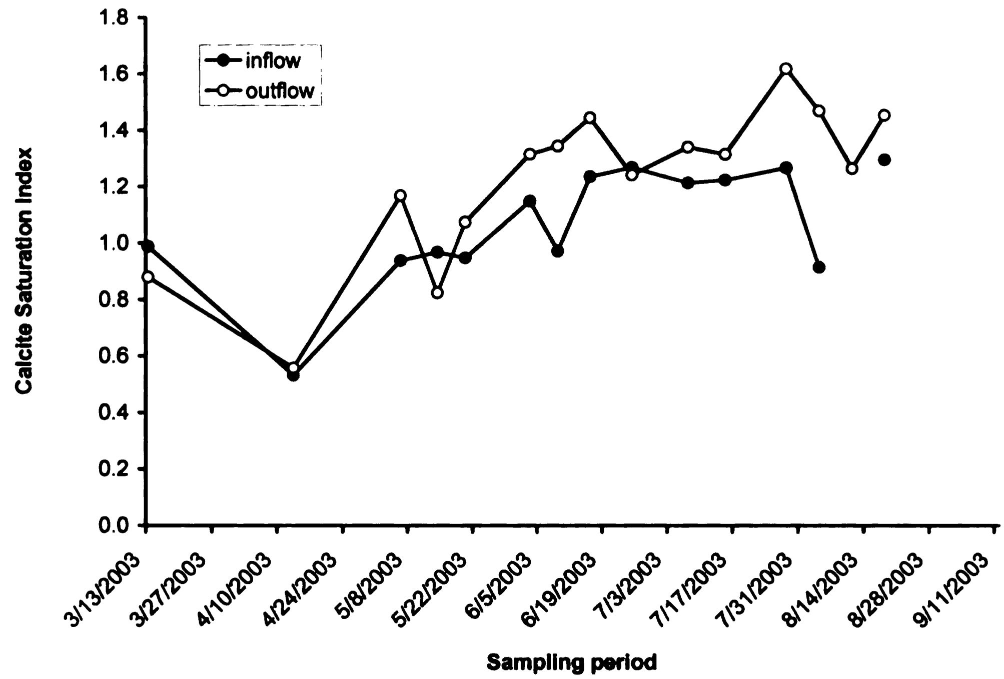



Figure 56. Morrow Lake inflow and outflow calcite saturation index for 2003.

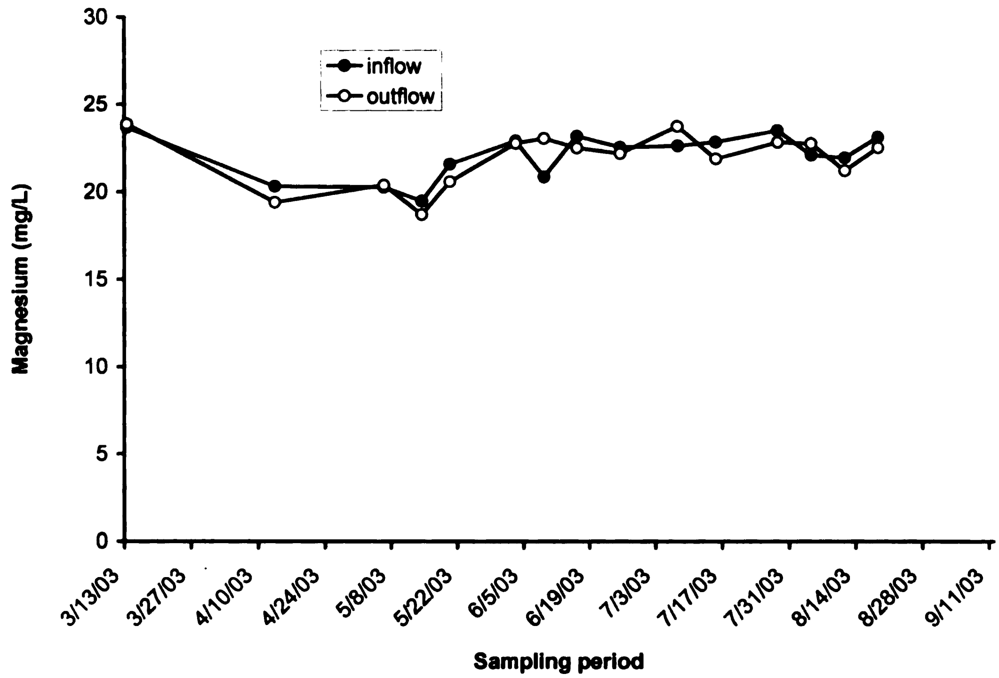



Figure 57. Morrow Lake inflow and outflow magnesium concentrations for 2003.

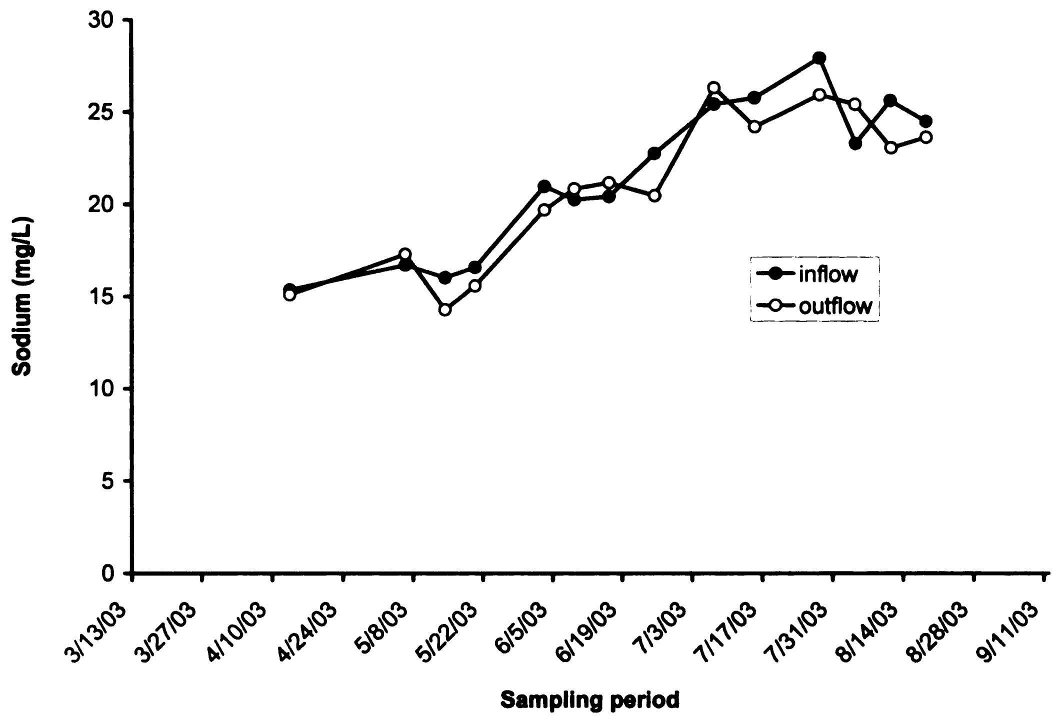



Figure 58. Morrow Lake inflow and outflow sodium concentrations for 2003.

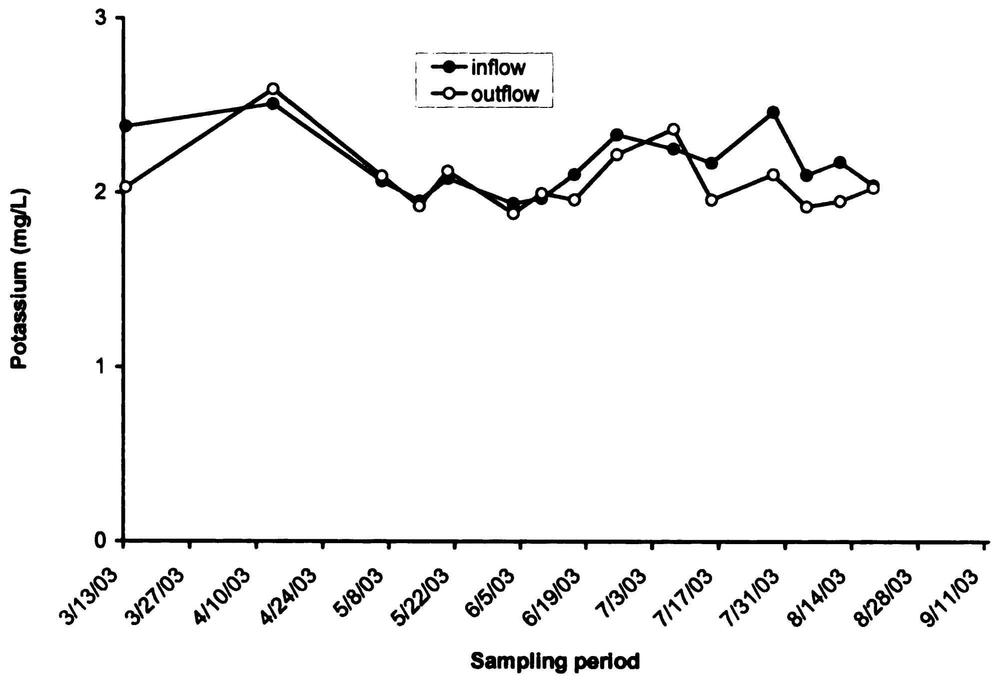



Figure 59. Morrow Lake inflow and outflow potassium concentrations for 2003.

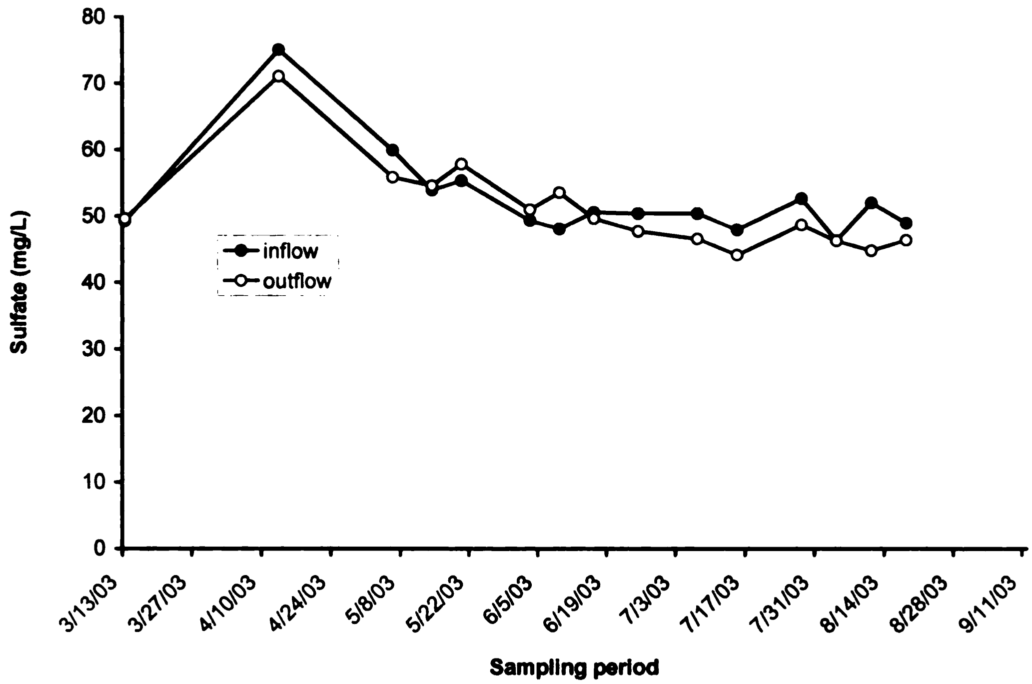



Figure 60. Morrow Lake inflow and outflow chloride concentrations for 2003.

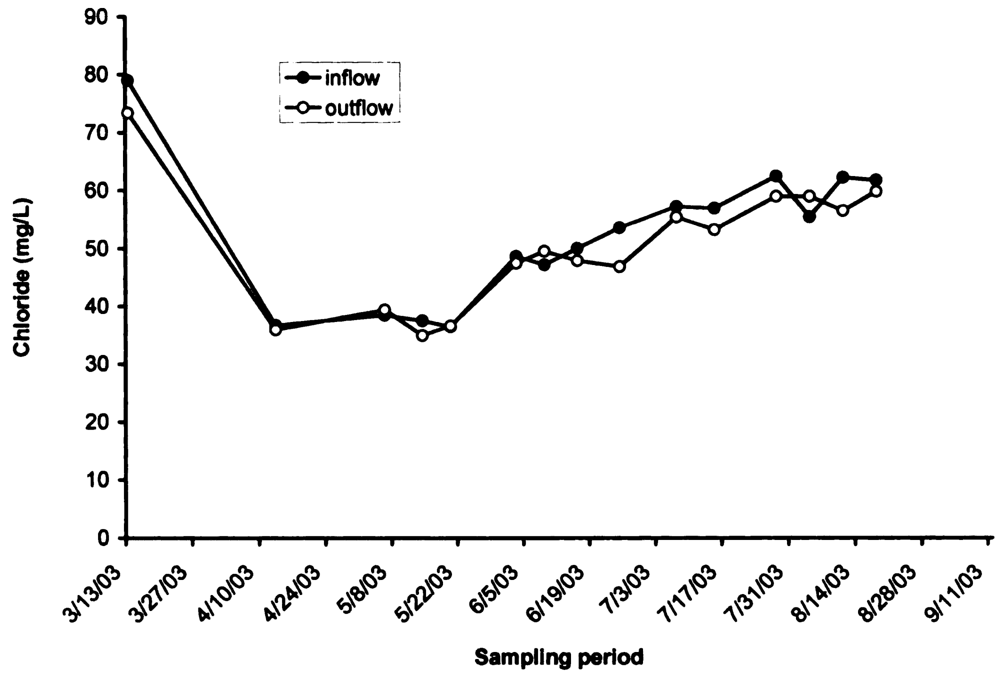



Figure 61. Morrow Lake inflow and outflow sulfate concentrations for 2003.

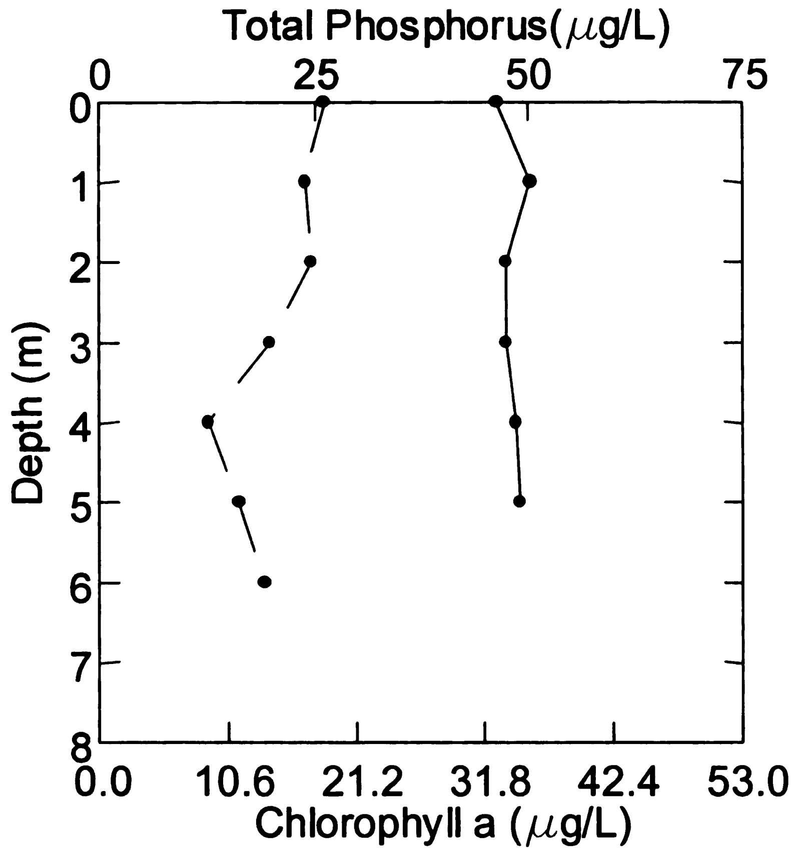



Figure 62. Morrow Lake vertical profile concentrations of total phosphorus (solid line) and chlorophyll *a* (dashed line). The inflow total phosphorus concentration for the day was 44.5 μg/L and the inflow chlorophyll *a* concentration was 2.7 μg/L.

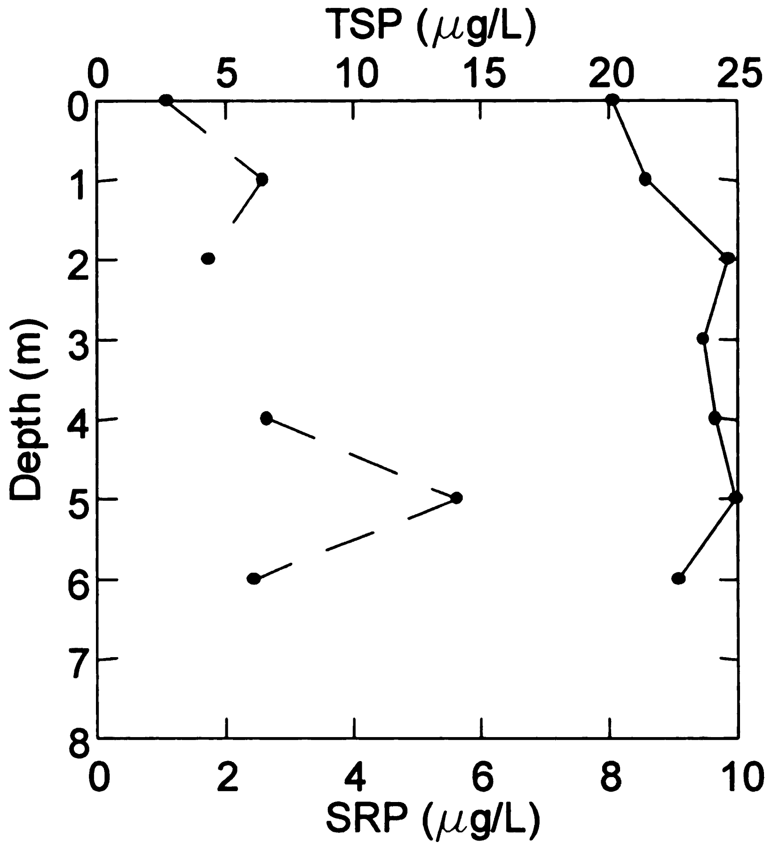



Figure 63. Morrow Lake vertical profile concentrations of total soluble phosphorus (TSP) (solid line) and soluble reactive phosphorus (SRP) (dashed line) . The inflow total soluble phosphorus concentration for the day was 31 µg/L and the inflow soluble reactive phosphorus concentration was 11.8 µg/L.

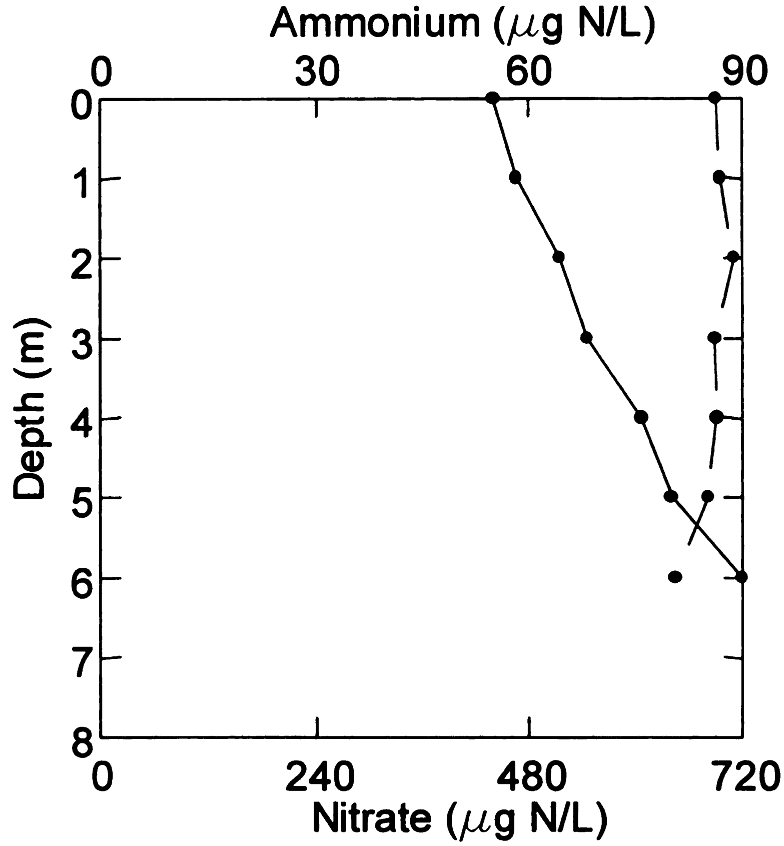



Figure 64. Morrow Lake vertical profile concentrations of ammonium (solid line) and nitrate (dashed line). The inflow ammonium concentration for the sampling day was 37.2 μg N/L and the inflow nitrate concentration was 777 μg N/L.

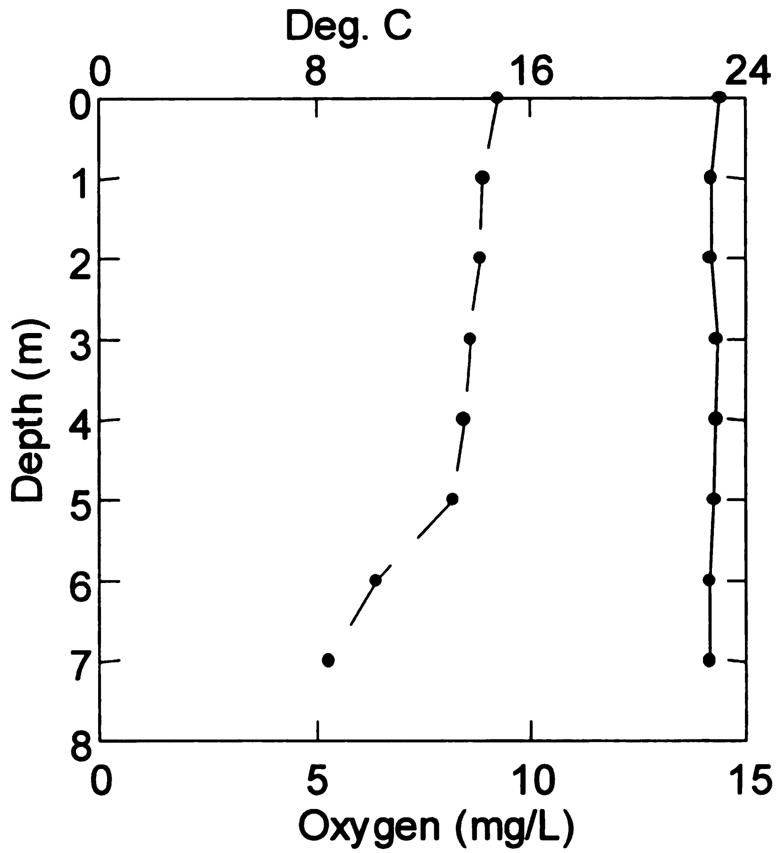



Figure 65. Lake Allegan vertical profile of temperature (solid line) and oxygen (dash line). The inflow temperature for the day was 23.1 C and the inflow oxygen concentration was 7.8 mg/L.

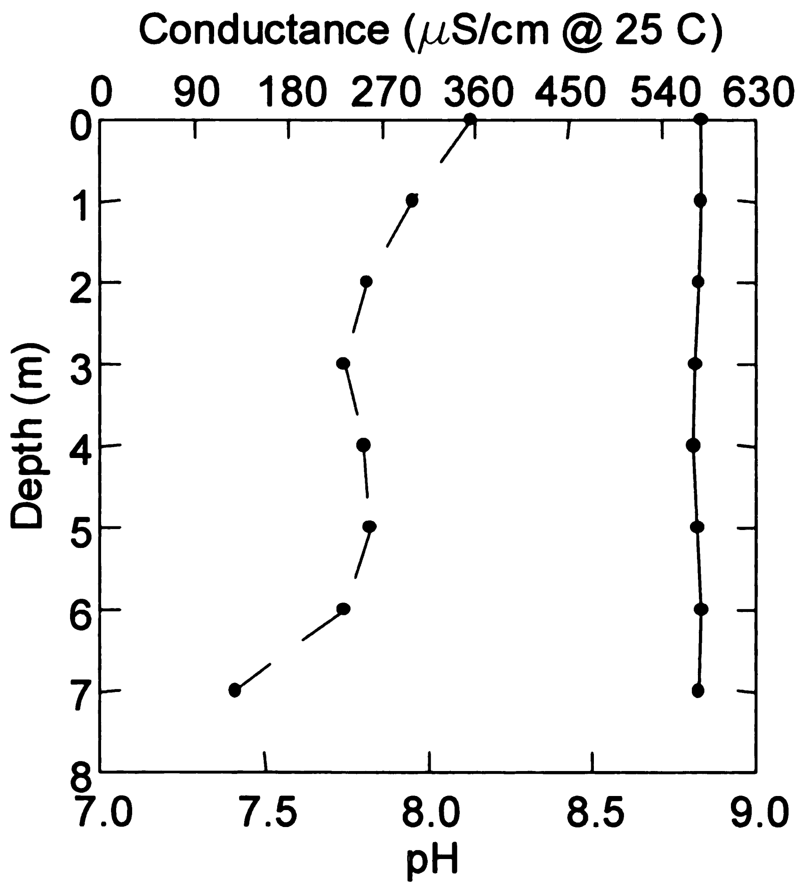



Figure 66. Morrow Lake vertical profile of conductance (solid line) and pH (dashed line). The inflow conductance for the day was 597 μ S/cm and the inflow pH was 7.9.

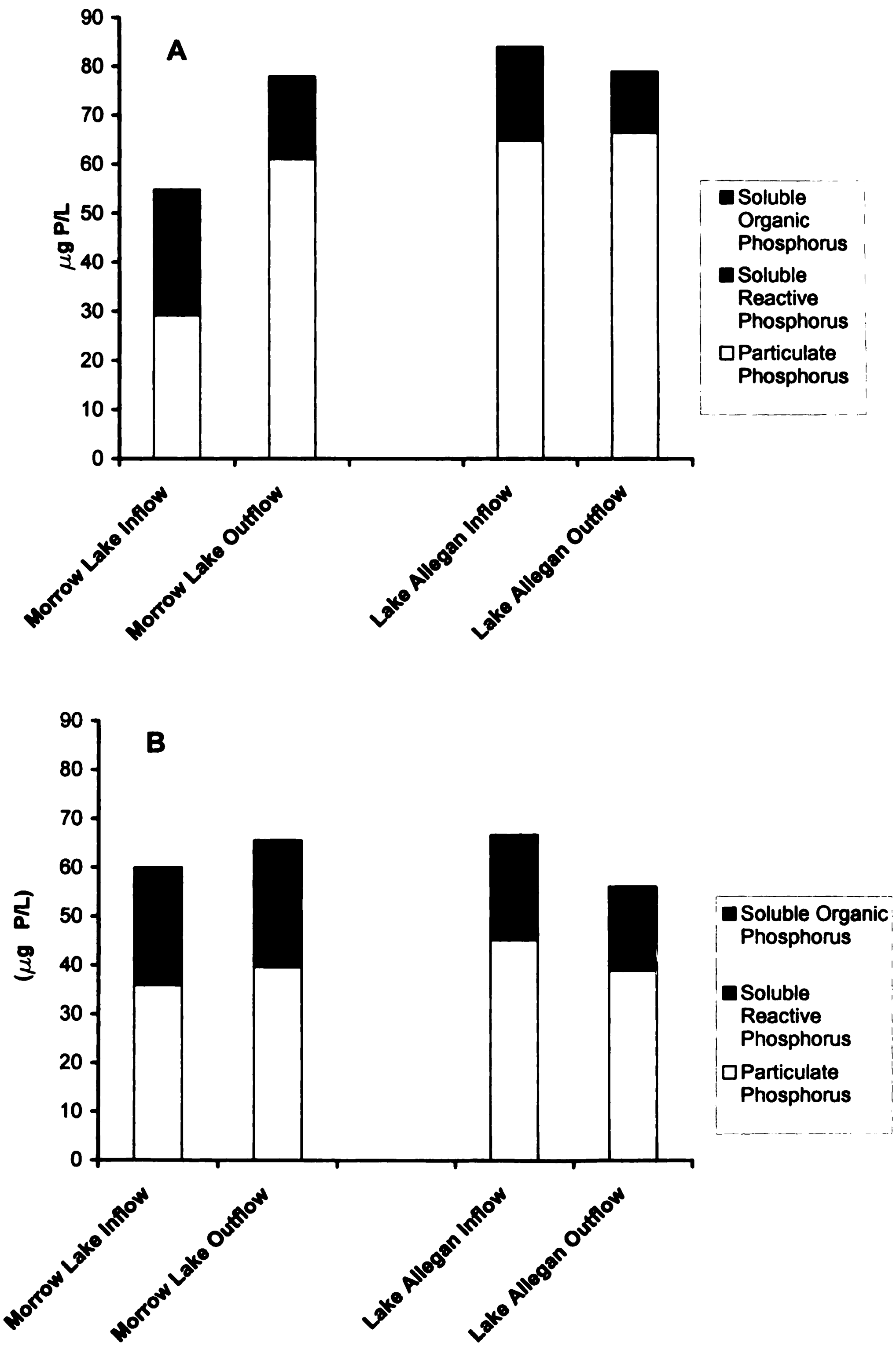



Figure 67. Morrow Lake and Lake Allegan mean phosphorus concentrations, A) 2003 and B) 2004.

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Chapter 2. Longitudinal biogeochemical patterns in river water passing through impoundments of varying residence times


**Abstract**

The Kalamazoo River (Michigan, USA) has six run-of-the-river dams (four small decommissioned ones and two larger ones producing hydropower). The hydropower reservoirs' residence times vary from 2 up to 11 days during the year. The decommissioned impoundments residence times vary from a quarter of day to 1.5 days during the year. Three longitudinal river surveys from Morrow Lake inflow to Lake Allegan outflow were conducted at varying discharges. Special emphasis was placed on above and below Plainwell, Otsego, Allegan City and Trowbridge decommissioned impoundments. Despite their spatial proximity a Total Maximum Daily Load for phosphorus (P) was deemed necessary for Lake Allegan to control summer algal blooms. High algal abundance was observed in Lake Allegan inflow, which may have resulted from Morrow Lake's algae transported downstream or algal biomass build-up as the river passed through semi-impounded reaches. The average river total phosphorus concentration was 79 μg/L during these surveys. Chlorophyll *a* concentrations declined below Morrow Lake by benthic filter feeders. The decommissioned impoundments greatly enhance algal biomass during low discharge below the Lake Allegan. The algal biomass would peak above and within Lake Allegan. The removal of some or all of those impoundments to restore a free-flowing river channel would seem likely to diminish the problem of excessive algal growth in Lake Allegan, converting the impounded reaches from a source to a sink of river phytoplankton.

## Introduction

The sources of phytoplankton in rivers are (1) periphyton sloughing due to physical disturbances or (2) a supplied source of phytoplankton from lakes, reservoirs or still waters. Compared with other aquatic systems, algal abundance counts (per unit total phosphorus) followed this sequences: rivers<impoundments<natural lakes (Soballe et. al. 1987). Abiotic factors regulate the presence of phytoplankton within the river. Light and temperature control growth but ultimately river discharge limits phytoplankton persistence (Allan 1995). River discharge and phytoplankton abundance are inversely related. Similarly, horizontal flow controls the available time attached or suspended algae interact with transport materials, such as nutrients (Soballe et. al. 1987).

Structural modifications in river channels ultimately usually result in decreasing river velocity. This decrease in velocity corresponds to an increase in water residence time within the river. Natural lakes (Hynes 1970) and man-made reservoirs (Coutant 1963) can supply plankton to the downstream river. In some cases, reservoirs can function as a sink for river algae (Soballe et. al. 1984), and algae released from the hypoliminion into the rivers immediately below the dam are unsuited for the lotic environment (Coutant 1963). However, this may not be true for natural lake outflows.

Water ages as it flows down the rivers and phytoplankton abundance will increase downstream (Hynes 1970). Phytoplankton will spend longer in the river and thus have time to reproduce especially in eddies and pools. Benthic algae can prosper in a river due to a mixture of biotic and abiotic factors. The balance between biomass accrual and losses controls benthic algal abundance within the river (Biggs 1996). Biomass losses due to high water flows, abrasion and grazing by scrapers transform benthic algae to suspended algae.

In this chapter, I examine longitudinal patterns of phytoplankton abundance and nutrient availability in the lower Kalamazoo River, between the two larger reservoirs (Morrow Lake and Lake Allegan). The roles of these reservoirs as well as several smaller impoundments as sources of algae to the river are emphasized.

*Study site*

The Kalamazoo River watershed is located in the southwestern Michigan, with a watershed area of approximately 5,231 $km^2$. The Kalamazoo River runs approximately 260 km through 10 counties of variety of land uses (developed areas, farmland, and forest including Allegan State Game Area). Six run-of-the-river impoundments (four small decommissioned ones and two larger ones producing hydropower) are located on the Kalamazoo River. A decommissioned impoundment is a remnant of an active dam where the turbines, gates and spillway were removed. The only remaining structures are the concrete walls that may be lowered and the foundation that forms the sill.

The order of impoundments starting upstream heading downstream are (1) Morrow Lake, a hydropower reservoir, (2) the Plainwell impoundment, a decommissioned impoundment, (3) the Otsego impoundment, a decommissioned impoundment, (4) the Trowbridge impoundment, a decommissioned impoundment, (5) Allegan City Dam, a non-hydropower dam, and (6) Lake Allegan, a hydropower reservoir. Table 1 lists the impoundments' morphometric characteristics. Morrow Lake is located 69 km upstream of Lake Allegan.

Consumers Power Company created Morrow Lake in 1939 for the Bryce E. Morrow Power Plant in Comstock, Michigan. The plant was fueled by coal, which supplied energy to the boiler to produce steam. Morrow Lake's water was pumped through condensers, which condensed hot steam from the boilers to hot water, which was then pumped back into boilers. The two electric generators were powered by steam turbines, which produced 35,000 kilowatts each.

In 1969, the plant was converted to natural gas power, and in 1971 was rebuilt to use oil. Consumers Power closed Morrow Plant in July 1982 due to high operating costs and reduction in power consumption. STS Consultants Ltd. purchased about 1,400 acres surrounding Morrow Plant (excluding the building and equipment) to construct a new hydroelectric facility. The hydroelectric plant now generates about 1,000 kilowatts of electricity. Currently, Morrow Impoundment is owned by STS Hydropower and is not licensed under the Federal Energy Regulation Commission (FERC).

Michigan Paper Company built the Plainwell Dam in 1902, as a part of Foote' hydroelectric facility. In 1965 operations at the Plainwell Dam were terminated and in 1967 Consumers Power Company deeded the dam to the Michigan Department of Natural Resources for recreational purposes. The dam was officially decommissioned in 1970-1971.

Otsego Dam was built in 1903-1904 as a part of Foote' Trowbridge dam hydroelectric facility downstream. In the 1980s, the dam was deeded to Michigan Department of Natural Resources and decommissioned.

Trowbridge Dam was constructed in 1898 and was Michigan's first high voltage hydroelectric generation and transmission system. The dam was designed by James Foote. In 1910 the dam operations were terminated and in 1965, the dam deeded to the Michigan Department of Natural Resources. The dam was decommissioned in 1986.

Allegan City Dam was constructed in 1837 and served as the central growing point for Allegan, Michigan. The dam water wheel provided energy for various mills in the area. In 1996 Allegan City purchased the dam from Imperial Carving Company. The current purpose of the dam is to maintain the water levels of the Kalamazoo River above the impoundment, where the pool is adjacent to city of Allegan downtown waterfront property.

Calkins Dam was constructed by the city of Allegan from 1931-1936. The city's municipal utility operated the dam from 1936 to 1968. In 1968, Consumers Energy purchased the dam and to date operates the dam.

A decommissioned impoundment is a remnant of an active dam where the turbines, gates and spillway were removed. The only remaining structures are the concrete walls that may be lowered and the foundation that forms the sill.

*Total Maximum Daily Load (TMDL) for Lake Allegan*

The Michigan Department of Environmental Quality (MDEQ) monitored Lake Allegan from April through September of the years 1988, 1994, 1996 and 1997, and determined that total phosphorus concentrations averaged 96 μg/L and ranged from 69 to 125 μg/L (Heaton 2001). In 1998, Lake Allegan remained classified as hypereutrophic, exhibiting high nutrient and chlorophyll *a* concentrations (67 μg/L), excessive turbidity (0.6 m Secchi depth), low dissolved oxygen, and an unbalanced fish community dominated by carp and channel catfish (87% community average) (MDEQ 2001). In 1999, MDEQ developed a phosphorus Total Maximum Daily Load (TMDL) for Lake Allegan. A reduction of total phosphorus in Lake Allegan should improve water quality conditions if it is indeed the main factor controlling algal growth, which is the premise of the TMDL

*Objective and Hypotheses*

This research was prompted by observing high algal abundances in Lake Allegan inflow water, and wondering if the algae exiting Morrow Lake were the same algae observed entering Lake Allegan. I hypothesized that the higher algal abundance in Lake Allegan was due to either or both of the following:

(1) Phytoplankton from Morrow Lake are transported 69 km downstream into Lake Allegan

(2) The higher algal biomass at the Lake Allegan inflow is due to the algal biomass build-up between Morrow Lake and Lake Allegan as the river passed through semi-impounded reaches caused by decommissioned impoundments (Plainwell, Otsego, Trowbridge and Allegan city dam), which decrease stream flow allowing for algal growth.

## Methods

### *Field Sampling*

Three longitudinal surveys were conducted over a two-year period (2003-2004) with one at a low discharge on 18 August 2003, one at a medium discharge on 3 September2004, and one at a high discharge on 2 July 2004. The surveys began at the Morrow Lake inflow and concluded at the Lake Allegan outflow. Table 2 shows the sampling locations with distances from the Morrow Lake inflow at E. Michigan Ave. Special emphasis was placed on sampling above and below the Plainwell, Otsego and Trowbridge decommissioned impoundments in addition to above and below Morrow Lake and Lake Allegan, the two active hydropower reservoirs. A longitudinal survey within Morrow Lake was conducted on 27 August 2004; the survey started at the riverine zone and progressed toward the impoundment wall.

### *Laboratory Analyses*

Water samples were analyzed for total phosphorus. Total soluble P (in filtered water) and total P (unfiltered water) were determined after persulfate digestion in a pressure steam sterilizer by colorimetric analysis of the resultant orthophosphate (Valderrama 1981, Langner and Hendrix 1982). The sterilizer was operated at 20 psi for two hours followed by a gradual cooldown period. Standards included ATP to ensure efficient oxidation of organic matter. Reagent and water contributions to the analytical blank were determined by varying the reagent amount and only the reagent contribution was subtracted from sample absorbances (this was also routinely done for ammonium analyses). Sestonic chlorophyll *a* was filtered onto a Type A/E glass fiber filter and frozen. The filters were later halved and one half was extracted with 95% ethanol, and chlorophyll a in the extract was measured by fluorometry (Welschmeyer 1994). Water residence time was calculated from USGS discharge records and reservoir volumes. For Morrow Lake the closest gauging station was Comstock, for the Otsego and Plainwell impoundments the gauging station was Plainwell, and for Trowbridge impoundment, Allegan City Dam, and Lake Allegan the gauging station was Trowbridge. Morrow Lake and Lake Allegan residence times represent the average residence time preceding each sampling date. To calculate the average residence time over days. First, the daily residence time for each sampling day was calculated from the daily discharge and reservoir volume. Once the daily residence time was determined for that sampling day, I started with that sampling day and counted back the number of days equal to the residence time estimate. Then the discharges for those proceeding days were summed and divided by the sampling day residence time. This yielded a more accurate estimate of the average residence time over the interval proceeding sampling, when discharge was variable. Residence times of the Plainwell, Otsego and Trowbridge decommissioned impoundments represent the residence time on the sampling date for 2003 and 2004, calculated from the mean daily discharge and the volumes of water behind each impoundment. Volumes were determined from digital elevation models of bathymetry obtain from Cynthia Rachol of the U.S. Geological Survey.

**Results**

Discharge varied throughout the season with the highest discharge during February through May and the lowest discharge during June through September (Figure 2). Discharge was higher overall in 2004 than in 2003. The mean discharge for March through September over 72 years (1931-2003) was 26.38 $m^3$/sec. The mean for March through September 2003 was 20.6 $m^3$/sec and 2004 it was 29.72 $m^3$/sec.

*Kalamazoo River longitudinal survey conducted at low discharge*

On the low-discharge survey date (18 August 2003), The mean daily discharge at the Comstock gauge was 9 $m^3$/sec and at the Trowbridge gauge it was 20 $m^3$/sec. River water temperature increased within Morrow Lake and fluctuated little as the river passed though the decommissioned impoundments, until the temperature increased again within Lake Allegan (Figure 3). Oxygen concentrations increased within Morrow Lake and slightly declined downstream, then gradually increased as the river passed through the decommissioned impoundments, peaking at the inflow to Lake Allegan (Figure 3).

Conductance declined within Morrow Lake, increased shortly thereafter, and remained constant downstream through the decommissioned impoundments into Lake Allegan, followed by declined in the Lake Allegan outflow (Figure 4). The pH increased within Morrow Lake and declined downstream, then gradually increased through the decommissioned impoundments, and peaking at the inflow to Lake Allegan followed by a decrease in the outflow (Figure 4).

Total phosphorus concentrations increased within Morrow Lake and gradually declined downstream, remained constant as the river passed through the decommissioned impoundments, then decreased within Lake Allegan followed by an increase in the outflow (Figure 5). Chlorophyll *a* concentrations increased considerably in Morrow Lake, followed by a marked decline downstream, then gradually increased again as the river passed through the decommissioned impoundments, until the concentration peak within Lake Allegan follow by a noticeable declined within Lake Allegan (Figure 5).

*Kalamazoo River longitudinal survey conducted at medium discharge*

On the medium-discharge survey date (3 September 2004), The mean daily discharge at the Comstock gauge was 25 $m^3$/sec and at the Trowbridge gauge it was 41 $m^3$/sec. River water temperature remained constant throughout the entire reach (Figure 6). Oxygen concentrations slightly decreased within Morrow Lake and remained fairly constant as the river passed though the decommissioned impoundments and Lake Allegan, except for a marked peak at one sampling station (Figure 6).

Conductance was fairly constant throughout the entire reach (Figure 7). The pH declined within Morrow Lake and fluctuated as the river passed through the decommissioned impoundments, there was a the pH peak before Lake Allegan (corresponding with the oxygen peak), followed by a noticeable decline above and within Lake Allegan (Figure 7).

Total phosphorus concentrations decreased within Morrow Lake, remained constant as the river passed through the decommissioned impoundments and decreased within Lake Allegan (Figure 8). The chlorophyll *a* concentration increased considerably within Morrow Lake followed by a decrease as the river passed through the decommissioned impoundments, then increased again within Lake Allegan (Figure 8).

Ammonium concentrations showed no pattern through out the river (Figure not shown). The nitrate concentrations decreased within Morrow Lake and gradually increased and remain steady through the river and declined within Lake Allegan (Figure not shown).

*Kalamazoo River longitudinal survey conducted at high discharge*

On the high-discharge survey date (2 July 2004), The mean daily discharge at the Comstock gauge was 56 $m^3$/sec and at the Trowbridge gauge it was 85 $m^3$/sec. River water temperature increased slightly within Morrow Lake and decreased immediately downstream, then remained fairly constant as the river passed through the decommissioned impoundments, and slightly increased within Lake Allegan (Figure 9). Oxygen concentrations increased within Morrow Lake and gradually increased as the river passed through the decommissioned impoundments, peaked within Lake Allegan (Figure 9).

Conductance was fairly constant throughout the entire reach (Figure 10). The pH increased within Morrow Lake and gradually increased as the river passed through the decommissioned impoundments until the concentration peaked above Lake Allegan followed by a declined in the outflow (Figure 10).

Total phosphorus concentrations increased between the Morrow Lake inflow and outflow and remained constant as the river passed through the decommissioned impoundments, until concentrations declined above and within Lake Allegan (Figure 11). Chlorophyll *a* concentrations were variable across the reach with an increase in Morrow Lake and through the decommissioned impoundments, peaking at the inflow to Lake Allegan with a large decline in the outflow (Figure 11).

Ammonium concentrations showed no pattern through out the river (Figure not shown).

*Morrow Lake longitudinal survey*

The river discharge at Comstock was 26 $m^3$/sec when the longitudinal transect within and just below Morrow Lake was sampled on 27 August 2004. Morrow Lake total phosphorus concentrations gradually increased in the riverine zone, yet chlorophyll *a* concentrations were low there (Figure 12). Chlorophyll *a* concentrations increased in the lower half of the reservoir and peaked at the dam. Downstream from the dam, total phosphorus concentrations were constant, whereas the chlorophyll *a* concentrations declined at first, then leveled out (Figure 12).

A graph of three measured forms of phosphorus shows that particulate phosphorus (total minus dissolved phosphorus) and soluble organic phosphorus (total dissolved minus soluble reactive phosphorus) were roughly equal in importance (Figure 13). Soluble reactive phosphorus concentrations were low throughout the entire reservoir and downstream. Downstream from the dam, total phosphorus, total soluble phosphorus, and soluble reactive phosphorus concentrations were constant (Figure 13).

**Discussion**

The nutrient concentrations of the Kalamazoo River make the river eutrophic by lakes and reservoirs standards (Vollenweider 1975, Rechow and Chapra 1983). There are many point-source discharges, including substantial wastewater treatment plants, at Battle Creek and Kalamazoo that influence my sampling reach. Nonpoint sources of phosphorus are also thought to be important because the sum of known point sources can only account for less than half of the river's phosphorus load (MDEQ 1999). The water quality problems associated with excessive nutrient loading into the river are largely due to phytoplankton growth, which is most evident in the impounded reaches. This study indicates that the smaller decommissioned impoundments are sites of significant algal growth, at least at low discharge, and thus they appear to exacerbate the water quality problems.

The 18 August 2003 survey was conducted at low discharge, the 3 September 2004 survey was conducted at medium discharge, and 2 July 2004 survey was conducted at high discharge. Longitudinal differences were most marked at low discharge. The average river temperature for the three surveys was 26 C. Water temperatures sometimes increased within Morrow Lake and Lake Allegan, but remained constant through the decommissioned impoundments. On 2 of the 3 dates, there was net oxygen production during the summer in the active reservoirs and gradual increases in oxygen as the river passed through the decommissioned impoundments. River conductance averaged 630 μS/cm with slight decreases on 2 of the 3 dates during the summer within Morrow Lake and Lake Allegan, whereas the decommissioned impoundments had no effect on conductance. The river pH increased during the summer within the active reservoirs and showed gradual increases on 2 of the 3 dates as the river passed through the decommissioned impoundments.

Total phosphorus concentrations were relatively high throughout the reach independent of river discharge. The active reservoirs either serve as a sink or a source for total phosphorus. The average total phosphorus concentrations for the surveys were 80 μg/L for the 18 August 2003 survey, 79 μg/L for the 2 September 2004 survey, and 79 μg/L for the 2 July 2004 survey. The decommissioned impoundments had a slight effect on increasing total phosphorus concentrations, possibly though sediment resuspension or bank erosion, regardless of discharge.

*Algal Growth in the River*

The surveys began at the Morrow Lake inflow and ended 69 km downstream at the Lake Allegan outflow. It is known that reservoirs prompt algal growth by increasing water residence time. Morrow Lake and Lake Allegan are shallow, well-mixed (non-stratifying), reservoirs with short residence times (less than 11 days for both; See chapter 1 for more detail. These two reservoirs are clearly sites of substantial algal growth, especially at lower discharge.

Phytoplankton was always present at high amounts in the reservoirs over the summer sampling periods and reservoir discharge may affect the algal abundance downstream. However, at least at low discharges, algae exiting Morrow Lake do not appear to be transported to Lake Allegan. Instead, that algae largely disappears and new algal growth appears. A noticeable phytoplankton decline occurred during low discharge below the Morrow Lake outflow, between 15-35 km river sampling distance (Figure 5), but this was not apparent at medium discharge (Figure 8). During the high discharge survey, the D Ave bridge sampling location was closed for construction and thus data are incomplete in this reach. Possible loss processes that could account for the disappearance of algae below Morrow Lake include consumption by benthic filter feeders and flocculation out of the water column. An invasive clam, *Corbicula fluminea*, was observed at high densities in this reach, and this species is capable of filtering phytoplankton from the river. Net-spinning cadisflies (Hydrosychidae) were also abundant. At low discharge such benthic filter feeders would be expected to reduce algal densities more effectively.

The five decommissioned impoundments (Plainwell, Otsego City, Otsego, Trowbridge and Allegan City) lie between the 40-65 km river sampling distances and their cumulative effect on water residence time could reestablish the algae population within the river. Decommissioned impoundments in the Kalamazoo River decrease river velocity and cause pooling behind the impoundments. For the 2003-2004 discharge year, each impoundment's residence time varied 0.01-0.73 days (Table 1), the cumulative residence time within the five decommissioned impoundments was only 1.5 days at low discharge and less than quarter of a day at high discharge. The decommissioned impoundments would thus not seem to encourage much additional phytoplankton growth by their effects on residence time. Yet, Figure 5 clearly showed a stepwise increase in chlorophyll *a* concentration as the river passed through the decommissioned impoundments, until concentrations peaked above and within Lake Allegan. Lake Allegan's residence time varied from 3-11 days, and during the summer of 2003 the residence time was as high as 11 days, which was long enough for algae to thrive. Retention times of around 7 days or less limit phytoplankton production and species composition (Thornton 1990). It is possible that the impoundments encourage algal growth not only by increasing water residence time, but also by discouraging benthic filter feeders, perhaps because of finer sediments and lower velocities. Another possibility is that within the impounded reaches there are significant off-channel waters with much longer residence times, and these supply algae to the rivers. My estimates of residence time assume thorough mixing of impounded waters.

During the summer even at relatively high discharge, the decommissioned impoundments increased chlorophyll *a* concentrations within the river, until concentrations peaked above Lake Allegan (Figure 11). It is unusual to observe algae abundance increasing at high flows, but the flows occurred during the summer when conditions are prime for algae. Lake Allegan's longest residence time for 2004 was 7 days. The Lake Allegan outflow had a noticeable decline in chlorophyll *a*, which suggested algae were reduced in abundance in the reservoir, perhaps via loss to zooplanktonic grazers. Zooplankton require a somewhat longer residence time than phytoplankton, and only Lake Allegan may provide sufficient time for zooplankton reproduction.

*Implications for the TMDL*

Net algal growth seems to be promoted by pools and backwaters created by the decommissioned impoundments. Therefore, removal of some or all of those impoundments to restore a free-flowing river channel would seem likely to diminish the problem of excessive algal growth in Lake Allegan, converting the impounded reaches from a source to a sink of river phytoplankton. This is especially true during the summer at a low discharge, which is when algal blooms in Lake Allegan are most likely to be a problem.

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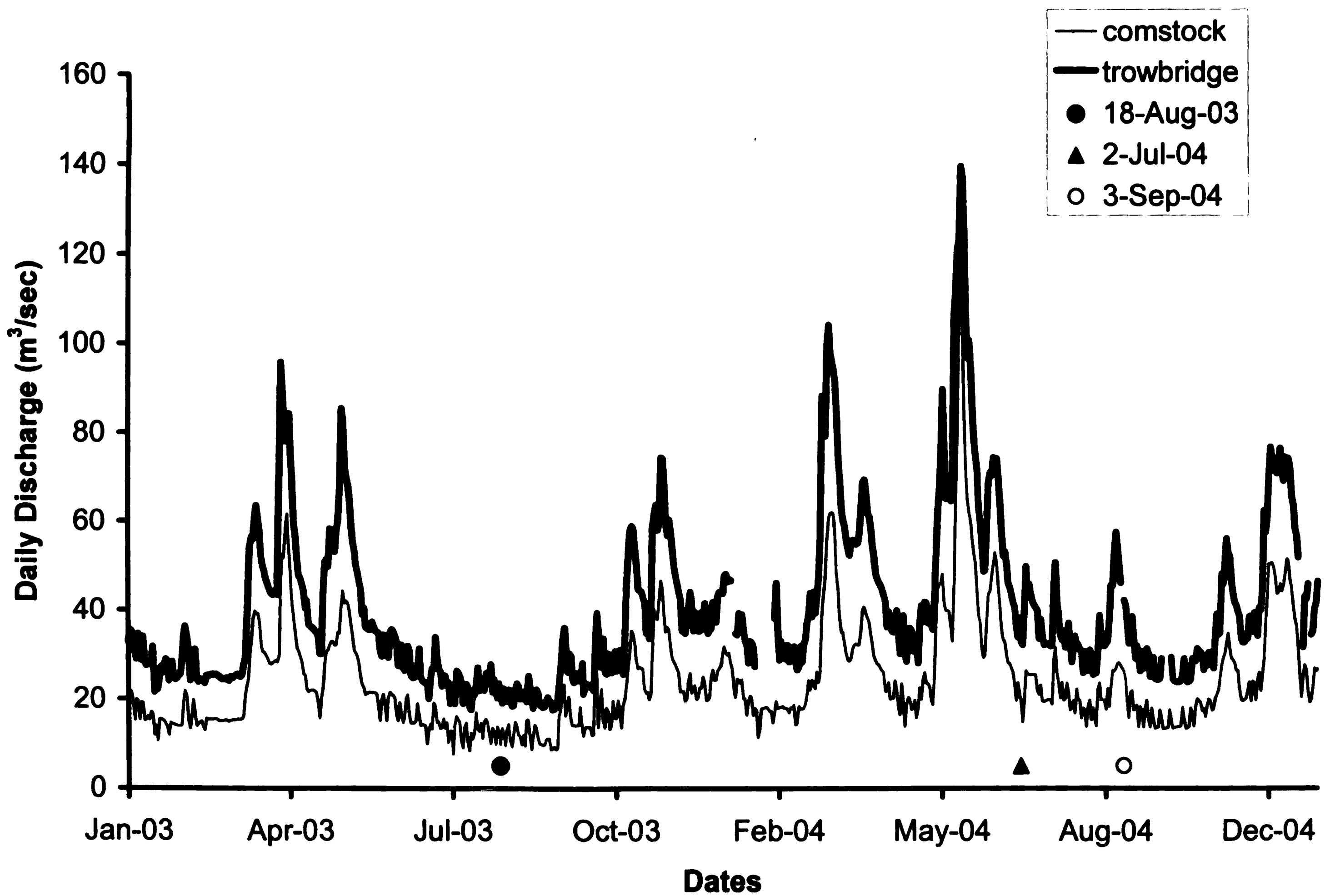



Figure 2. Mean daily discharge below Morrow Lake (Comstock gauge) and above Lake Allegan (Trowbridge gauge). The individual symbols represent survey sample days. Data from the U.S. Geological Survey.

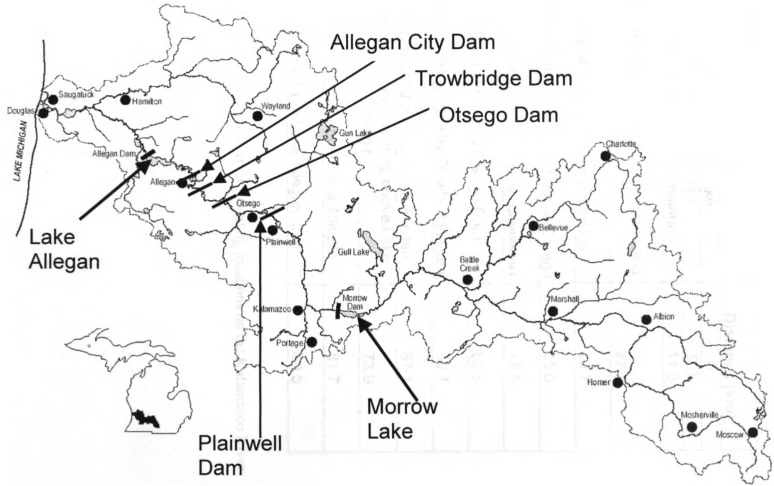



Figure 1. Kalamazoo River and Watershed

| Location | Distance (km) |
| --- | --- |
| Above Morrow Lake | 0 |
| Below Morrow Lake | 9.3 |
| Mosel Rd near Parchment | 11.3 |
| D Ave bridge (between Kalamazoo and Plainwell) | 27.7 |
| City of Plainwell, Railroad bridge | 40.7 |
| Below Plainwell Dam and above Otsego | 45.0 |
| Farmer Rd in Otsego (below Menasha) | 47.5 |
| River Rd. below Otsego Dam | 52.5 |
| 26th St. Bridge (below Trowbridge Dam) | 60.1 |
| Williams Rd. bridge above Allegan | 67.1 |
| Allegan city waterfront, above Lake Allegan | 73.9 |
| M89 Bridge at upper Lake Allegan | 81.7 |
| Outflow from Lake Allegan dam | 89.5 |

Table 2: Longitudinal river sampling locations on the Kalamazoo River

| Reservoirs | Area (m2) | Mean depth (m) | Volume (103m3) | Residence Time (days) | The distance from Morrow Dam (km) |
|---|---|---|---|---|---|
| Morrow Pond [H] | 4,451,542 | 1.66 | 7,401 | 2 - 6 | 0 |
| Plainwell [D] | 407,257 | 1.30 | 529.00 | 0.05 - 0.73 | 34.70 |
| Otsego [D] | 129,737 | 0.88 | 114.00 | 0.01-0.15 | 42.98 |
| Trowbridge [D] | 431,054 | 0.75 | 322.00 | 0.02 - 0.21 | 50.39 |
| Allegan City Dam [D] | 546,326 | 1.80 | 986.00 | 0.08-0.65 | 64.63 |
| Lake Allegan [H] | 6,422,361 | 3.30 | 21,200 | 3 - 11 | 80.177 |

Table 1. Morphometric data: Hydropower Reservoir [H] and Decommissioned Impoundments [D]

Figure 3. Longitudinal river survey of temperature and oxygen at low discharge (18 August 2003). The solid line boxes represent the active hydropower reservoirs (Morrow Lake and Lake Allegan) and dashed line boxes represent the decommissioned impoundments (Plainwell dam, Otsego dam, Trowbridge dam and Allegan City dam).

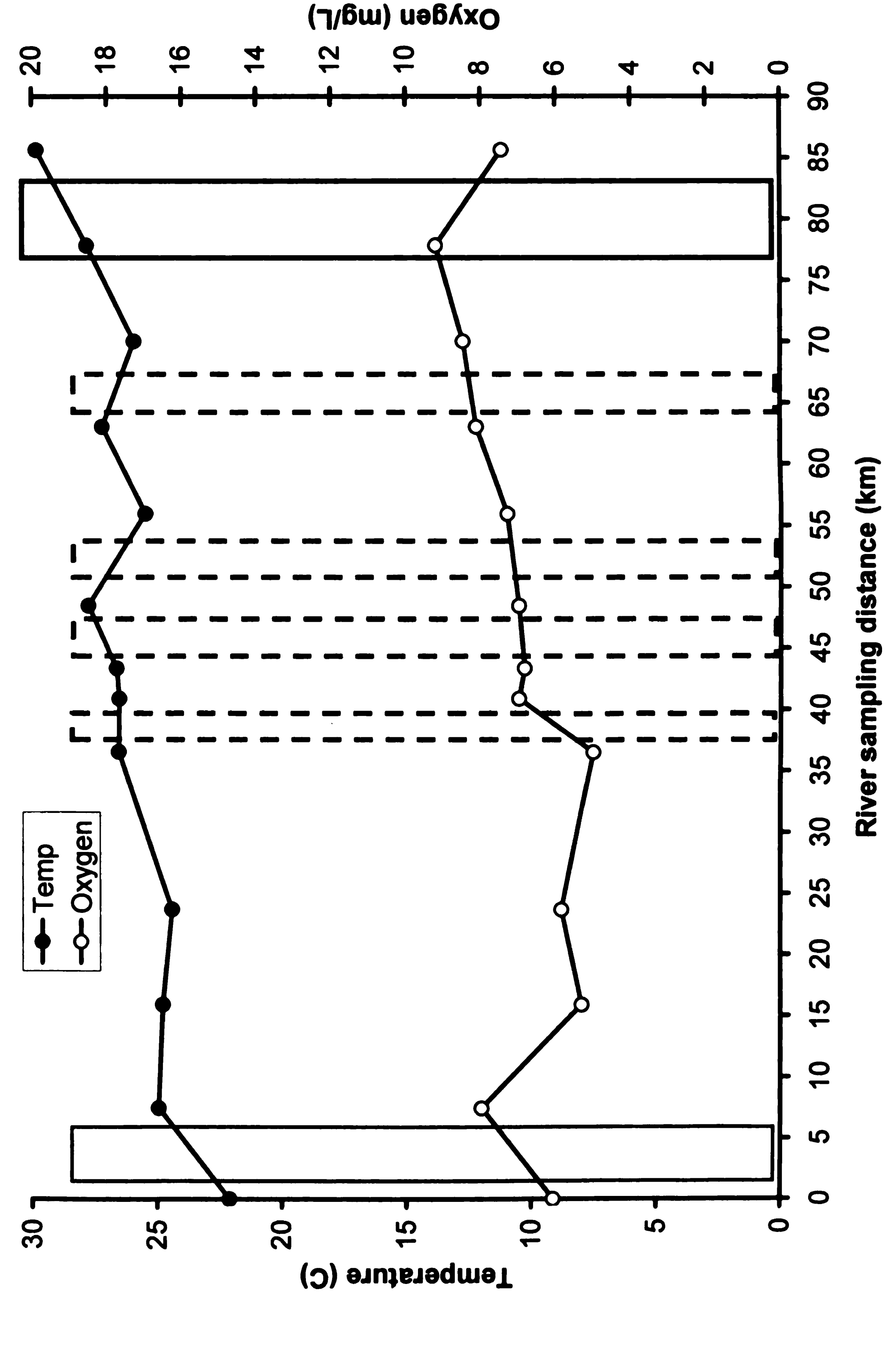
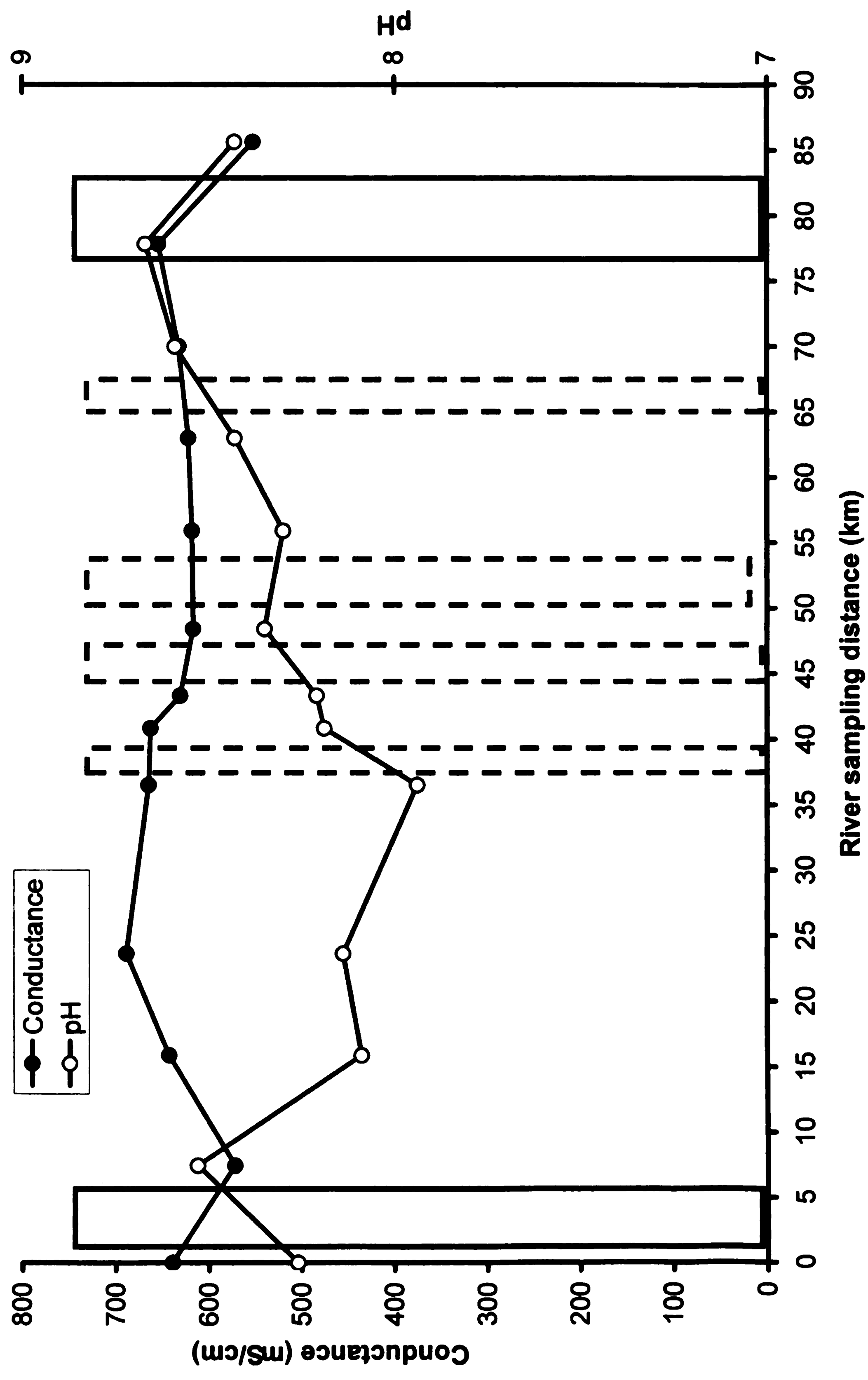
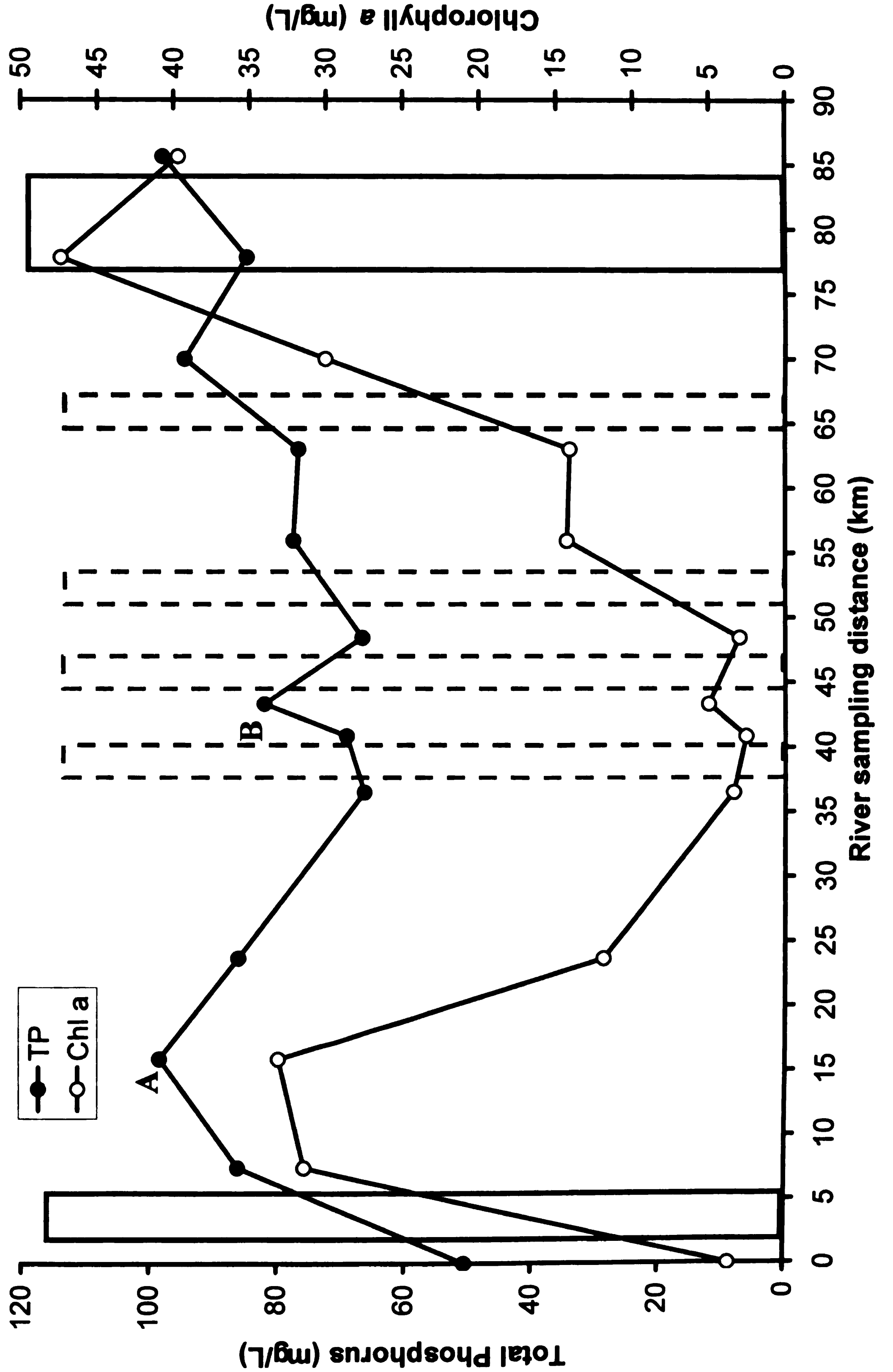

Temp
Oxygen
Temperature (C)
Oxygen (mg/L)
River sampling distance (km)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
0
5
10
15
20
25
30
0
2
4
6
8
10
12
14
16
18
20

Figure 4. Longitudinal river survey of conductance and pH at low discharge (18 August 2003). The solid line boxes represent the active hydropower reservoirs (Morrow Lake and Lake Allegan) and dashed line boxes represent the decommissioned impoundments (Plainwell dam, Otsego dam, Trowbridge dam and Allegan City dam).



Conductance
pH
Conductance (mS/cm)
pH
River sampling distance (km)

Figure 5. Longitudinal river survey of total phosphorus and chlorophyll *a* at low discharge (18 August 2003). The solid line boxes represent the active hydropower reservoirs (Morrow Lake and Lake Allegan) and dashed line boxes represent the decommissioned impoundments (Plainwell dam, Otsego dam, Trowbridge dam and Allegan City dam). The letters represent point source discharges to the Kalamazoo River (A) Kalamazoo Waste Water Treatment Plant and (B) Menasha Paper Company.



TP
Chl a
A
B
Total Phosphorus (mg/L)
Chlorophyll a (mg/L)
River sampling distance (km)
0
20
40
60
80
100
120
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90

Figure 6. Longitudinal river survey of temperature and oxygen at medium discharge (3 September 2004). The solid line boxes represent the active hydropower reservoirs (Morrow Lake and Lake Allegan) and dashed line boxes represent the decommissioned impoundments (Plainwell dam, Otsego dam, Trowbridge dam and Allegan City dam).

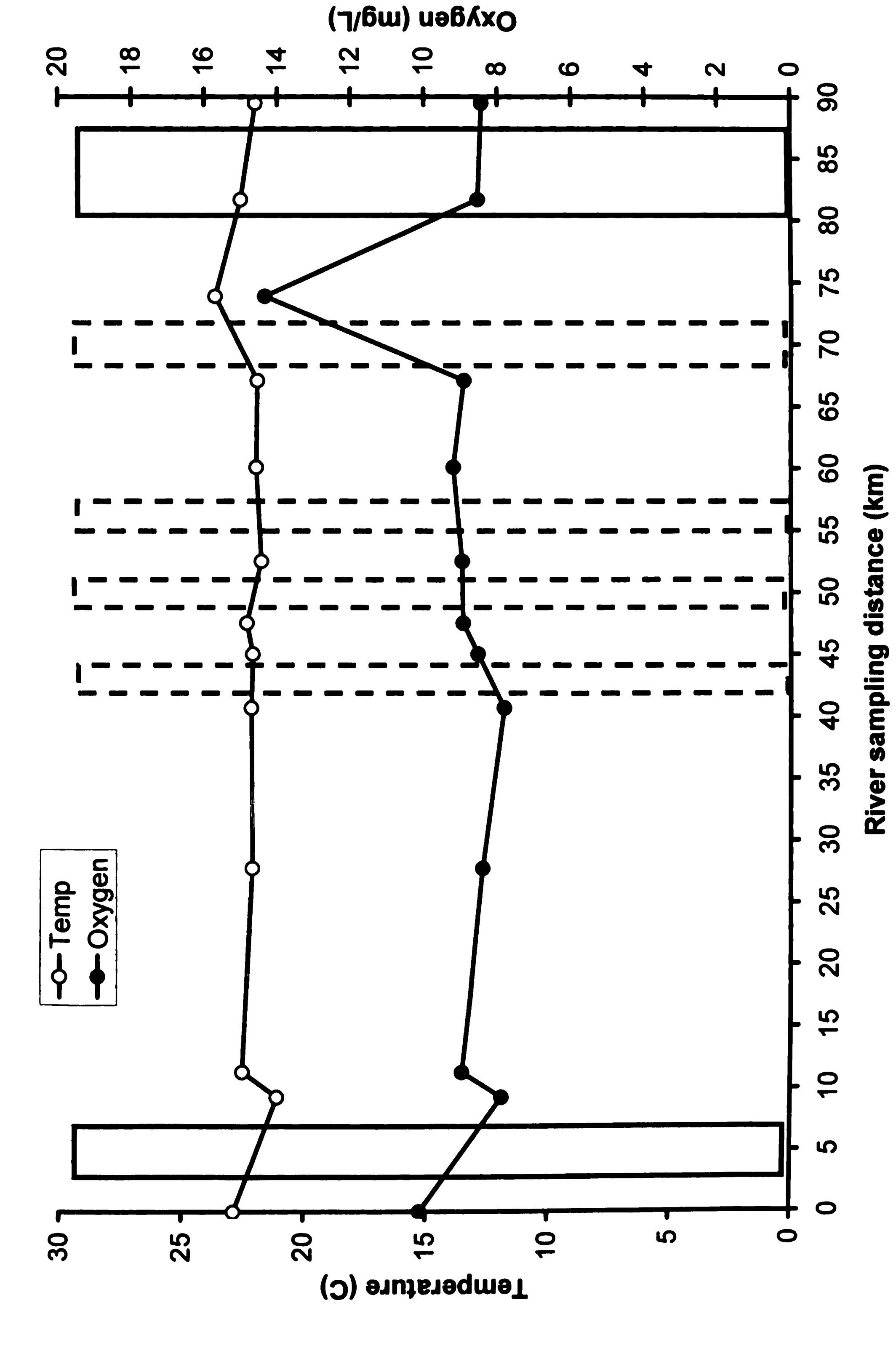
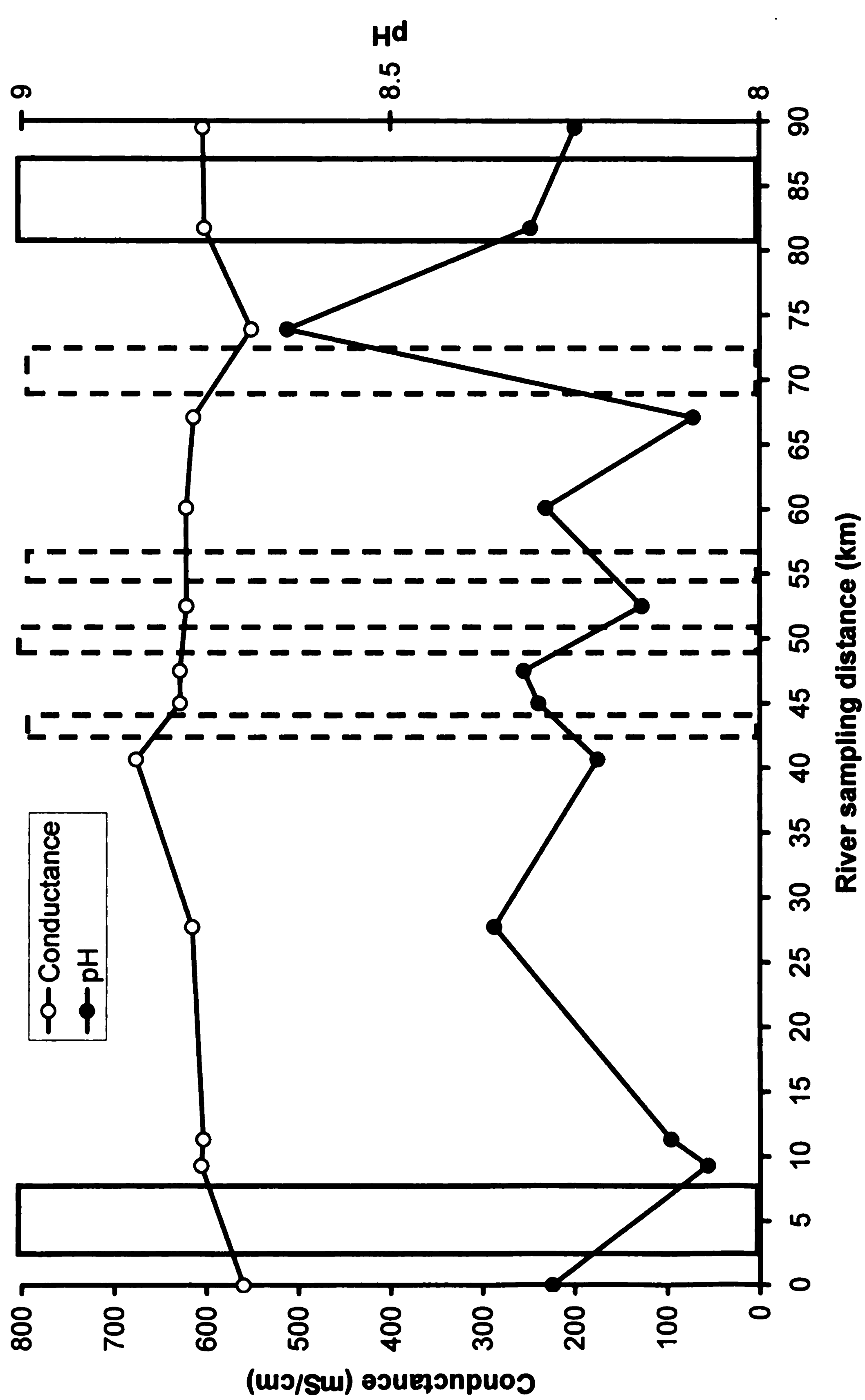
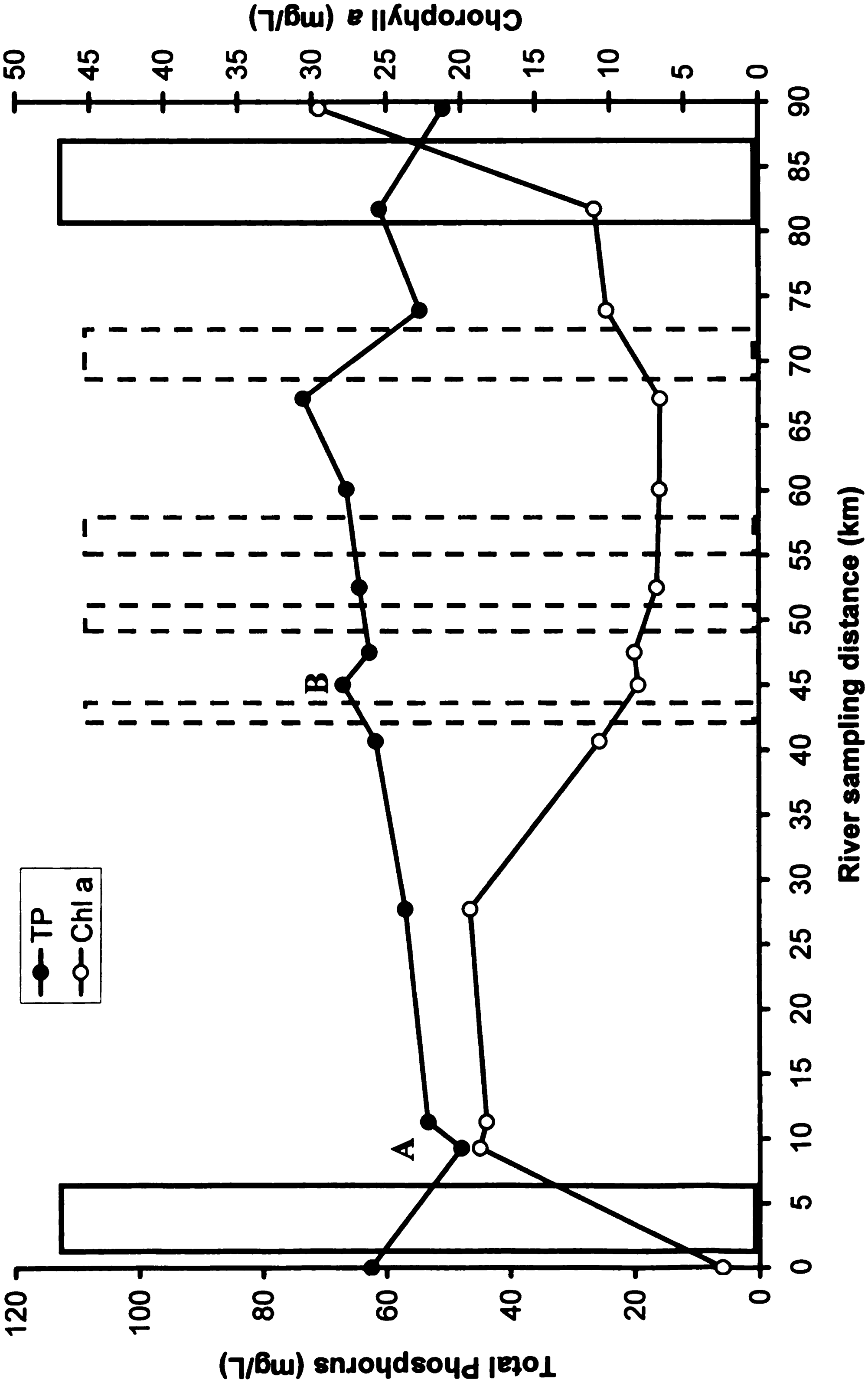

Oxygen (mg/L)
Temperature (C)
River sampling distance (km)
Temp
Oxygen
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
0
2
4
6
8
10
12
14
16
18
20
0
5
10
15
20
25
30

Figure 7. Longitudinal river survey of conductance and pH at medium discharge (3 September 2004). The solid line boxes represent the active hydropower reservoirs (Morrow Lake and Lake Allegan) and dashed line boxes represent the decommissioned impoundments (Plainwell dam, Otsego dam, Trowbridge dam and Allegan City dam).



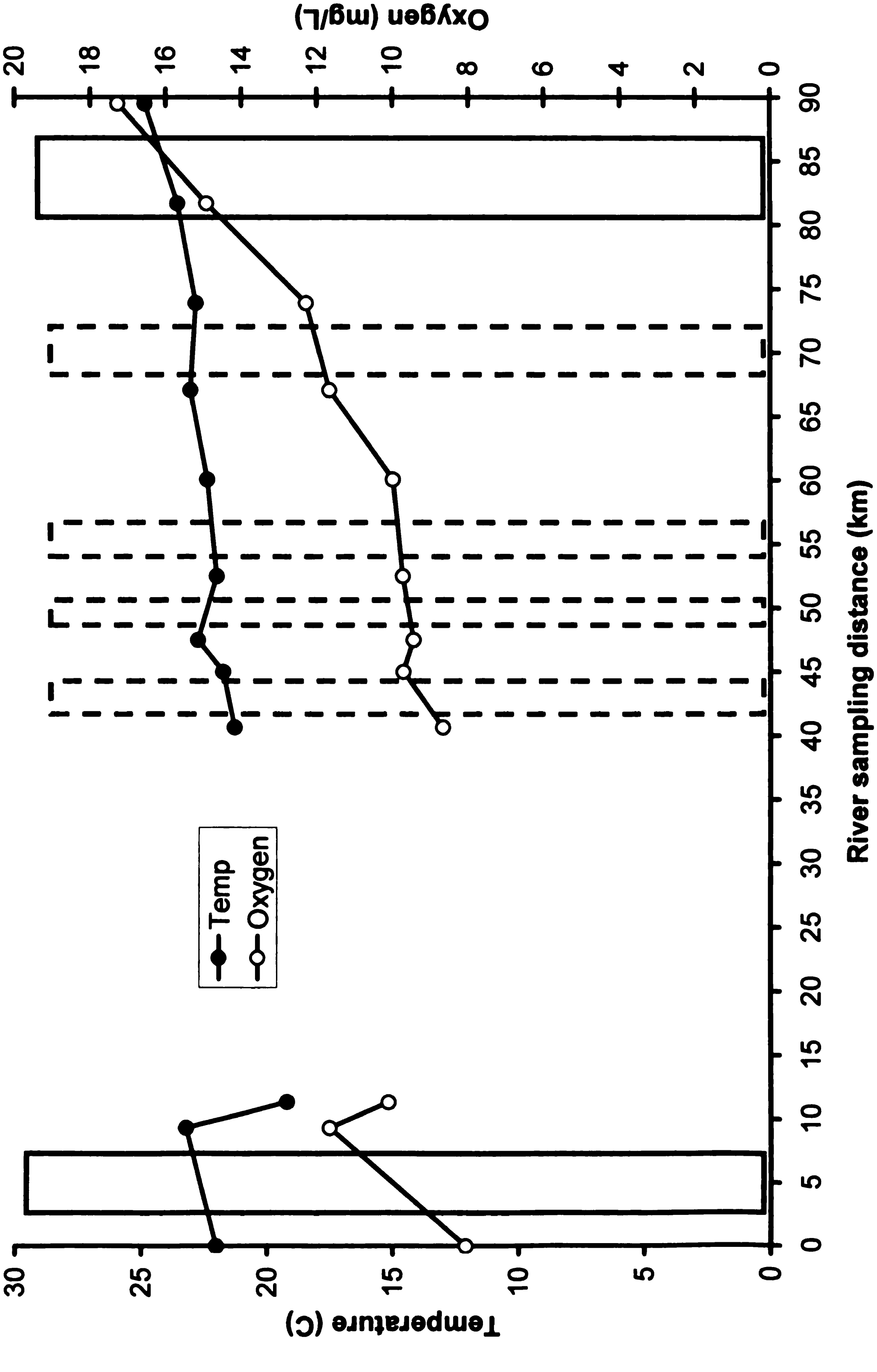
Conductance
pH
Conductance (mS/cm)
800
700
600
500
400
300
200
100
0
River sampling distance (km)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
pH
9
8.5
8

Figure 8. Longitudinal river survey of total phosphorus and chlorophyll *a* at medium discharge (3 September 2004). The solid line boxes represent the active hydropower reservoirs (Morrow Lake and Lake Allegan) and dashed line boxes represent the decommissioned impoundments (Plainwell dam, Otsego dam, Trowbridge dam and Allegan City dam). The letters represent point source discharges to the Kalamazoo River (A) Kalamazoo Waste Water Treatment Plant and (B) Menasha Paper Company.



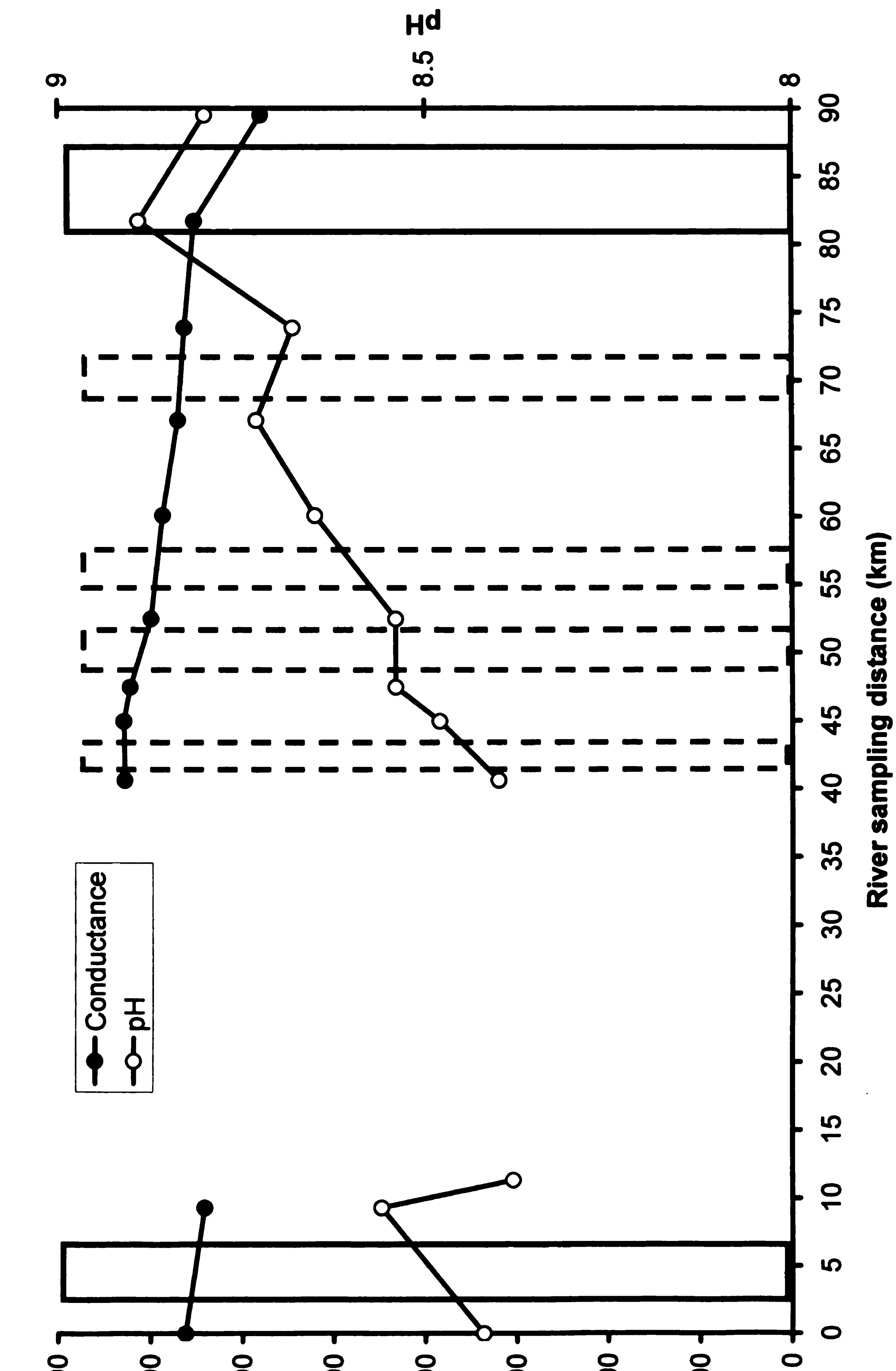
TP
Chl a
A
B
Total Phosphorus (mg/L)
0
20
40
60
80
100
120
Chorophyll a (mg/L)
0
5
10
15
20
25
30
35
40
45
50
River sampling distance (km)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90

Figure 9. Longitudinal river survey of temperature and oxygen at high discharge (2 July 2004). The solid line boxes represent the active hydropower reservoirs (Morrow Lake and Lake Allegan) and dashed line boxes represent the decommissioned impoundments (Plainwell dam, Otsego dam, Trowbridge dam and Allegan City dam).



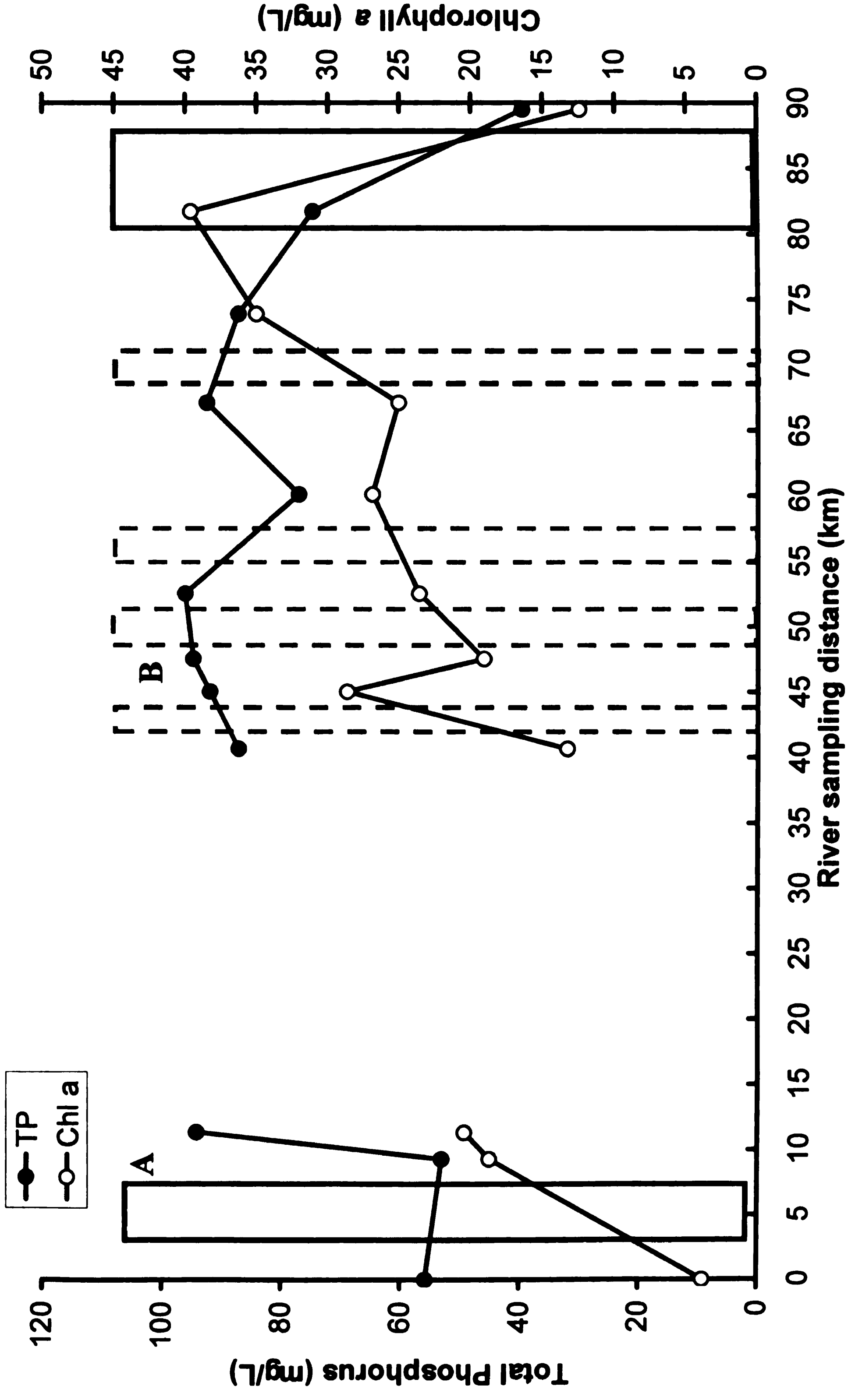
Temp
Oxygen
Temperature (C)
Oxygen (mg/L)
River sampling distance (km)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
2
4
6
8
12
14
16
18

Figure 10. Longitudinal river survey of conductance and pH at high discharge (2 July 2004). The solid line boxes represent the active hydropower reservoirs (Morrow Lake and Lake Allegan) and dashed line boxes represent the decommissioned impoundments (Plainwell dam, Otsego dam, Trowbridge dam and Allegan City dam).



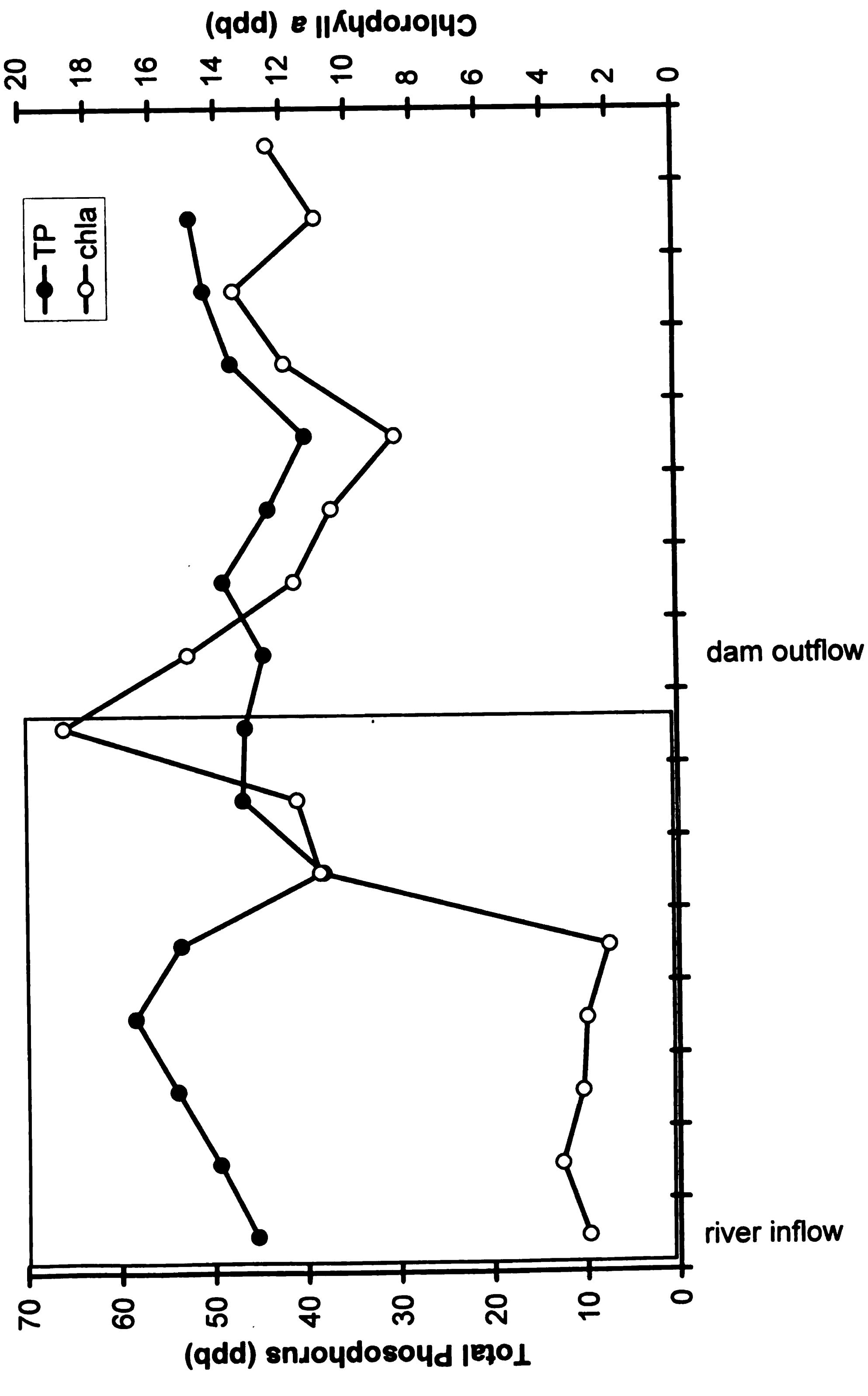
Conductance
pH
Conductance (ms/cm)
800
700
600
500
400
300
200
100
0
pH
9
8.5
8
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
River sampling distance (km)

Figure 11. Longitudinal river survey of total phosphorus and chlorophyll *a* at high discharge (2 July 2004). The solid line boxes represent the active hydropower reservoirs (Morrow Lake and Lake Allegan) and dashed line boxes represent the decommissioned impoundments (Plainwell dam, Otsego dam, Trowbridge dam and Allegan City dam). The letters represent point sources to the Kalamazoo River (A) Kalamazoo Waste Water Treatment Plant and (B) Menasha Paper Company.



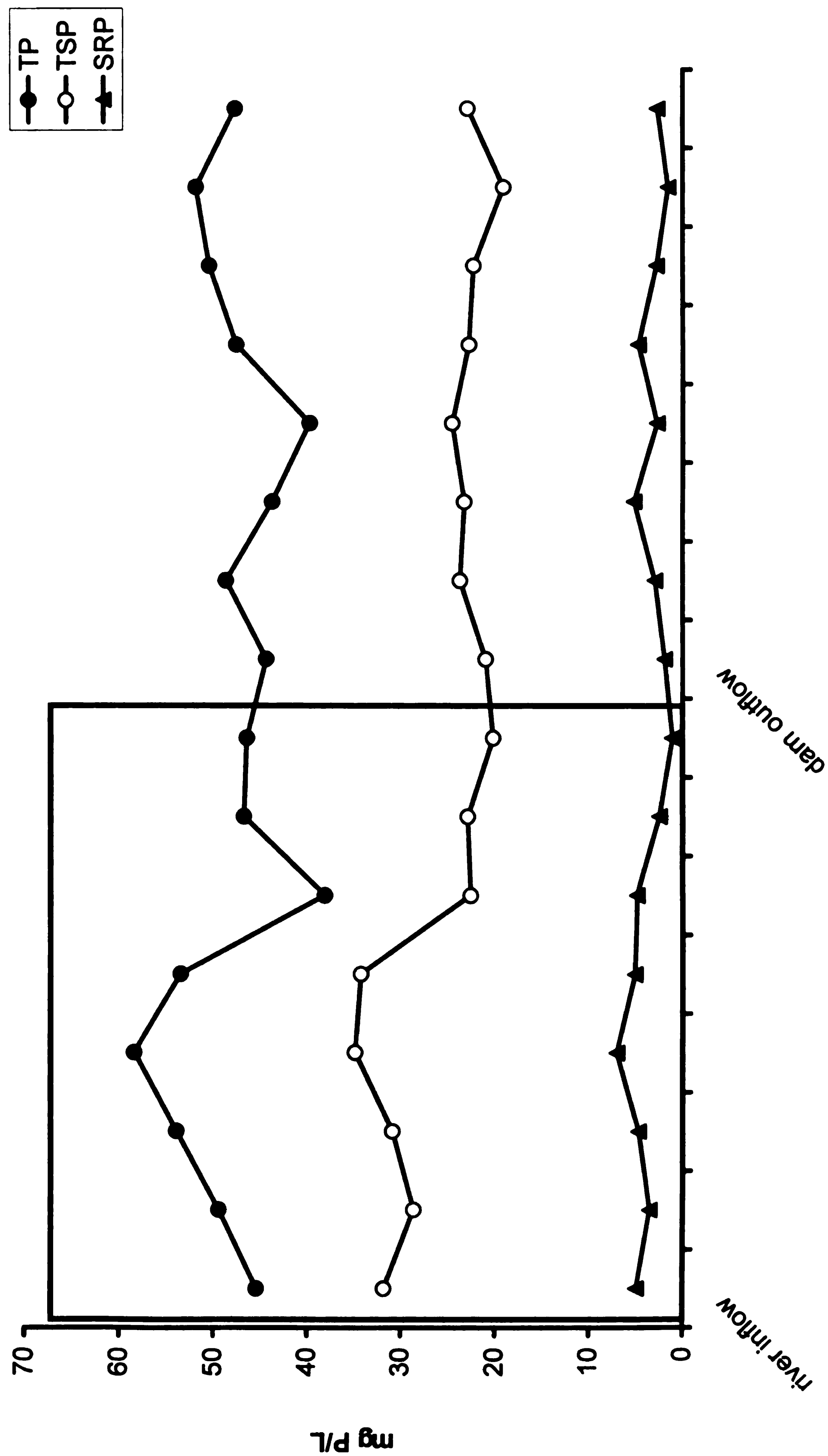
Total Phosphorus (mg/L)
Chlorophyll a (mg/L)
River sampling distance (km)
TP
Chl a
A
B

Figure 12. Longitudinal river survey of total phosphorus and chlorophyll *a* within Morrow Lake and downstream in the river (27 August 2004). The solid line box represents Morrow Lake.



Chlorophyll a (ppb)
Total Phosophorus (ppb)
TP
chla
river inflow
dam outflow

Figure 13. Longitudinal river survey of total phosphorus (TP), total soluble phosphorus (TSP), and soluble reactive phosphorus (SRP) within Morrow Lake and downstream in the river (27 August 2004). The solid line box represents Morrow Lake.



TP
TSP
SRP
mg P/L
70
60
50
40
30
20
10
0
river inflow
dam outflow