Limnological Analysis of Lake Eau Claire, Wisconsin

by

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PREFACE

This study was conducted in response to a request from the Lake Eau Claire Improvement Association, Eau Claire County and the State of Wisconsin Department of Natural Resources (WI-DNR) to the U.S. Army Engineer District (USAED), St. Paul, for planning assistance under Section 22 of the Water Resources Development Act (Public Law 93-251). Funding was provided by Eau Claire County, WI-DNR, and USAED, St. Paul. The study coordinator for Eau Claire County was Ms. Jean Schomish. The study coordinator for WI-DNR was Mr. Patrick Sorge. The Section 22 coordinator for the USAED, St. Paul, was Mr. Terry Engel.

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ABSTRACT

We examined external constituent loadings from major tributaries, discharges from Eau Claire Dam, internal phosphorus (P) fluxes from profundal sediments, and water quality conditions in Lake Eau Claire, Wisconsin in 1998. Water samples for external loadings and discharge determinations were collected from the Eau Claire River, and Hay and Muskrat Creeks, and the discharge of Lake Eau Claire Dam. Three stations were established in the main basin of the reservoir for limnological profiling during the ice-free period. Station 1 was located near the dam, station 2 at mid-reservoir, and station 3 near the headwaters.

There were a number of storm/snowmelt inflow periods to the reservoir during the ice-free period. During periods of snowmelt and storm inflow, the residence time of the reservoir declined to between 30 and < 15 days. During periods of nominal inflow the residence time was often > 50 days. The Eau Claire River dominated (>90%) annual water income and suspended seston, particulate organic matter, total nitrogen, and total P loading to the reservoir. Lake Eau Claire retained 51% and 24% of the annual seston and POM load, respectively and15% of the total P load, but was not a sink for total nitrogen (N).

Internal loading of P via release from oxic profundal sediment, measured in laboratory incubation systems, ranged between 0.5 and 2.1 mg m^{-2} d^{-1} (mean=1.1 mg m^{-2} d^{-1} ± 0.2 S.E.), while P release from anoxic sediment was very high (range = 9.1 to 17.5 mg m^{-2} d^{-1}; mean = 13.3 mg m^{-2} d^{-1} ± 1.0 S.E.). Lake-wide rates of P release from oxic and anoxic sediment, estimated via laboratory incubation techniques that were extrapolated over the summer period (June - August), averaged 4.9 mg m^{-2} d^{-1} (± 1.5 S.D.) which was similar to the rate of internal P loading of 7.2 mg m^{-2} d^{-1} (± 2.0 S.D.),

estimated via P mass balance in the reservoir during the summer. Overall, internal and external P loadings were equally important P sources to the reservoir during the summer.

Lake Eau Claire exhibited an extended period of thermal stratification and strong thermal stability in mid-June through early August. Associated with stratification was the occurrence of dissolved oxygen depletion and development of anoxia in the bottom waters of all stations. Coincident with hypolimnetic anoxic was the development of marked concentration gradients in phosphorus and ammonium-N, indicating internal loading of nutrients from the sediments. The Carlson and Wisconsin Trophic State Indices for Secchi disk transparency, viable chlorophyll *a* and total P ranged between 63 and 71, indicative of eutrophic conditions during the summer.

We evaluated two P management scenarios for Lake Eau Claire. The first scenario constituted management of external P loading (i.e., 25%, 50%, 75%, and 90% reduction in external loading) while the second scenario included management of external P loading with an 85% reduction in internal P loading (i.e., from 7 mg m^{-2} d^{-1} to 1 mg m^{-2} d^{-1}) to simulate a possible outcome of managing internal P loading in Lake Eau Claire via, for instance, an alum treatment. For scenario 1, only modest declines in total P and chlorophyll accompanied reductions in phosphorus loading, due to the important role that internal P loading played in sustaining algal blooms in the reservoir. With control of both internal and external P loadings, total P and chlorophyll reductions in the lake were much more dramatic. Thus, the value of watershed management for P reduction and improved water quality will probably be diminished by high internal P loading from the sediments within the reservoir. Nevertheless, we recommend reduction in external P loading from the watershed before attempting to achieve improvements in water quality through sediment P inactivation.

INTRODUCTION

The overall objectives of these investigations were to examine water quality conditions and constituent fluxes in tributary inflows, the main basin, and tail waters of Lake Eau Claire, Wisconsin. In particular, the relative importance of various internal and external nutrient (primarily phosphorus) loadings were evaluated in relation to water quality conditions and phytoplankton biomass (chlorophyll) in the lake. Predicted impacts of P loading reduction on viable chlorophyll *a* concentrations in the lake were examined using the model *Bathtub* (Walker 1996).

METHODS

EXTERNAL LOADINGS AND DISCHARGES

Stage elevations on the Eau Claire River at County Road D, Hay Creek at County Road NL, and Muskrat Creek at Stony Lonesome Road were monitored using continuous stage height recorders (ISCO Model 4120 and Model 6700). Stage elevations were converted to volumetric flow using a rating curve generated by the U.S. Geological Survey. Lake Eau Claire pool elevation fluctuations were obtained from the Eau Claire Claire Dam Manager (T. Mayor). Discharges from Lake Eau Claire were determined via hydrological mass balance.

Water samples from the Eau Claire River at County Road D and at the dam were collected over 4 hour intervals and composited daily using automated sampling devices (ISCO Model 6700 or 2700). Grab samples were collected from Hay and Muskrat Creeks at biweekly intervals during periods of nominal flow, and at daily intervals during periods of elevated flow.

Water samples collected at various inflows and the discharge were analyzed for the variables listed in Table 1. For suspended seston and particulate organic matter (POM) analyses, suspended material retained on a precombusted glass fiber filter (Gelman (A/E) was dried to a constant weight at 105 ^{o}C, and then combusted at 500 ^{o}C for 1 hour (APHA 1992; Methods 2540 D. and E.). Samples for total nitrogen and phosphorus were predigested with potassium persulfate according to Ameel et al. (1993) before analysis. Total nitrogen and phosphorus were measured colorimetrically on a Lachat QuikChem automated system (Lachat Methods 10-107-04-1-A and 10-115-01-1-A; Zellweger Analytics, Lachat Div., Milwaukee, WI). Subsamples (integrated over the upper 3-m water column) for phytoplankton enumeration were collected approximately monthly and preserved with acid Lugal's solution (Vollenweider 1969). Taxonomic identification and enumeration followed the procedures of Lund et al. (1958. Cell volume for individual species was computed from average cell dimension (Munawar and Munawar 1976). Phytoplankton biomass is reported as g fresh weight
m^{-3}, assuming a cellular specific gravity of 1.0.

Annual and daily loadings by various external sources were estimated using the computer model *Flux* (Walker 1996). Loadings were estimated via either weighting concentrations with respect to flow (Method 2) or via a regression algorithm (Method 6).

INTERNAL LOADINGS

In August of 1998, six replicate intact sediment cores were collected from the profundal sediments of stations 1, 2, and 3 (Fig. 1), for determination of rates of soluble reactive phosphorus release from the sediment. A total of 18 sediment cores were collected for analysis. Sediment cores were collected using a Wildco KB sediment core sampler (Wildco Wildlife Supply Co.) equipped with an acrylic core liner (6.5-cm ID and 50-cm length). Additional lake water was collected from the epilimnion for incubation with the collected sediment.

Sediment systems, constructed according to the methods of James et al. (1995), were incubated in an environmental chamber at 20 ^{o}C for 1-2 weeks. One set of 3 replicate sediment incubation systems was subjected to an oxic environment while the other set (3 replicates) was subjected to an anoxic environment for each station. The oxidation-reduction environment in each system was controlled by gently bubbling either air (oxic) or nitrogen (anoxic) through an air stone placed just above the sediment surface. Bubbling action insured complete mixing of the water column but did not disrupt or resuspend the sediment. Water samples were collected daily from the overlying water of each sediment system, filtered through a 0.45 µm membrane filter, and analyzed colorimetrically for soluble reactive phosphorus using the ascorbic acid method (APHA 1992). Rates of phosphorus release from the sediment (mg m^{-2} d^{-1}) were calculated as linear changes in phosphorus mass in the overlying water (corrected for dilution effects due to daily replacement of lake water) divided by time and the area of the incubation system. Internal P loading was also determined via mass balance according to the equation:

$$\spadesuit P_{\text{lake}} = (P_{\text{External load}} + P_{\text{Internal Load}}) - P_{\text{dscharge}}$$

Where, $\spadesuit P_{\text{lake}}$ was the change in lake total P mass over the summer (13 May through 03 August, 1998). Total P mass was calculated as the product of concentration and volume over all 1-m depth interval strata in the reservoir.

LIMNOLOGICAL MONITORING

Three stations (stations 1, 2, and 3) were established along the longitudinal axis of Lake Eau Claire for limnological monitoring purposes (Fig. 1). During the ice-free period, water samples were collected biweekly at 1-m intervals from the surface (i.e., 0.1 m) to within 0.5 m from the bottom for the water quality variables listed in Table 1. For soluble constituents (i.e., soluble reactive phosphorus), samples collected from anoxic water in the lake were filtered immediately without exposure to oxygen. Turbidity (APHA 1992; Method 2130 B.) was measured using a Hach nephelometric turbidimeter (Model 16800). Water samples for analysis of soluble constituents were filtered through a 0.45 µm filter (Gelman Metricel) prior to analysis. Soluble reactive phosphorus (Lachat Method 10-115-01-1-A) and ammonium-nitrogen (Lachat Method 10-107-04-01-A) were analyzed colorimetrically using automated procedures (Zellweger Analytics, Lachat Div., Milwaukee, WI). Samples for chlorophyll were extracted in Dimethyl-sulfoxide (DMSO)-acetone (50:50) at < 0 ^{o}C for a minimum of 12 hours. Viable chlorophyll *a* was determined fluorometrically (Turner model TD-700) according to Welschmeyer (1994). In conjunction with the water sampling schedule, measurements of water temperature, dissolved oxygen, pH, and conductivity were collected using a Hydrolab Surveyor III that was precalibrated against Winkler titrations (APHA 1992) and buffer solutions. The Carlson Trophic State Index (Carlson 1977) was estimated using the computer program *Profile* (Walker 1996) using Secchi transparency values and total phosphorus and viable chlorophyll *a* concentrations determined over the upper 1 m of the reservoir. In addition, the Wisconsin Trophic State Index was estimated using equations described in Lillie et al. (1993).

The stability of the reservoir was calculated as:

S = 1/A SCALESYM 300 int from 0 to z_m (z - z_g) (p_z - p_g) `dz

where A is the surface area (m^2), z_m is the maximum depth (m), z is the depth at stratum *z*, z_g is the depth of the center of mass or p_g , and p_z is the density of water (kg/m^3) at depth *z* (Idso 1973). P_g was calculated as :

p_g = 1/V SCALESYM 300 int from 0 to
z_m V_z`p_z `dz

where V is lake volume (m^3) and V_z is the volume at depth z. Areal (mg m^{-2} d^{-1}) and volumetric (mg m^{-3} d^{-1}) dissolved oxygen depletion rates were determined for station 1 using the computer program *Profile* (Walker 1996).

The computer model *Bathtub* (Walker 1996) was used as a management tool to forecast the trophic response of Lake Eau Claire to reductions and increases in P loading. We used surface (upper 1 m) measurements of chlorophyll and total phosphorus weighted over the period June through August as average summer conditions. The computer program *Profile* (Walker 1996) was used to estimate weighted summer concentrations for input into *Bathtub*.

RESULTS

HYDROLOGICAL CONDITIONS

The Eau Claire River provided the greatest annual water income (~91%) to the lake in 1998 while Hay and Muskrat Creeks collectively accounted for only about 9% of the measured inflow (Fig. 2). Seasonally, periods of Spring snowmelt and several storm-related peaks in water income occurred during study period (Fig. 3). Flows were elevated in late February to early March (peak = ~5000 cms) as a result of snowmelt (Fig. 3). A large storm-related inflow occurred in late March, then flows declined substantially between mid-April and late May. Storm-related inflows occurred in June, early and mid-August, late September, and mid-October while extended periods of low flow occurred in July, mid-August to early September, and late September to early October. During periods of snowmelt and storm inflow, the residence time of the reservoir declined to between 30 and < 15 days (Fig. 4). During periods of nominal inflow the residence time was often > 50 days (Fig. 4).

SEDIMENT AND NUTRIENT SOURCES AND SINKS

External Loadings . The Eau Claire River dominated annual and seasonal loadings of suspended seston, particulate organic matter, total nitrogen, and total phosphorus to the lake in 1998, contributing over 90% of the material income (Fig. 5 and Table 2). Lake Eau Claire was a sink for suspended seston and particulate organic matter, retaining 51 and 24% of the annual loading, respectively (Table 2). The reservoir was also a sink for total phosphorus on an annual basis (Table 2), but net retention was affected by export of P during the summer as an apparent result of high internal P loading (see below). There was no net retention of nitrogen in Lake Eau Claire on an annual basis.

Internal Loadings. Rates of phosphorus release from the sediments, measured in the laboratory, were substantial under anoxic conditions, ranging between a mean of 9.9 and 15.1 mg m^{-2} d^{-1} for the 3 stations (Table 3). In contrast, rates of phosphorus release under oxic conditions were much lower, averaging ~ 1.1 mg m^{-2} d^{-1} (0.2 S.E.) at all stations. Due to high P release from sediments under anoxic conditions, profundal sediments were a potentially very important source of P to the water column of Lake Eau Claire during the summer period.

LIMNOLOGICAL CONDITIONS

During the ice-free period of 1998, the reservoir exhibited temporary stratification and strong thermal stability at stations 1, 2, and 3 in mid- May (Fig. 6). In mid-May, the mixed layer depth, reflected by the center of mass (Zg), varied between 1 m at station 3 and nearly 3 m at station 1 (Fig. 7). Isothermal conditions occurred at the three stations in June, coincident with the occurrence of storm-related inflows, then strong thermal stratification was observed between mid-June and early August (Fig. 6). During this mid-summer period, Zg was ~ 1m at station 1, 2 m at station 2, and 3 m at station 3 as thermal stability was very strong (Fig. 7). After a brief period of water column mixing at all three stations in early August, weakly stratified conditions redeveloped at station 1 in late-August (Fig. 6). The shallower stations did not, however, exhibit this stratification pattern. Water column cooling, isothermal conditions, and autumnal turnover occurred in late September to early October (Fig. 6). The shallow station 3 cooled more rapidly than the deeper stations 2 and 1.

Coincident with periods of stratification and strong thermal stability in Lake Eau Claire was the occurrence of rapid dissolved oxygen depletion in the bottom waters and the development of anoxic conditions (Fig. 8). For instance, concentrations of dissolved oxygen were < 2 mg/L in the bottom waters of station 1 during the period of temporary stratification in mid-May. During the strongly stratified period of mid-June through early August, hypolimnetic anoxia redeveloped at station 1, with low (i.e., < 2 mg/L) dissolved oxygen conditions extending from the sediment interface to the 4 m depth between late June and early August. The areal hypolimnetic dissolved oxygen demand during this period was 313 mg m^{-2} d^{-1}, which was moderate compared to other lakes worldwide (Nürnberg 1996). Anoxic conditions were also observed in the hypolimnion at stations 2 and 3 during July, in conjunction with thermally stratified conditions. After the brief period of isothermal conditions in mid-August, hypolimnetic anoxia again developed at station 1 in association with stratification. Dissolved oxygen levels increased to > 4 mg/L in mid-September to October as a result of turnover and mixing.

During July through early August, total P concentrations exhibited marked vertical gradients in the bottom waters of stations 1 and 2, in conjunction with the development of strong thermal stratification and anoxic conditions, indicating the occurrence of internal P loading from anoxic sediments (Fig. 9). At station 1, concentrations of total P increased in the bottom waters from < 0.10 mg/L in late June to > 0.50 mg/L in mid-July through early August in conjunction with anoxia. Concentration gradients of declining P extended up into the metalimnion (i.e., 2-3 m depth) by late July, indicating vertical transport of P derived from anoxic sediments (Fig. 9). Concentrations of SRP exhibited a similar pattern at station 1 during this period (Fig. 10). Concentration gradients of high total P also developed above the sediment interface at station 2 in late July as a result of hypolimnetic anoxia (Fig. 9). The very shallow station 3, which exhibited only a very brief period of hypolimnetic anoxia, did not develop gradients of high total P near the sediment interface (Fig. 9). Longitudinally, the development of hypolimnetic gradients in total P coincided with strong thermal stratification and anoxia, which occurred at depths > 4 m in late July (Fig. 11).

Total N exhibited a complex spatial and vertical distribution pattern in Lake Eau Claire (Fig. 12). Concentrations exceeded 1.0 mg/L in early April in conjunction with a period of elevated storm inflow. Associated with declines in inflow to the reservoir in late Spring, total N declined at all stations between mid-April and early June. Increases in total N in the surface waters of the reservoir in mid-June, July through August, and September through October appeared to coincide with the occurrence of algal blooms (see Fig. 14). In contrast, high total N concentrations in the bottom waters in July, particularly at station 1, appeared to be associated with the development of hypolimnetic anoxia and the establishment of marked gradients of high ammonium-N concentrations in the water column near the sediment interface (Fig. 13). This pattern indicated that anoxic sediment was an important source of N as well as P during the summer.

Viable chlorophyll *a* concentrations exhibited several maxima in the reservoir during the growing season (Fig. 14). Shortly after ice-out (i.e., late March) and early April storm inflows, concentrations of viable chlorophyll *a* increased throughout the water column in April, with concentrations exceeding 20 mg/m^3 at stations 1 and 2. In mid-June, shortly after the occurrence of an elevated inflow period, concentrations of viable chlorophyll *a* exhibited a maximum at all three stations. In particular, concentrations exceeded 60 mg/m^3 in the upper 1 m of the water column at station 1 during this period. Viable chlorophyll *a* was > 40 mg/m3 at the other stations in mid-June. Viable chlorophyll *a* declined slightly in the surface waters in late-June through early July, coincident with the occurrence of late June freshet that exceeded >1000 cms, suggesting possible washout and/or dilution of algae. However, concentrations were still > 20 mg/m^3 in the upper 1 m during this period.

In late July through early August, concentrations again increased dramatically at all stations, exceeding 80 mg/m^3 in the surface waters (Fig. 14). This pattern of high viable chlorophyll *a* occurred shortly after the development of hypolimnetic anoxia and establishment of marked P gradients in the bottom waters. Disruption of thermal stratification in August, and the occurrence of small storm-related inflows, was accompanied by a decline in viable chlorophyll *a* concentrations at all stations by mid- to late August. With the onset of autumnal overturn in September through October, peaks in viable chlorophyll *a* exceeding 40 mg/m^3 in the surface waters were observed. During the overturn period, maxima in viable chlorophyll *a* occurred in early September at station 3 and progressed down-reservoir to station 1 by October. These observations coincided with overturn and establishment of isothermal conditions starting first at the shallow station 3 in early September and progressing down-reservoir to station 1 by October.

The algal assemblage at station 1 in Lake Eau Claire was generally dominated by blue green bacteria during April through October (Fig. 15 and Appendix A). In June *Anabaena spiroides* dominated the species assemblage (Fig. 16). During peaks in chlorophyll in July, the blue green bacteria *Aphanizomenom flos aquae* comprised > 90% of the species assemblage (Fig. 16). In May, the Diatom *Melosira granulata* dominated the algal community assemblage (Fig. 16). Chrysophytes (*Ochromonas sp.*) and blue green bacteria (*Aphanizomenom flos aquae*) codominated the algal community in October (Fig. 16).

Overall, Lake Eau Claire exhibited high concentrations of total P and viable chlorophyll *a* , and low Secchi disk transparency, in the surface waters during the summer period (Table 4). The Carlson and Wisconsin Trophic State Indices for Secchi disk transparency, viable chlorophyll *a* and total P ranged between 63 and 71, indicative of eutrophic conditions during the summer.

BUDGETARY ANALYSIS AND BATHTUB MODELING FOR THE SUMMER PERIOD OF 1998

Budgetary Analysis. External P loadings and discharges, calculated for the period June through August using the program FLUX (Table 5), were used as input for the model *Bathtub*. In general, the reservoir exhibited net export of total P during the summer period, due to discharge of P derived via substantial internal P loading from anoxic sediments during the summer.

For *Bathtub* modeling, we estimated internal P loading from sediments using laboratory-based rates (method 1) and via mass balance over the summer period (method 2). For method 1, we weighted maximum rates of P release from sediments under oxic and anoxic conditions at station 1 (1.5 and 15 mg m^{-2} d^{-1} for oxic and anoxic conditions, respectively; Table 3) with respect to surface areas of the reservoir that exhibited dissolved oxygen concentrations ∃ 2 mg/L (i.e., oxic conditions) or < 2 mg/L (i.e., anoxic conditions). We used the maximum extent of anoxia to calculate sediment surface areas (Fig. 11) for area-weighting purposes. Thus, our laboratory-based estimate represents a maximum rate of internal P loading from sediments. The estimated lakewide rate of P release, based on laboratory measurements, was 4.9 mg m^{-2} d^{-1} (S.D. = 1.5).

For method 2, we examined lakewide changes in total P mass over the summer in conjunction with inflow and discharge total P to and from the lake, respectively (Fig. 17). Lakewide total P mass increased markedly between mid-May and August, coinciding with periods of strong thermal stability, hypolimnetic anoxia, and development of hypolimnetic total P gradients. With the exception of brief periods of external total P loading from the watershed in June, inflows were nominal and could not account for the large increases in total P mass observed in the reservoir.

We used the period late May through early August to estimate internal P loading via mass balance. The estimated lakewide rate of P release, based on mass balance, was 7.2 mg m^{-2} d^{-1} (S.D. = 2.0), which was higher than the rate (4.9 mg m^{-2} d^{-1}) estimated via method 1 and represented ~ 50% of the total measured P load (i.e., internal P load + external P load) to Lake Eau Claire during the summer (Fig. 18). However, S.D. values overlapped means for the two methods, suggesting that both methods (i.e., sediment cores versus P mass balance) provided a similar approximation of internal P loading. We used the internal P loading estimated via mass balance as input for the model *Bathtub*.

Bathtub Modeling. Since internal P loading during the summer potentially plays an important role in the P economy and chlorophyll dynamics of Lake Eau Claire, we explored two phosphorus management scenarios; 1) management of external P loading and 2) management of external P loading with an 85% reduction in internal P loading (i.e., from 7 mg m^{-2} d^{-1} to 1 mg m^{-2} d^{-1}). We arbitrarily chose an 85% reduction in internal P loading to simulate a possible outcome of managing internal P loading in Lake Eau Claire via, for instance, an alum treatment.

For scenario 1, external phosphorus loading via the Eau Claire River and Hay and Muskrat Creeks was incrementally increased and decreased under 1998 summer flow conditions to examine effects of changes in phosphorus loading on chlorophyll concentrations in the reservoir (Fig.19). Both total phosphorus and chlorophyll varied linearly as a function of changes in phosphorus loading, while Secchi transparency responded positively primarily as a function of phosphorus loading reduction. With 50% phosphorus loading reduction, chlorophyll concentrations were reduced only by ~ 30%, while Secchi transparency increased by only ~ 20%, over 1998 nominal levels (Fig. 19). These modest responses to external P loading reduction were attributed to the important role that internal P loading plays in sustaining algal blooms in the reservoir, even when external P loading is diminished. In contrast, increasing external P loading 100% over 1998 levels via, for example changing land use patterns (increasing agricultural land use and urbanization coupled with declining forested lands, wetlands, and buffer strips), resulted in a near doubling of estimated summer chlorophyll levels over 1998 conditions to nearly 80 mg/m^3.

Changes in the estimated frequency of bloom for 1998 summer flow conditions are shown in Fig. 20. Overall, bloom frequency and the concentration level of bloom diminished with a 50% reduction in phosphorus loading. However, blooms of chlorophyll of ~ 10 mg/m^3 potentially occurred over 90% of the time and blooms > 30 mg/m^3 potentially occurred over 40% of the time, with a 50% reduction in external P loading. As with chlorophyll concentration, this modest change in bloom frequency was attributed to the occurrence of high internal P loading from sediments within the system, which sustained algal growth. Conversely, if phosphorus loading was increased by 100%, both the frequency of blooms and concentration levels potentially increased dramatically (Fig. 20).

For scenario 2, we incrementally decreased external P loading with an 85% reduction in internal P loading. Under these conditions, chlorophyll response was much more dramatic (Fig. 21). A 50% reduction in external P loading resulted in a nearly 50% reduction in chlorophyll *a*, from ~ 30 mg/m^3 to ~15 mg/m^3. Secchi disk transparency also increased to a greater extent with reductions in both internal and external P loads.

With control of internal P loading, the estimated bloom frequency also responded more dramatically to incremental decreases in external P loading (Fig. 22). For instance, a 50% reduction in external P loading, coupled with internal P loading management, resulted in a marked decline in the percentage of blooms that occur at concentration levels exceeding 30 mg/m^3 (Fig. 22).

CONCLUSIONS

Internal P loading from sediments during periods of thermal stratification and hypolimnetic anoxia in the summer was clearly important to the P economy and algal community of Lake Eau Claire. Based on P mass balance analysis, internal P loading accounted for up to 50% of the total P load to the reservoir during the summer and rates of P release measured for the sediments of Lake Eau Claire were significantly greater than rates observed for profundal sediments of a variety of eutrophic lakes (Nürnberg et al. 1986).

The Eau Claire River dominated both the hydrological budget and external sediment and nutrient loading to Lake Eau Claire. Net sedimentation appeared to be an important flux for seston and POM, as the lake retained > 50% and 24%, respectively, of these constituents on an annual basis. However, net retention of external nutrient loads such as nitrogen and phosphorus was much lower. These patterns were due, in large part, to internal recycling of these nutrients from sediments into the water column and discharge from the system. In particular, there was no net retention of nitrogen in Lake Eau Claire on an annual basis. Although we do not precisely know reasons for this unusual pattern, they may be due, in part, to export via the outlet structure of nitrogen in the form of ammonium-N mobilized from anoxic, hypolimnetic sediments during the summer. Nitrogen fixation and/or uptake of mobilized ammonium-N by cyanobacteria, prevalent in Lake Eau Claire, and discharge of algal N from the lake during the summer may also be a factor in net nitrogen export from the system. Direct loss of N from the lake as N_2 represents another avenue of N flux from the system.

External phosphorus loading reduction via BMPs, development of vegetated shoreline buffer strips, and restoration of wetlands may be important avenues for controlling chlorophyll and the frequency of algal blooms in Lake Eau Claire during the summer. However, the efficacy of watershed management for P reduction on reservoir recovery to less eutrophic conditions will likely be compromised by high internal P loading from the sediments within the reservoir. Control of internal P loading from sediments via P inactivation techniques (Cooke et al. 1993) is not recommended for Lake Eau Claire until significant reduction in external P loading from the watershed can be achieved. In particular, Barko et al. (1990) and James et al. (1991) have indicated that control of internal P loading via treatment of profundal sediments with aluminum salts can be very short-lived (on the order of 1 year or less) in reservoirs due to 1) high external P loading that can sustain algal productivity even with reduction in internal P loading and 2) rapid burial of the alum layer with P-rich sediments due to typically higher sedimentation in reservoirs than in natural lakes.

RECOMMENDATIONS FOR MONITORING

It is recommended that a sampling program be implemented on the Eau Claire River and in the reservoir to monitor long-term changes in watershed water income and nutrient loading and lake response. The sampling program will require flow gauging of the Eau Claire River and grab sampling for suspended seston and total P under baseline and storm flow conditions. In-lake sampling will be required at a minimum of 1 station in Lake Eau Claire. Vertical profiles of water temperature and dissolved oxygen should be collected at 1-m intervals at this station at least once a month during June through August or September. Water samples should be collected for total P and viable chlorophyll *a* in the upper 1 m of the water column. An additional water sample should also be collected near the lake bottom for total P to monitor impacts of internal P loading on P concentrations in the overlying water immediately above the sediment. Finally, a Secchi Disk transparency measurement should be collected during each sampling period. This sampling recommended program will provide a valuable tool for monitoring changes in lake and watershed water quality and for making future decisions for restoration.

REFERENCES

Ameel, J.J., R.P. Axler, and C.J. Owen. 1993. Persulfate digestion for determination of total nitrogen and phosphorus in low nutrient waters. Am. Environ. Lab. (October 1993) pages 8-10.

APHA (American Public Health Association). 1992. Standard methods for the examination of water and wastewater. 18th ed.

Barko, J.W., W.F. James, W.D. Taylor, and D.G. McFarland. 1990. Effects of alum treatment on phosphorus and phytoplankton dynamics in Eau Galle Reservoir: A synopsis. Lake Res. Manage. 6:1-8.

Carlson, R.E. 1977. A trophic state index for lakes. Limnol. Oceanogr. 22:361-369.

Cooke, G.D., E.B. Welch, S.A. Peterson, and P.R. Newroth. 1993. Restoration and management of lakes and reservoirs. 2nd edition. CRC Press, Lewis Publishers.

Idso, S.B. 1973. On the concept of lake stability. Limnol. Oceanogr. 18:681-683.

James, W.F., J.W. Barko, and W.D. Taylor. 1991. Effects of alum treatment on phosphorus dynamics in a north-temperate reservoir. Hydrobiologia 215:231-241.

James, W.F., J.W. Barko, and H.L. Eakin. 1995. Internal phosphorus loading in Lake Pepin, Upper Mississippi River. J. Freshwat. Ecol. 10:269-276.

Lillie, R.A., S. Graham, and P. Rasmussen 1993. Trophic state index equations and regional predictive equations for Wisconsin Lakes. Research Management Findings, No. 35. Bureau of Research - Wisconsin Department of Natural Resources Publication, Madison, Wisconsin.

Lund, J.W.G., C. Kipling, and E.D. LeCren. 1958. The inverted microscope method of estimating algal numbers and the statistical basis of estimations by counting. Hydrobiologia 11:143-170.

Munawar, M., and I.F. Munawar. 1976. A lakewide study of phytoplankton biomass and its species composition in Lake Erie, April-December, 1970. J. Fish. Res. Board. Can. 33:581-600.

Nürnberg, G.K., M. Shaw, P.J. Dillon, and D.J. McQueen. 1986. Internal phosphorus loading in an oligotrophic precambrian shield lake with an anoxic hypolimnion. Can. J. fish. Aquat. Sci. 44:960-966.

Walker, W.W. 1996. Simplified Procedures for eutrophication assessment and prediction: User Manual. Instruction Report W-96-2. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Welschmeyer, N.A. 1994. Fluorometric analysis of chlorophyll a in the presence of chlorophyll b and pheopigments. Limnol. Oceanogr. 39:1985-1992.

TABLES

Table 1. Variable list for tributary loadings

FLOW, cms
POOL ELEVATION, m
SUSPENDED SESTON, mg/L
POM, mg/L
TOTAL NITROGEN, mg/L
TOTAL PHOSPHORUS, mg/L

Variable list for limnological monitoring of Lake Eau Claire.

WATER TEMPERATURE, ^{o}C
DISSOLVED OXYGEN, mg/L
pH
CONDUCTIVITY, $\mu S/cm^2$
SECCHI TRANSPARENCY, cm
SUSPENDED SESTON, mg/L
POM, mg/L
TURBIDITY, NTU
TOTAL NITROGEN, mg/L
AMMONIUM-NITROGEN, mg/L
TOTAL PHOSPHORUS, mg/L
SOLUBLE REACTIVE PHOSPHORUS, mg/L
VIABLE CHLOROPHYLL *a*, µg/L

Table 2. Summary statistics for annual external loads to and discharges from Lake Eau Claire. CV represents the coefficient of variation.

Tributary	Seston			Particulate Organic Matter			Total N			Total P		
	LOAD kg y^{-1}	CONC. mg L^{-1}	CV	LOAD kg y^{-1}	CONC. mg L^{-1}	CV	LOAD kg y^{-1}	CONC. mg L^{-1}	CV	LOAD kg y^{-1}	CONC. mg L^{-1}	CV
Eau Claire River	6.8×10^8	24.7	0.152	1.5×10^6	5.4	0.115	415400	1.599	0.064	44233	0.160	0.097
Hay Creek	1.4×10^5	9.9	0.126	3.5×10^4	2.5	0.142	23369	1.677	0.078	2346	0.168	0.082
Muskrat Creek	8.7×10^4	7.1	0.144	4.5×10^4	3.7	0.255	15482	1.264	0.070	1004	0.082	0.086
Eau Claire Dam	3.3×10^8	11.0	0.140	1.2×10^6	3.9	0.084	514804	1.697	0.067	38312	0.126	0.067

Table 3. Mean (± 1 S.E.) rates of phosphorus release from the profundal sediments (mg m^{-2} d^{-1}) of various stations measured under oxic and anoxic conditions.

Station	Oxic Rate	Anoxic Rate
1	1.4 (0.3)	14.9 (1.4)
2	0.9 (0.4)	9.9 (0.6)
3	1.0 (0.4)	15.1 (0.6)

Table 4. Estimates of Carlson and Wisconsin Trophic State Index (TSI) values for Stations 1, 2, and 3 in Lake Eau Claire. Concentrations of chlorophyll *a* and total phosphorus (TP) and Secchi transparency represent means (CV) over the upper 1 m water column of the reservoir for the period June through August.

					Carlson TSI			WI TSI	
Station	Secchi, m	Chla, µg/L	TP, µg/L	TSI_{SD}	TSI_{chla}	TSI_{TP}	$WTSI_{SD}$	$WTSI_{chla}$	$WTSI_{TP}$
1	0.88 (0.13)	51.8 (0.22)	107 (0.17)	62	69	72	62	65	64
2	0.85 (0.13)	43.4 (0.21)	102 (0.16)	62	67	71	62	63	64
3	0.72 (0.17)	41.9 (0.21)	94 (0.19)	65	69	69	65	65	63
Lake	0.82 (0.13)	45.7 (0.23)	101 (0.14)	63	68	71	63	64	64

Table 5. Summary statistics for summer (June-August) external loads to and discharges from Lake Eau Claire. CV represents the coefficient of variation.

Tributary	Total P		
	LOAD, kg/d	CONC. mg L^{-1}	CV
Eau Claire River	24.1	0.076	0.067
Hay Creek	2.5	0.116	0.138
Muskrat Creek	0.7	0.071	0.112
Discharge	52.9	0.151	0.056

FIGURE CAPTIONS

Fig. 1. Map of Lake Eau Claire showing water and sediment sampling stations.

Fig. 2. Relative contributions (%) by various measured sources to the annual water income to Lake Eau Claire.

Fig. 3. Seasonal variations in measured tributary water income to Lake Eau Claire for the year 1998.

Fig. 4. Seasonal variations in pool elevation and theoretical hydraulic residence time of Lake Eau Claire during 1998.

Fig. 5. Relative loading contributions (%) by measured tributary sources to Lake Eau Claire.

Fig. 6. Contour plot of seasonal and vertical variations in water temperature at stations 1, 2, and 3 in Lake Eau Claire during 1998.

Fig. 7. Seasonal variations in Schmidt thermal stability and the depth of the center of mass (Zg) at stations 1, 2, and 3 in Lake Eau Claire during 1998.

Fig. 8. Contour plot of seasonal and vertical variations in dissolved oxygen at stations 1, 2, and 3 in Lake Eau Claire during 1998.

Fig. 9. Contour plot of seasonal and vertical variations in total phosphorus at stations 1, 2, and 3 in Lake Eau Claire during 1998.

Fig. 10. Contour plot of seasonal and vertical variations in soluble reactive phosphorus at stations 1, 2, and 3 in Lake Eau Claire during 1998.

Fig. 11. Contour plot of longitudinal and vertical variations in (upper panel) temperature, (middle panel) dissolved oxygen, and (lower) total phosphorus on 23 July, 1998.

Fig. 12. Contour plot of seasonal and vertical variations in total nitrogen at stations 1, 2, and 3 in Lake Eau Claire during 1998.

Fig. 13. Contour plot of seasonal and vertical variations in ammonium-nitrogen at stations 1, 2, and 3 in Lake Eau Claire during 1998.

Fig. 14. Contour plot of seasonal and vertical variations in viable chlorophyll *a* at stations 1, 2, and 3 in Lake Eau Claire during 1998.

Fig. 15. Relative phytoplankton biomass distribution among different algal groups during the summer in Lake Eau Claire.

Fig. 16. Seasonal variations in biomass of major taxonomic algal groups in Lake Eau Claire.

Fig. 17. Seasonal variations in lakewide total phosphorus mass during 1998. The bar represents the time period used to estimate internal phosphorus loading via mass balance.

Fig. 18. Relative contributions of measured external and internal total phosphorus loading to Lake Eau Claire during the summer (June - August) of 1998.

Fig. 19. Estimated changes in total phosphorus (P), chlorophyll, and Secchi transparency as a function of external phosphorus loading increases or decreases. External phosphorus loading was increased or reduced relative to nominal external total phosphorus loading conditions that occurred during the summer (June - August) of 1998. Internal phosphorus loading was not adjusted.

Fig. 20. Estimated changes in the frequency of algal bloom occurrence of different concentrations of chlorophyll versus different external phosphorus loading conditions. External phosphorus loading was increased or reduced relative to nominal loading conditions that occurred during the summer (June - August) of 1998. Internal phosphorus loading was not adjusted.

Fig. 21. Estimated changes in total phosphorus (P), chlorophyll, and Secchi transparency as a function of external phosphorus loading decreases and an 85% reduction in internal phosphorus loading. External phosphorus loading was increased or reduced relative to nominal external total phosphorus loading conditions that occurred during the summer (June - August) of 1998.

Fig. 22. Estimated changes in the frequency of algal bloom occurrence of different concentrations of chlorophyll versus different external phosphorus loading conditions and an 85% reduction in internal phosphorus loading. External phosphorus loading was reduced relative to nominal loading conditions that occurred during the summer (June - August) of 1998.

LAKE EAU CLAIRE

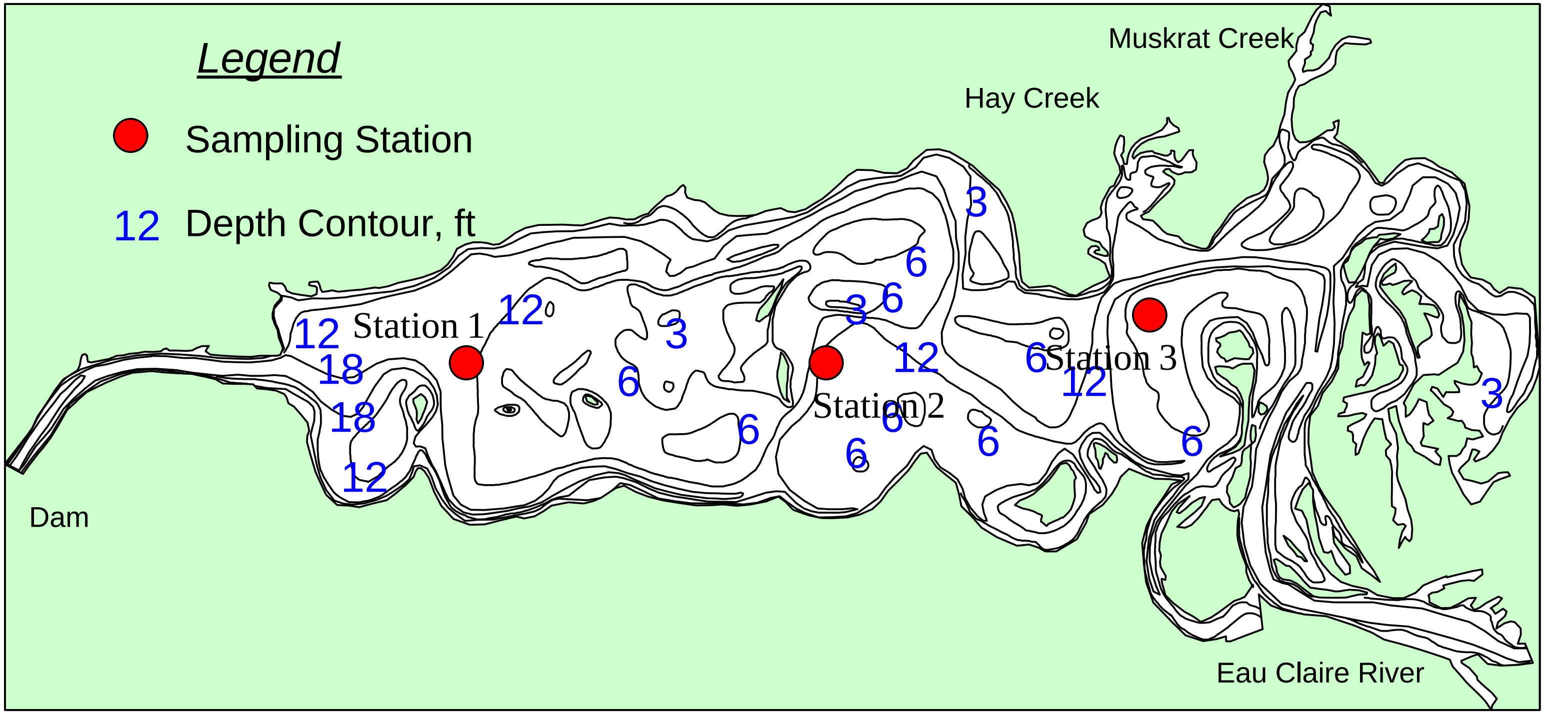


Figure 1

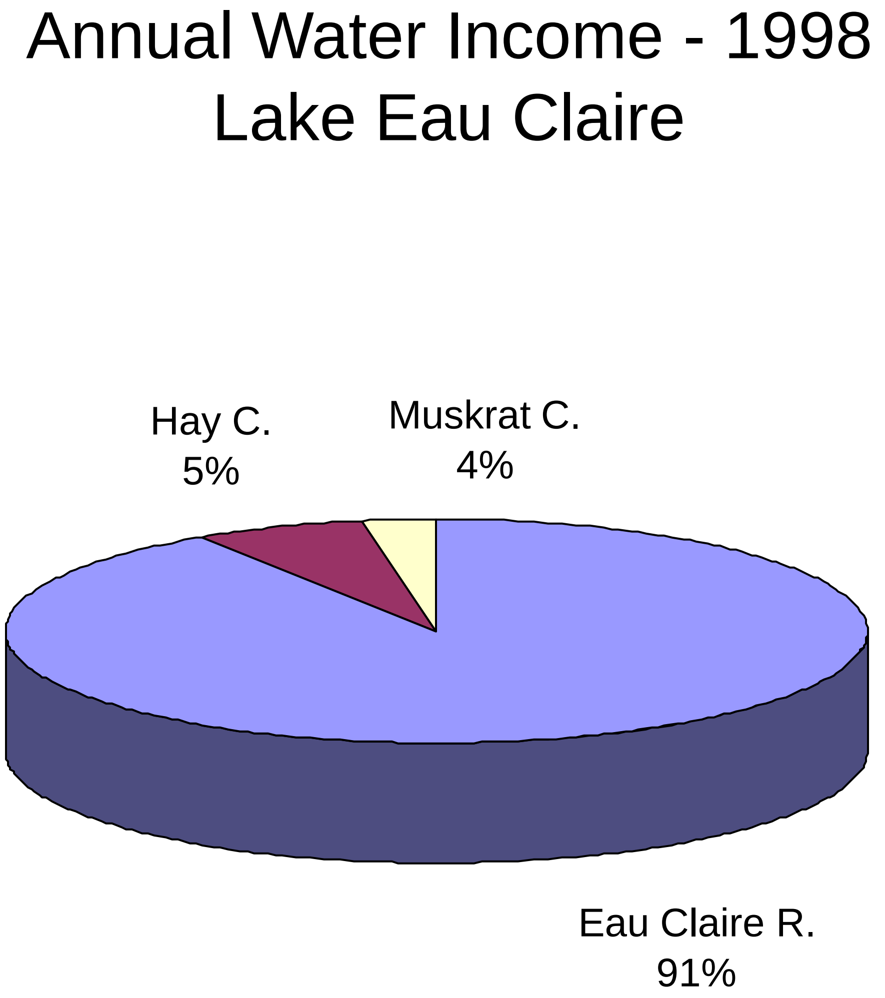

Annual Water Income - 1998
Lake Eau Claire
Hay C.
5%
Muskrat C.
4%
Eau Claire R.
91%

Figure 2

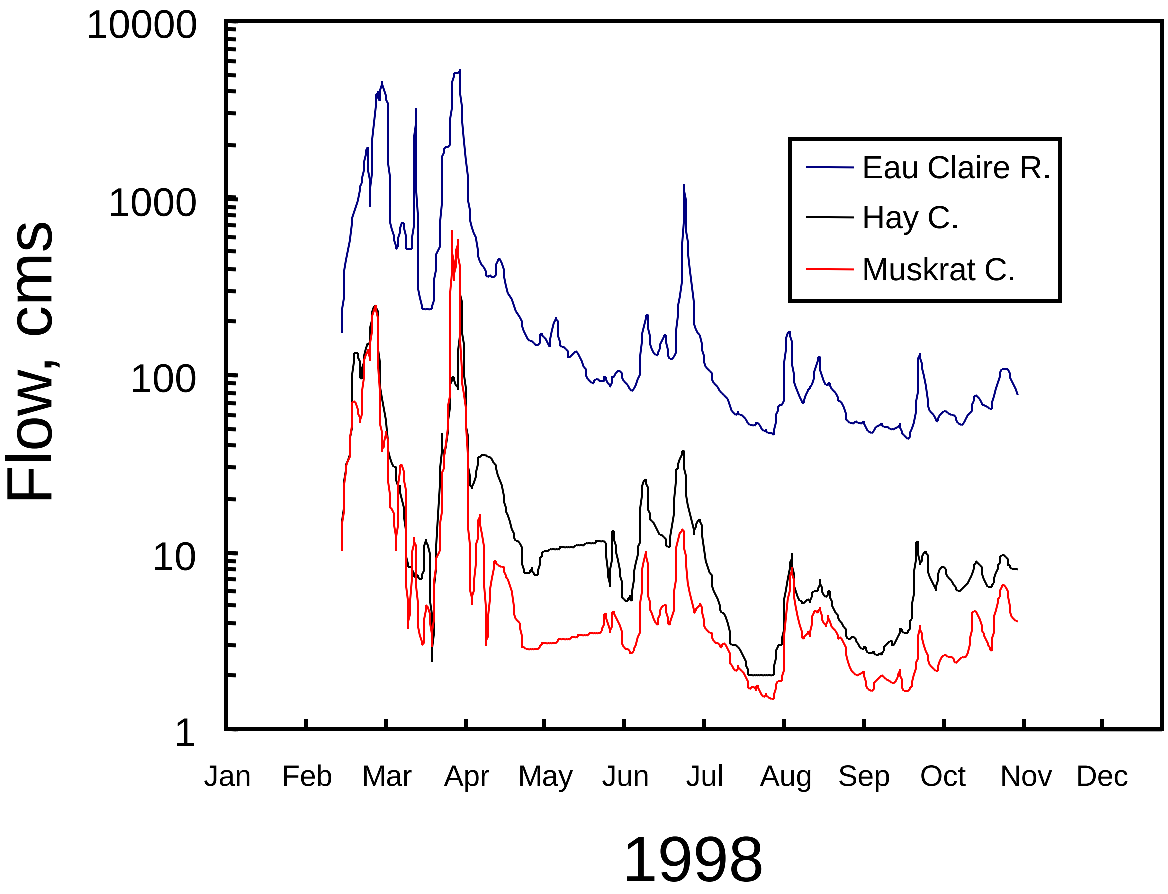
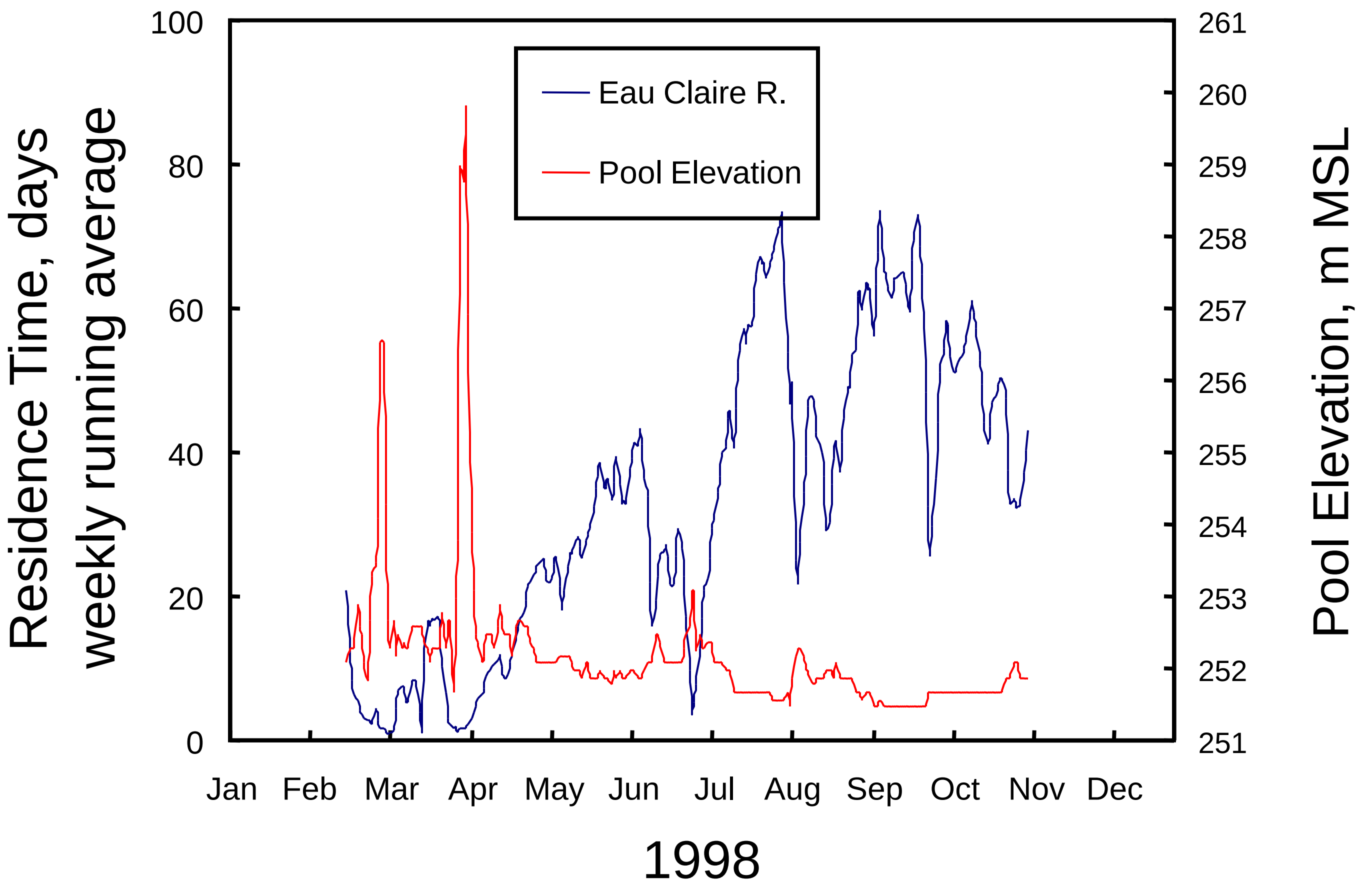

10000
1000
100
10
1
Flow, cms
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
1998
Eau Claire R.
Hay C.
Muskrat C.

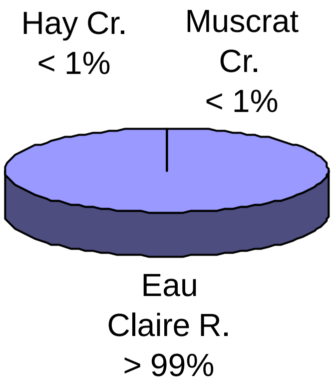
Figure 3



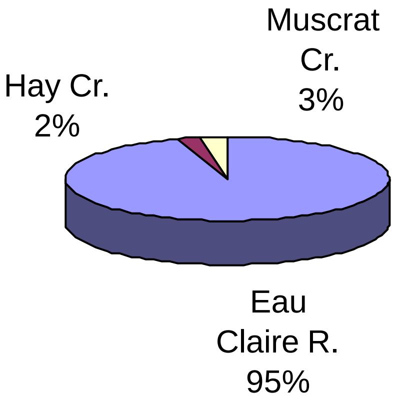
Eau Claire R.
Pool Elevation
Residence Time, days
weekly running average
100
80
60
40
20
0
261
260
259
258
257
256
255
254
253
252
251
Pool Elevation, m MSL
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
1998

Figure 4

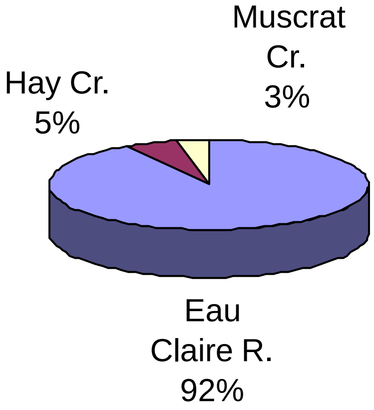
Seston Loading 1998, kg/y



POM Loading 1998, kg/y



Nitrogen Loading 1998, kg/y



Phosphorus Loading 1998, kg/y

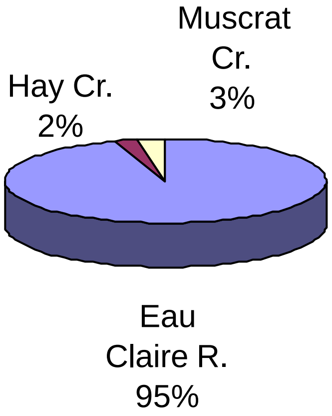


Figure 5

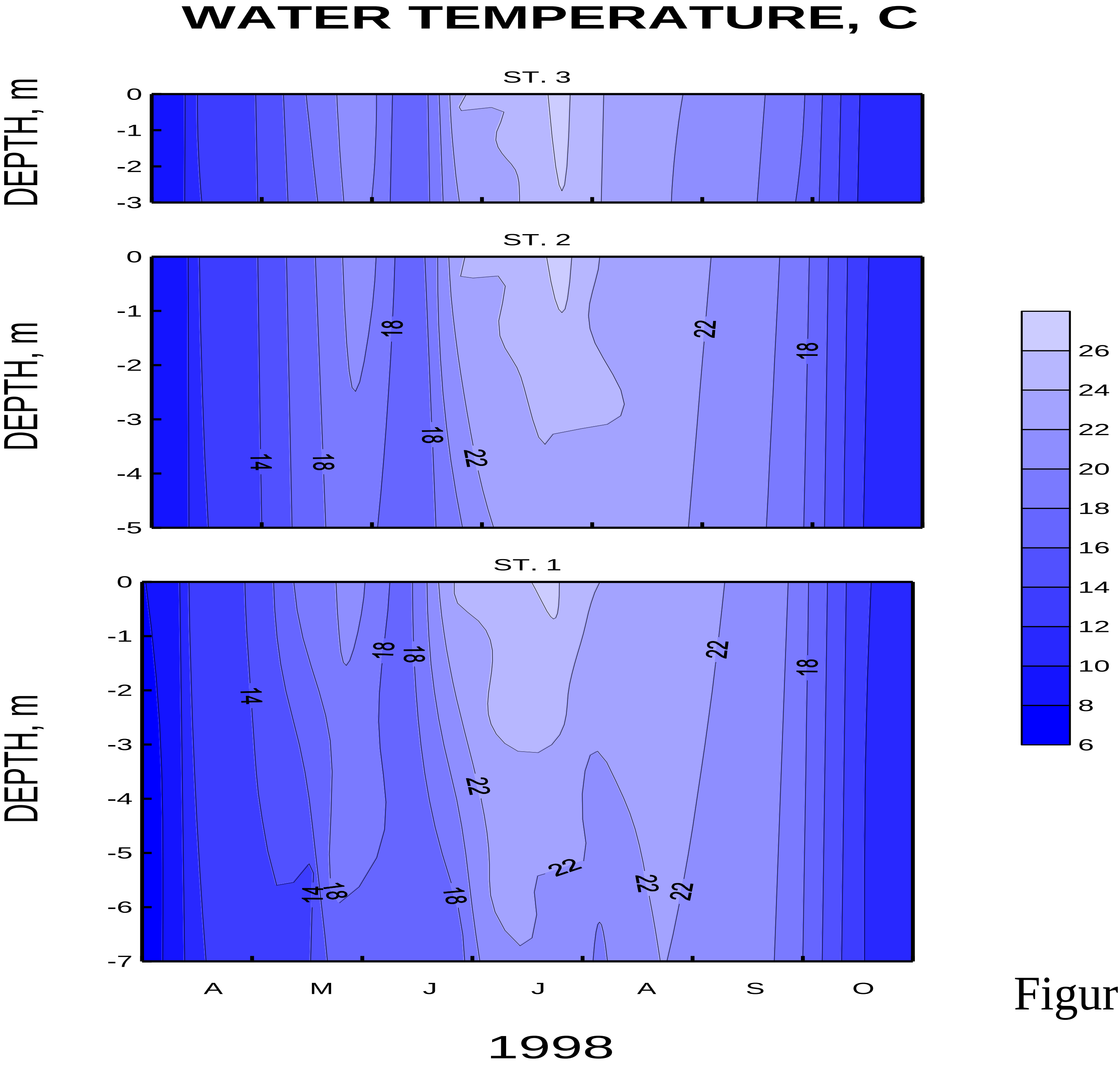

WATER TEMPERATURE, C
ST. 3
ST. 2
ST. 1
DEPTH, m
0
-1
-2
-3
-4
-5
-6
-7
14
18
22
A
M
J
J
A
S
O
1998
6
8
10
12
14
16
18
20
22
24
26

Figure 6

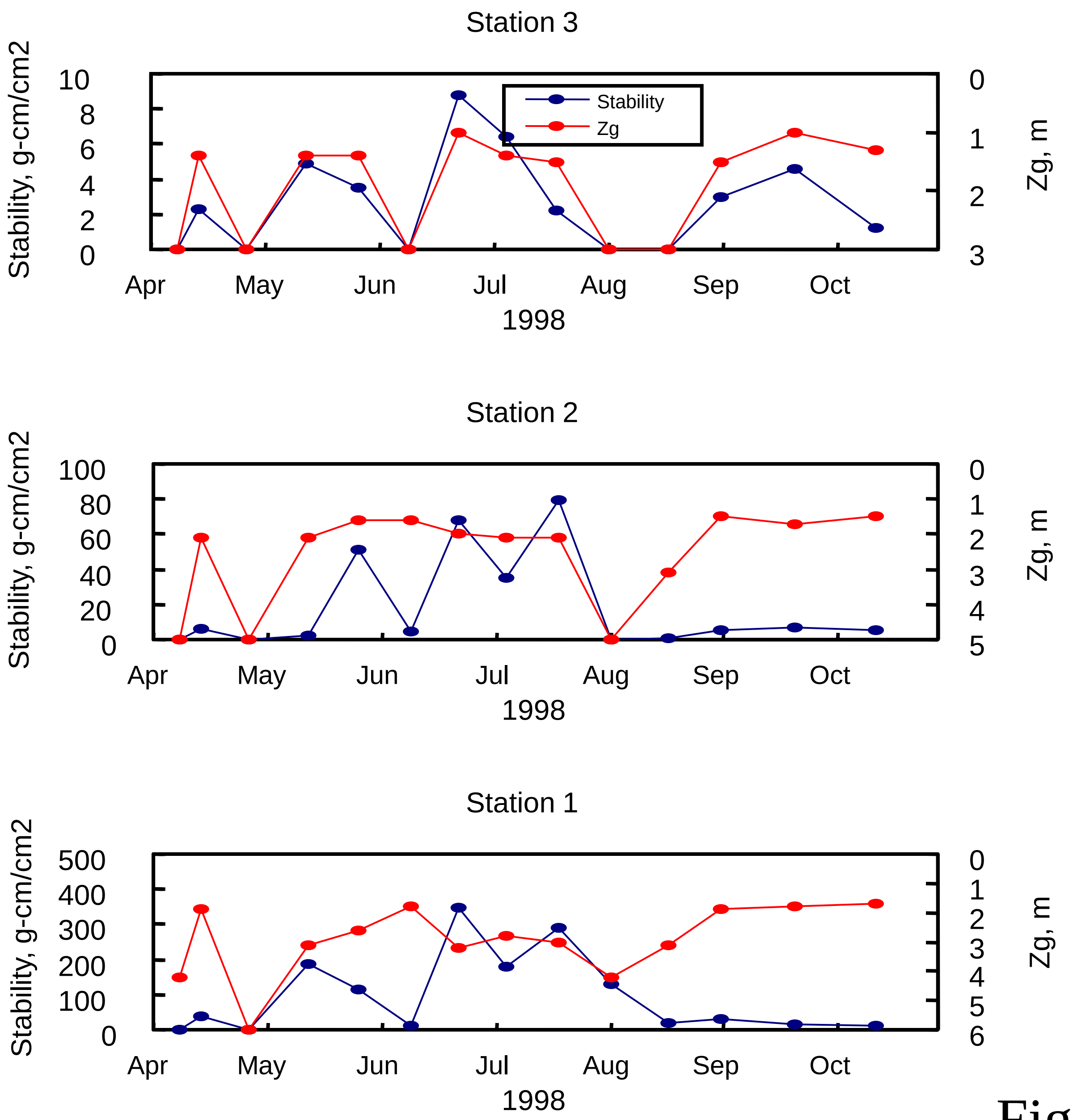

Station 3
Stability, g-cm/cm2
10
8
6
4
2
0
0
1
2
3
Zg, m
Stability
Zg
Apr
May
Jun
Jul
Aug
Sep
Oct
1998
Station 2
Stability, g-cm/cm2
100
80
60
40
20
0
0
1
2
3
4
5
Zg, m
Apr
May
Jun
Jul
Aug
Sep
Oct
1998
Station 1
Stability, g-cm/cm2
500
400
300
200
100
0
0
1
2
3
4
5
6
Zg, m
Apr
May
Jun
Jul
Aug
Sep
Oct
1998

Figure 7

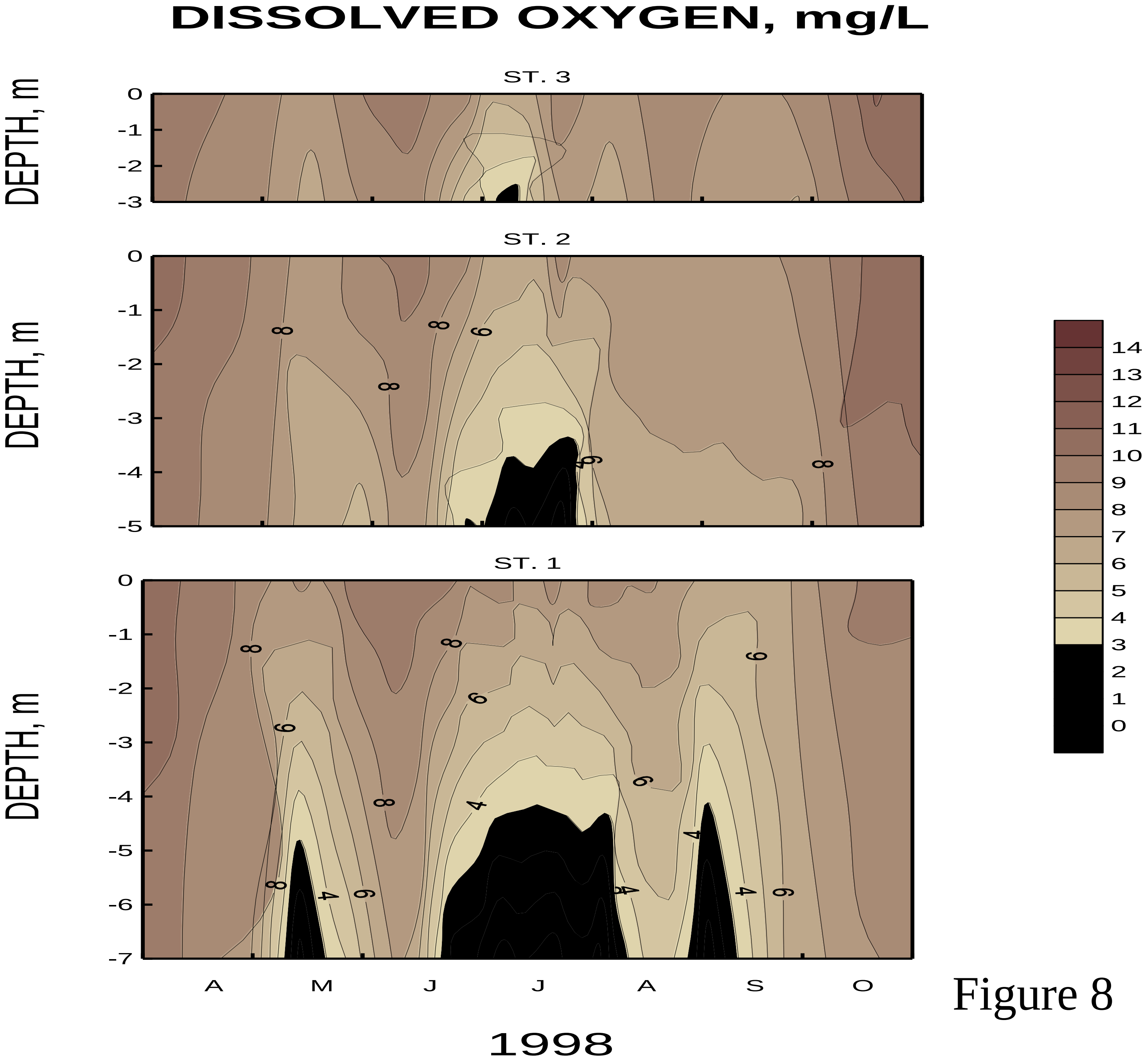

DISSOLVED OXYGEN, mg/L
ST. 3
ST. 2
ST. 1
DEPTH, m
0
-1
-2
-3
-4
-5
-6
-7
8
6
4
A
M
J
J
A
S
O
1998
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0

Figure 8

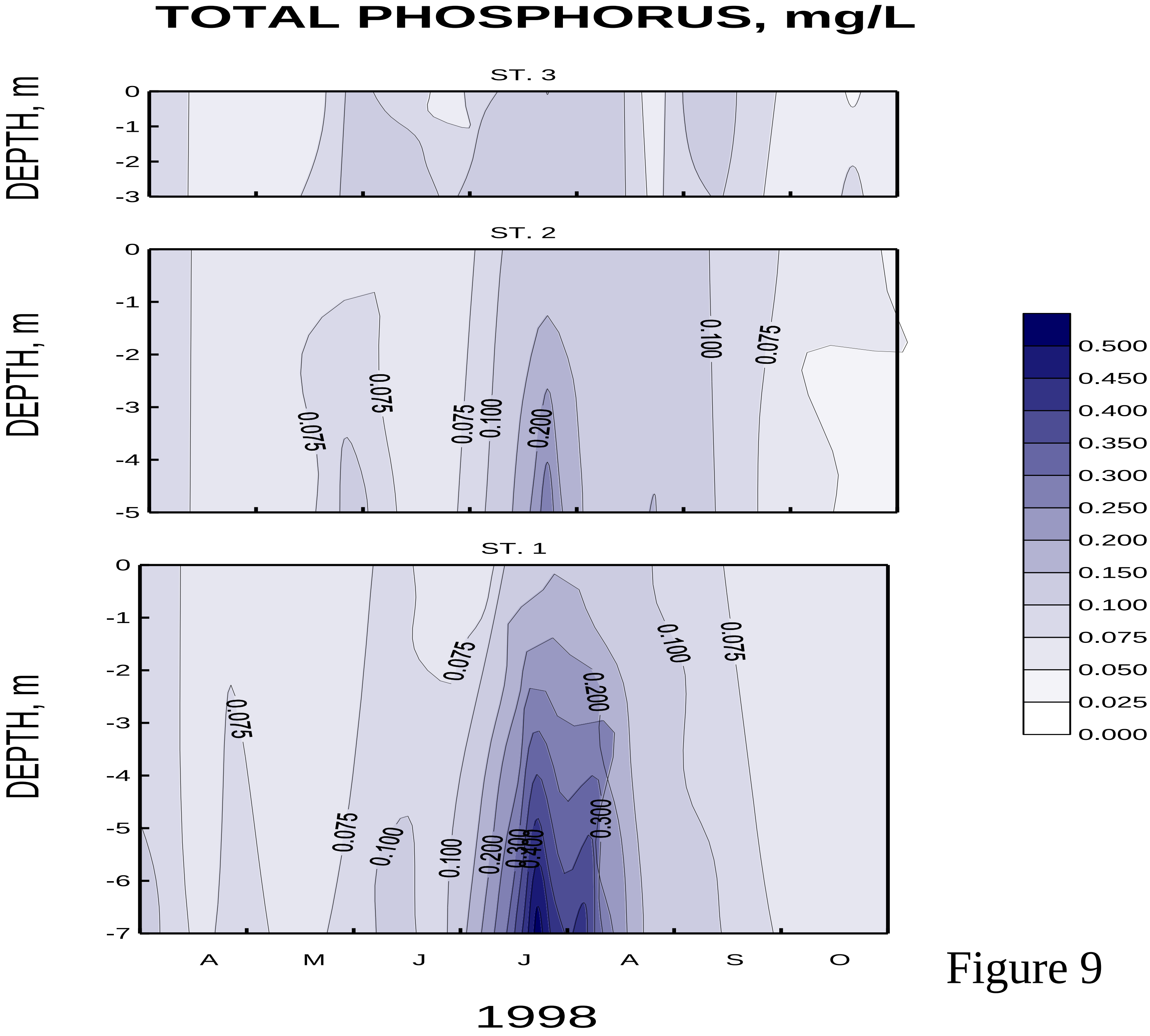

TOTAL PHOSPHORUS, mg/L
ST. 3
ST. 2
ST. 1
DEPTH, m
0
-1
-2
-3
-4
-5
-6
-7
0.075
0.100
0.200
0.300
0.400
A
M
J
J
A
S
O
1998
0.500
0.450
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.075
0.050
0.025
0.000

Figure 9

SOLUBLE REACTIVE PHOSPHORUS, mg/L

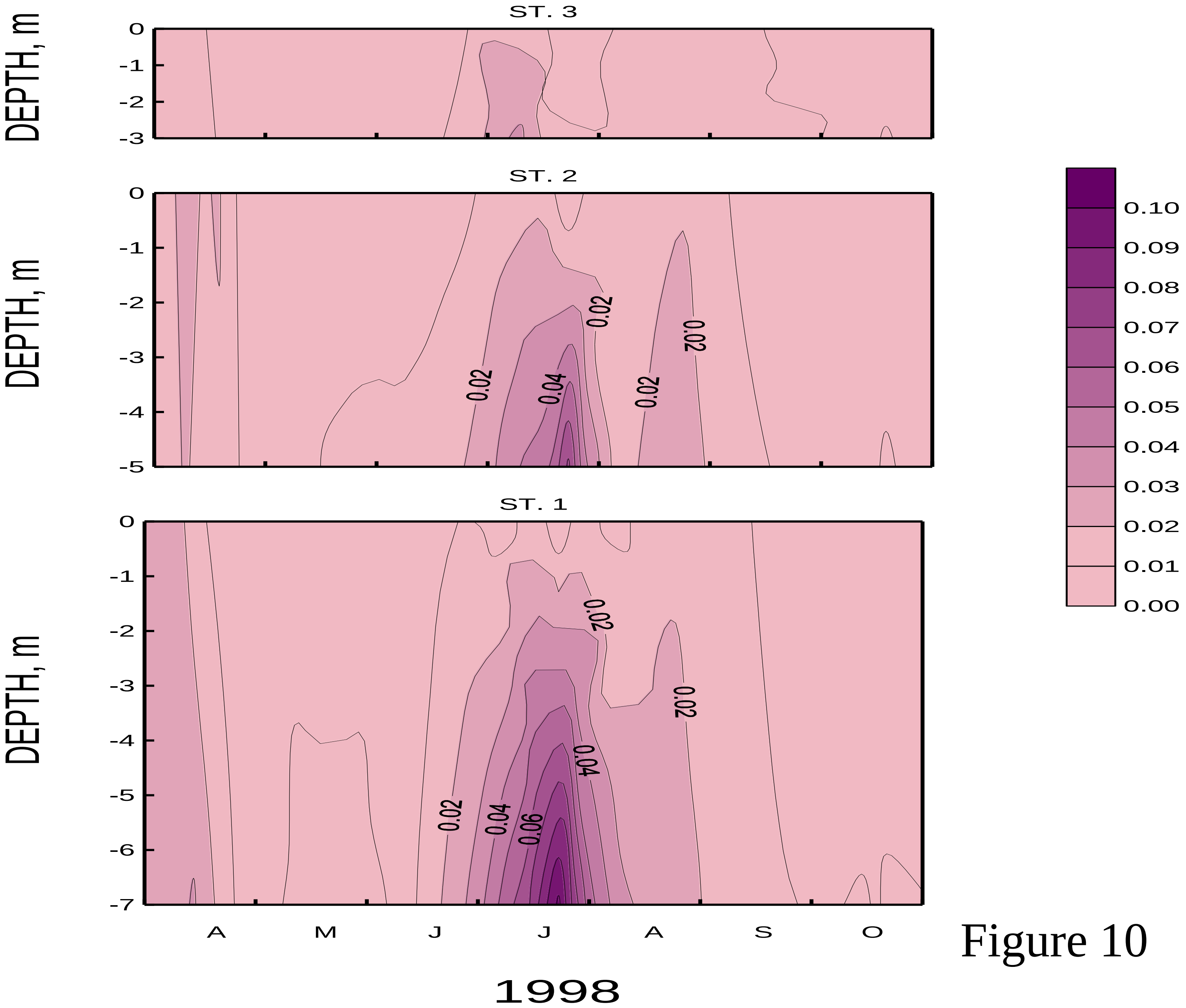
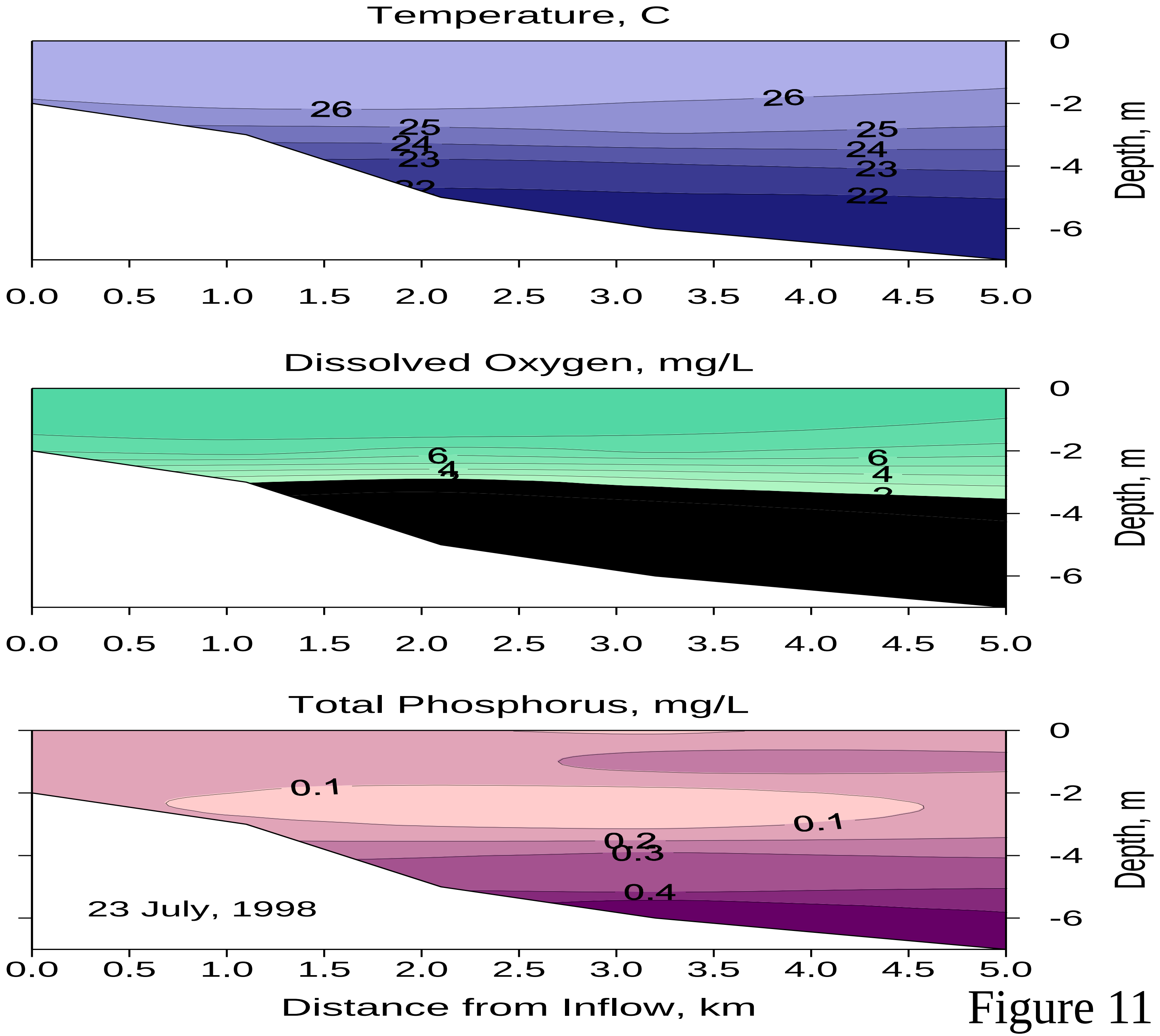


Figure 10



23 July, 1998

Figure 11

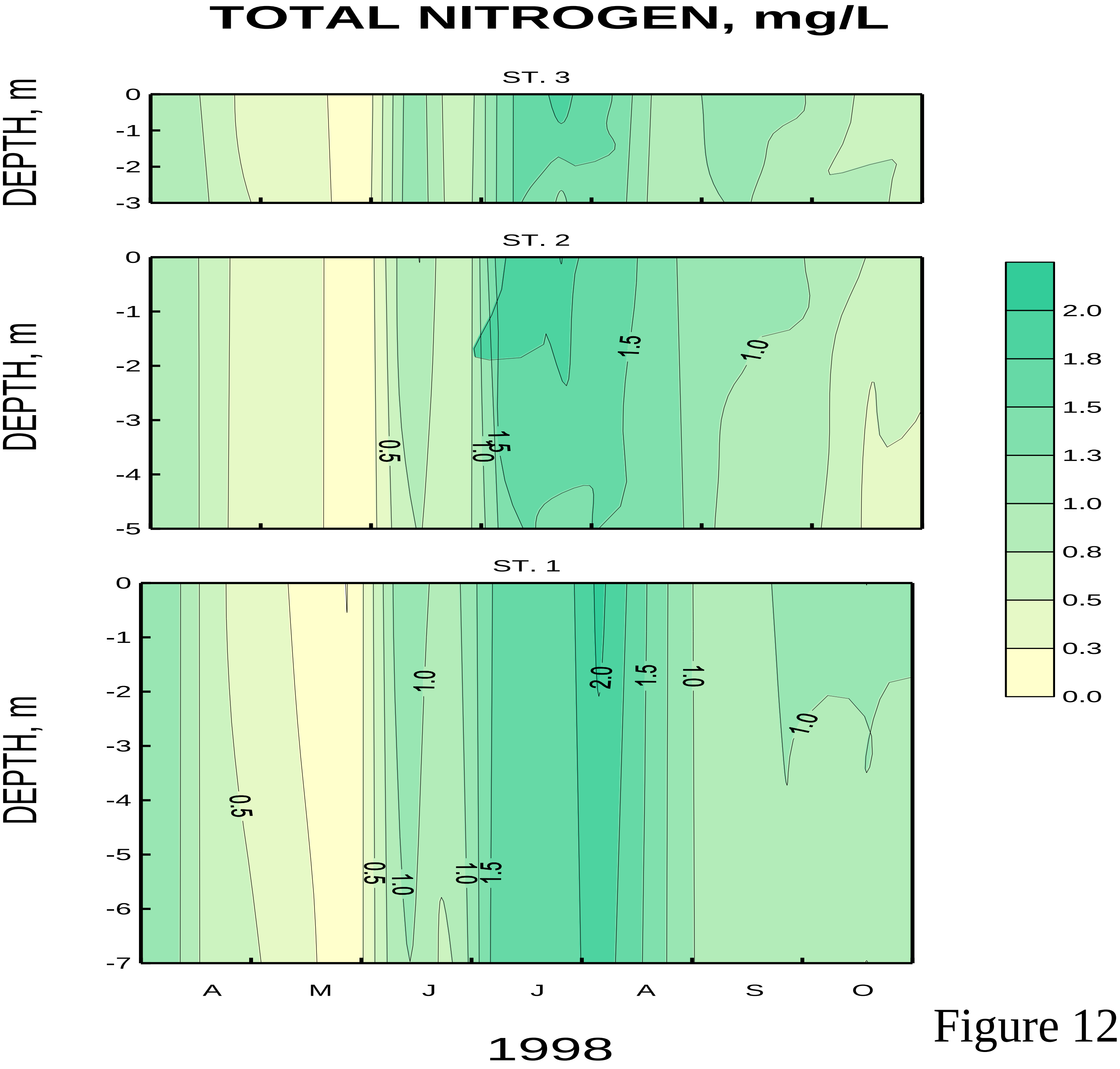

TOTAL NITROGEN, mg/L
ST. 3
DEPTH, m
0
-1
-2
-3
ST. 2
DEPTH, m
0
-1
-2
-3
-4
-5
0.5
1.0
1.5
1.5
1.0
ST. 1
DEPTH, m
0
-1
-2
-3
-4
-5
-6
-7
1.0
2.0
1.5
1.0
1.0
0.5
0.5
1.0
1.0
1.5
A
M
J
J
A
S
O
1998
2.0
1.8
1.5
1.3
1.0
0.8
0.5
0.3
0.0

Figure 12

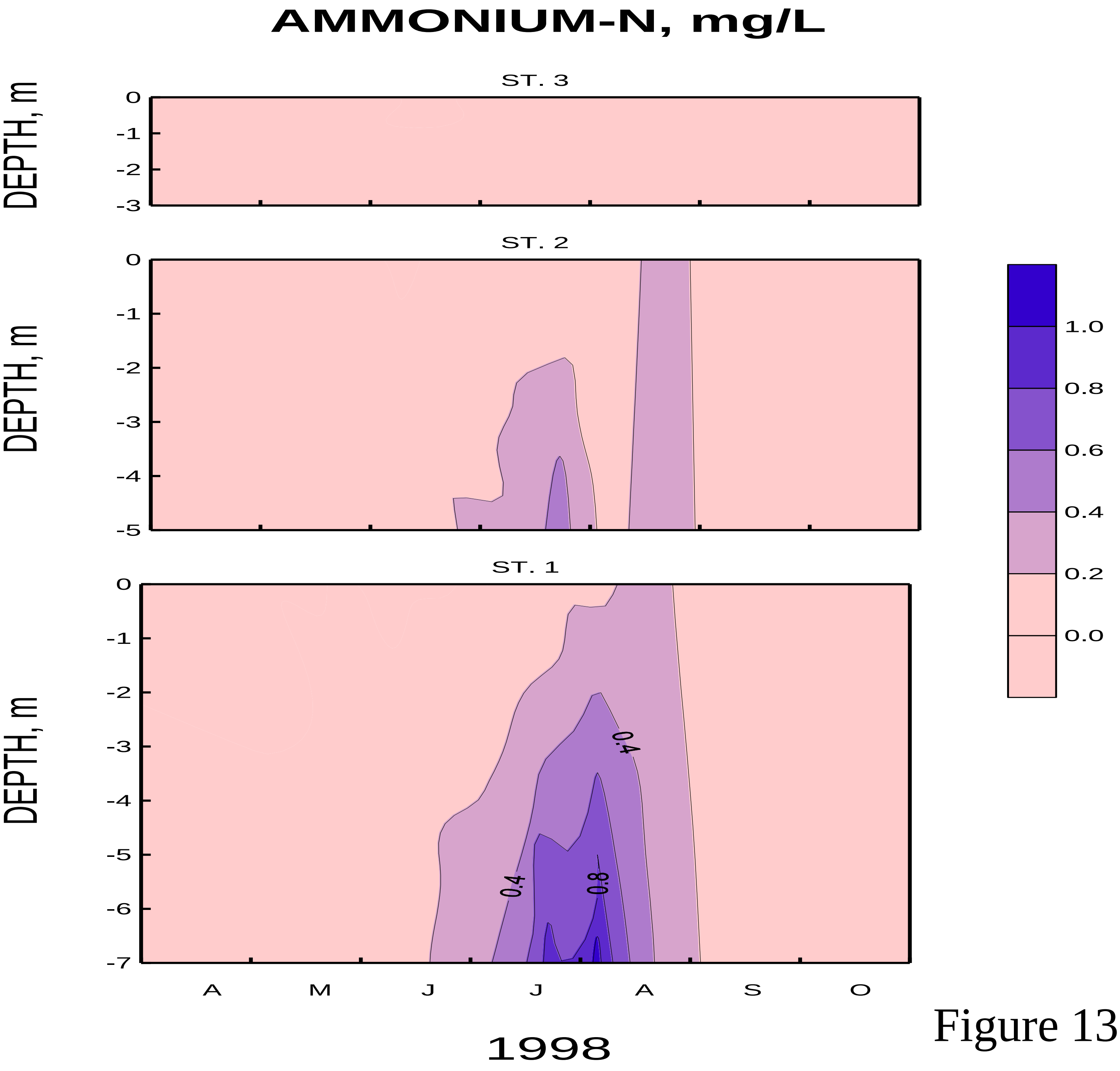

AMMONIUM-N, mg/L
ST. 3
ST. 2
ST. 1
DEPTH, m
0
-1
-2
-3
-4
-5
-6
-7
0.4
0.8
1.0
0.8
0.6
0.4
0.2
0.0
A
M
J
J
A
S
O
1998

Figure 13

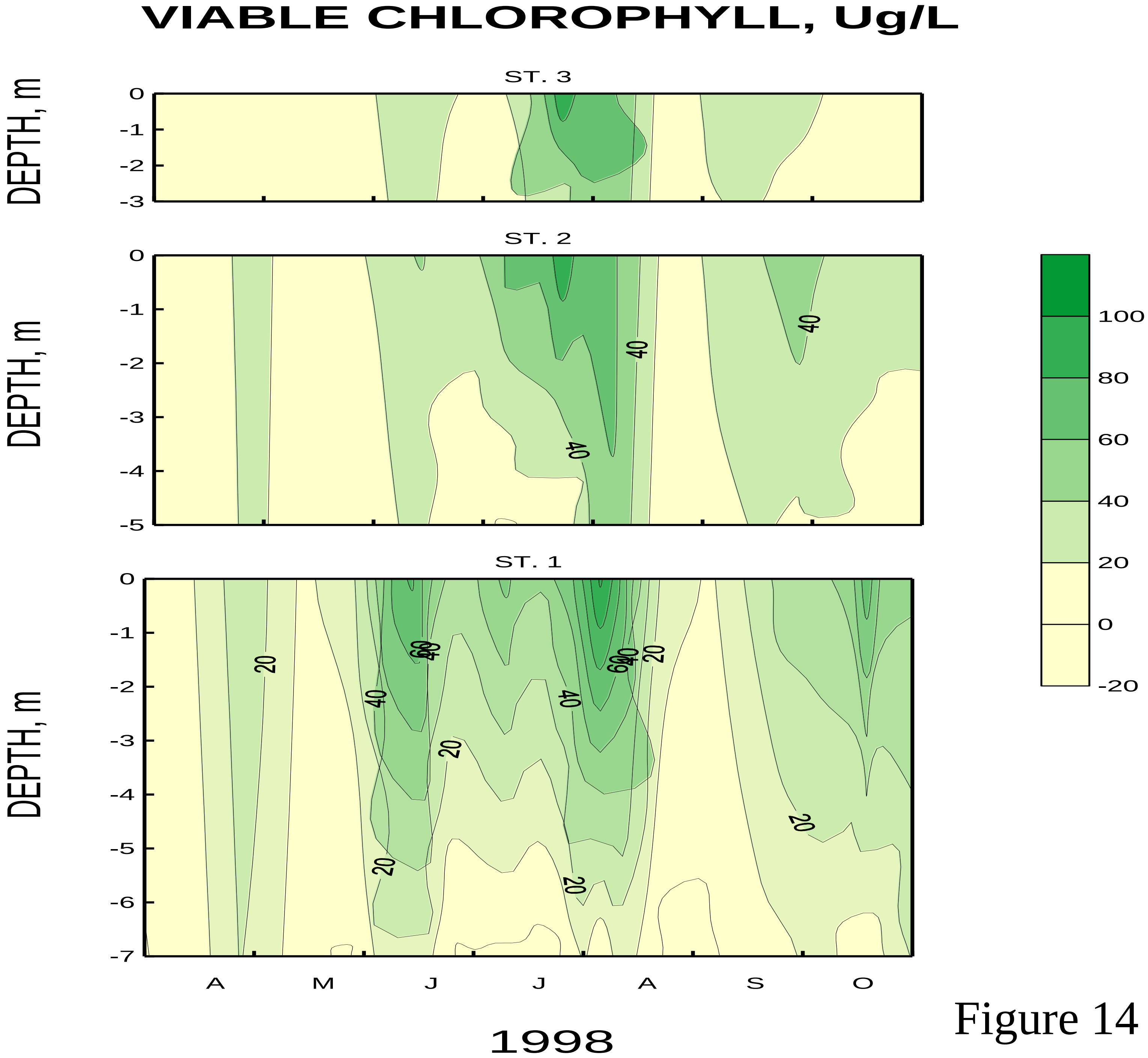

VIABLE CHLOROPHYLL, Ug/L
ST. 3
ST. 2
ST. 1
DEPTH, m
DEPTH, m
DEPTH, m
0
-1
-2
-3
-4
-5
-6
-7
40
60
20
A
M
J
J
A
S
O
1998
100
80
60
40
20
0
-20

Figure 14

LAKE EAU CLAIRE RELATIVE PHYTOPLANKTON BIOMASS DURING APRIL-OCTOBER, PERCENT

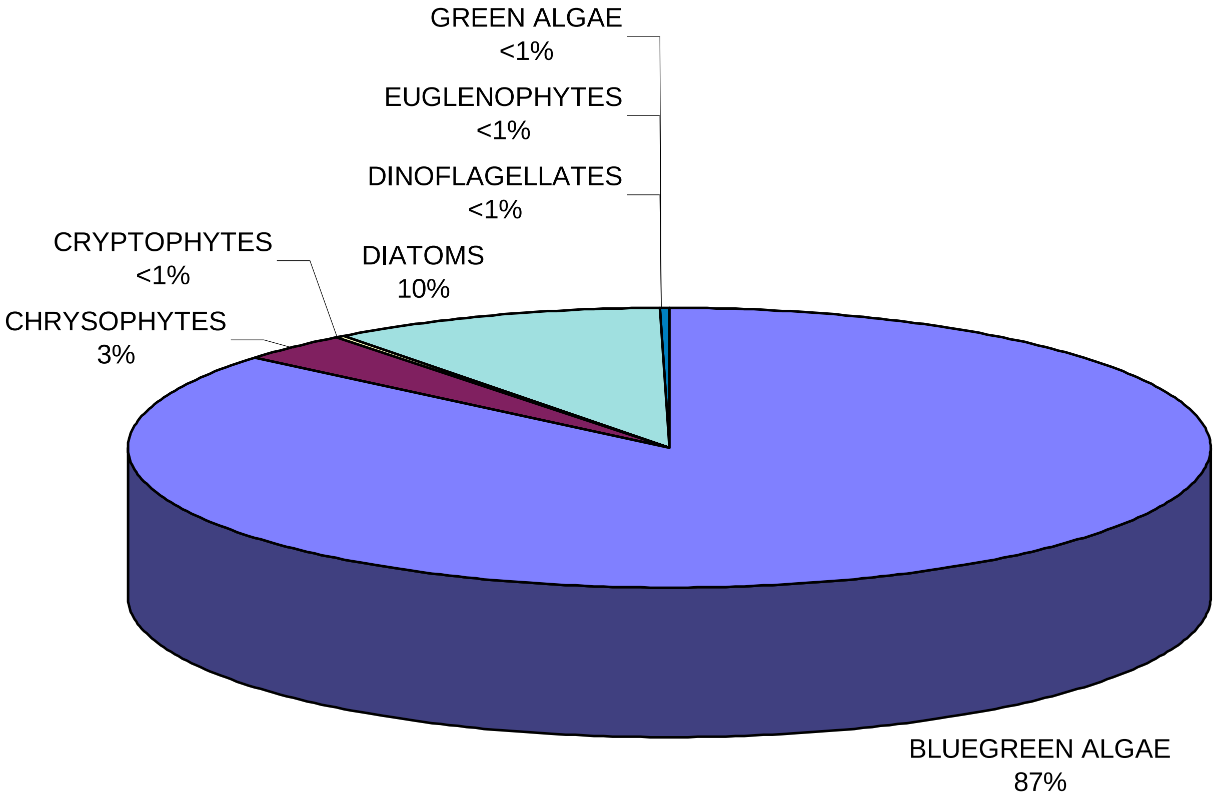


Figure 15

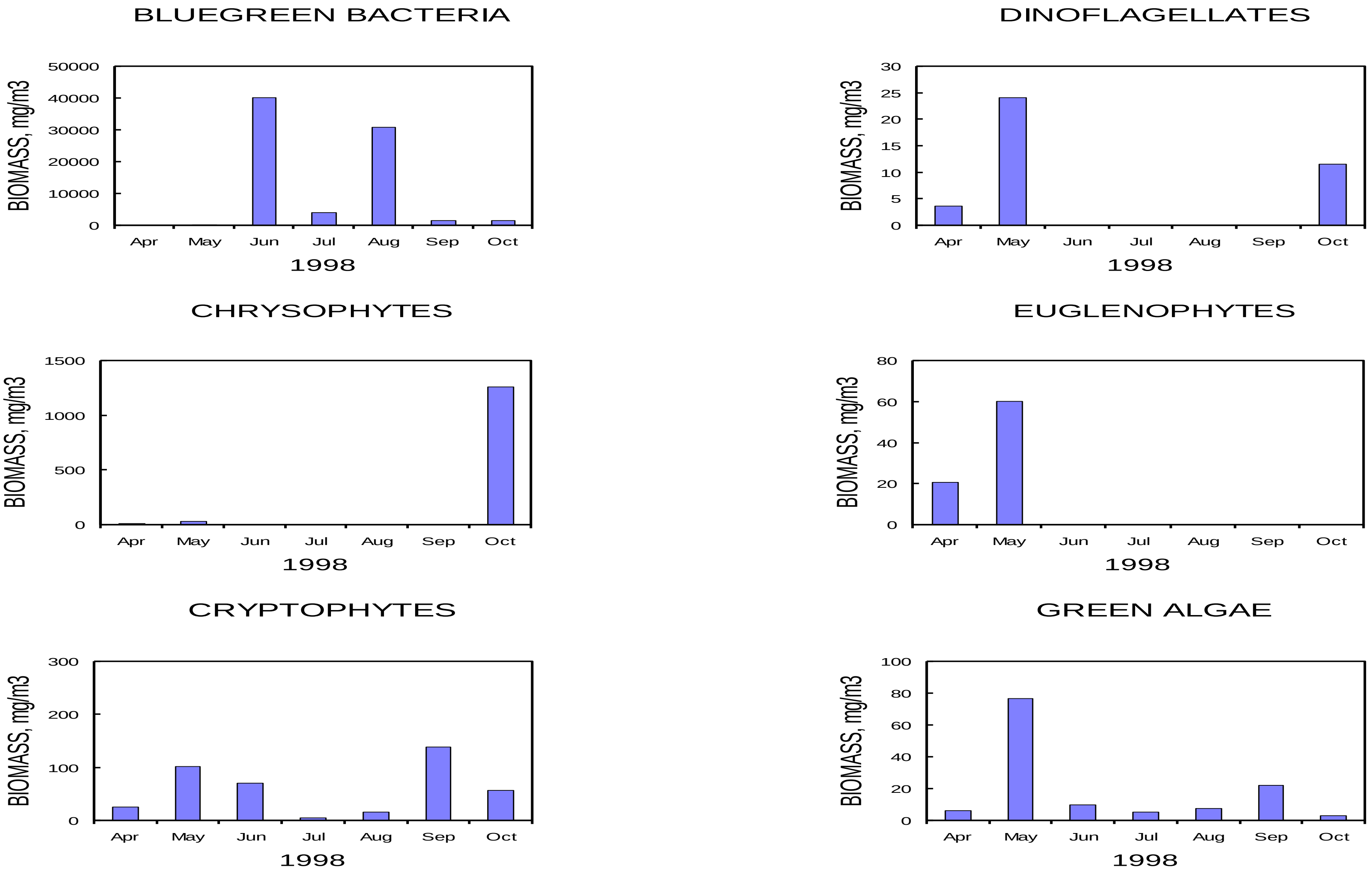

BLUEGREEN BACTERIA
BIOMASS, mg/m3
50000
40000
30000
20000
10000
0
Apr
May
Jun
Jul
Aug
Sep
Oct
1998
DINOFLAGELLATES
BIOMASS, mg/m3
30
25
20
15
10
5
0
Apr
May
Jun
Jul
Aug
Sep
Oct
1998
CHRYSOPHYTES
BIOMASS, mg/m3
1500
1000
500
0
Apr
May
Jun
Jul
Aug
Sep
Oct
1998
EUGLENOPHYTES
BIOMASS, mg/m3
80
60
40
20
0
Apr
May
Jun
Jul
Aug
Sep
Oct
1998
CRYPTOPHYTES
BIOMASS, mg/m3
300
200
100
0
Apr
May
Jun
Jul
Aug
Sep
Oct
1998
GREEN ALGAE
BIOMASS, mg/m3
100
80
60
40
20
0
Apr
May
Jun
Jul
Aug
Sep
Oct
1998

Figure 16

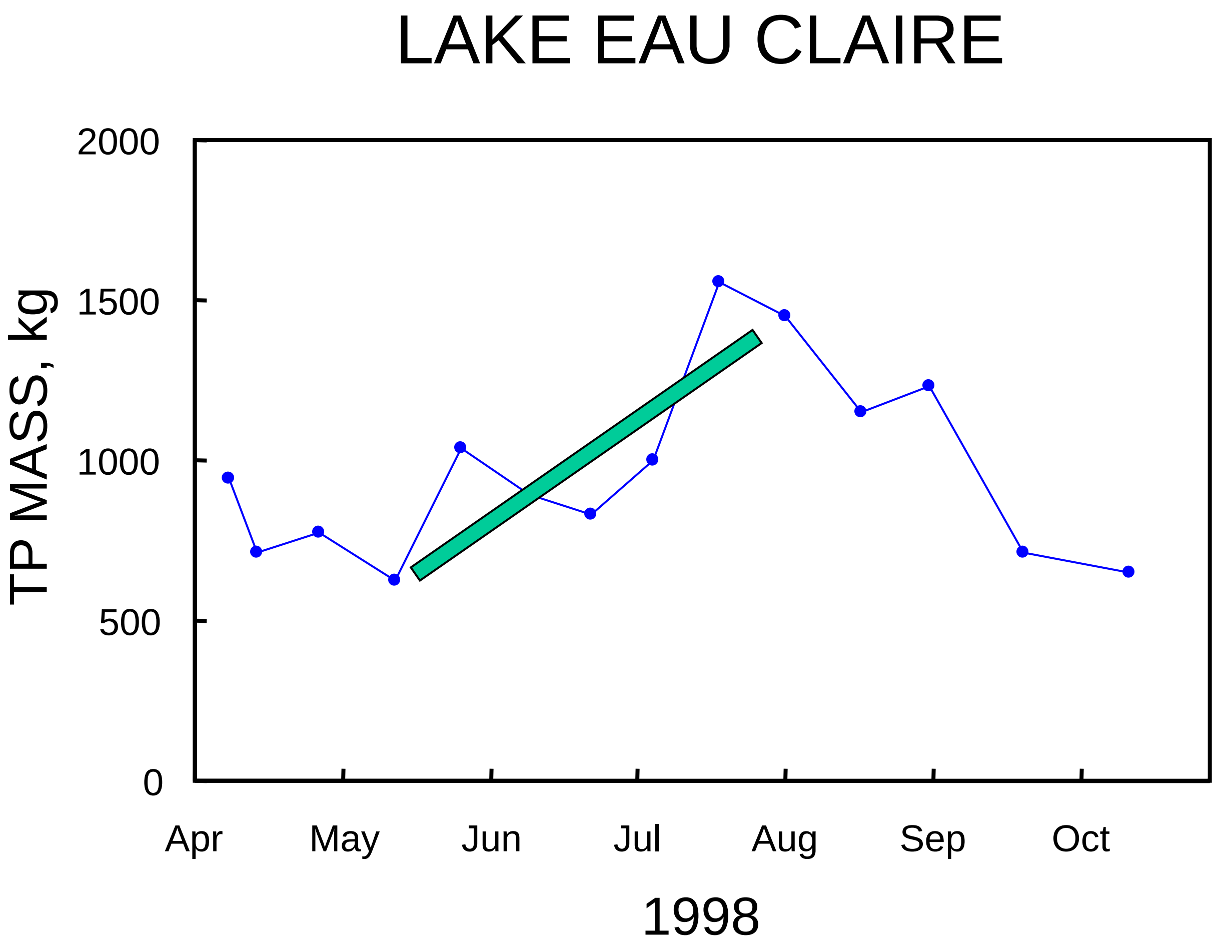

LAKE EAU CLAIRE
TP MASS, kg
2000
1500
1000
500
0
Apr
May
Jun
Jul
Aug
Sep
Oct
1998

Figure 17

PERCENT CONTRIBUTION OF MEASURED EXTERNAL AND INTERNAL P LOADS TO LAKE EAU CLAIRE
JUN-AUG 1998

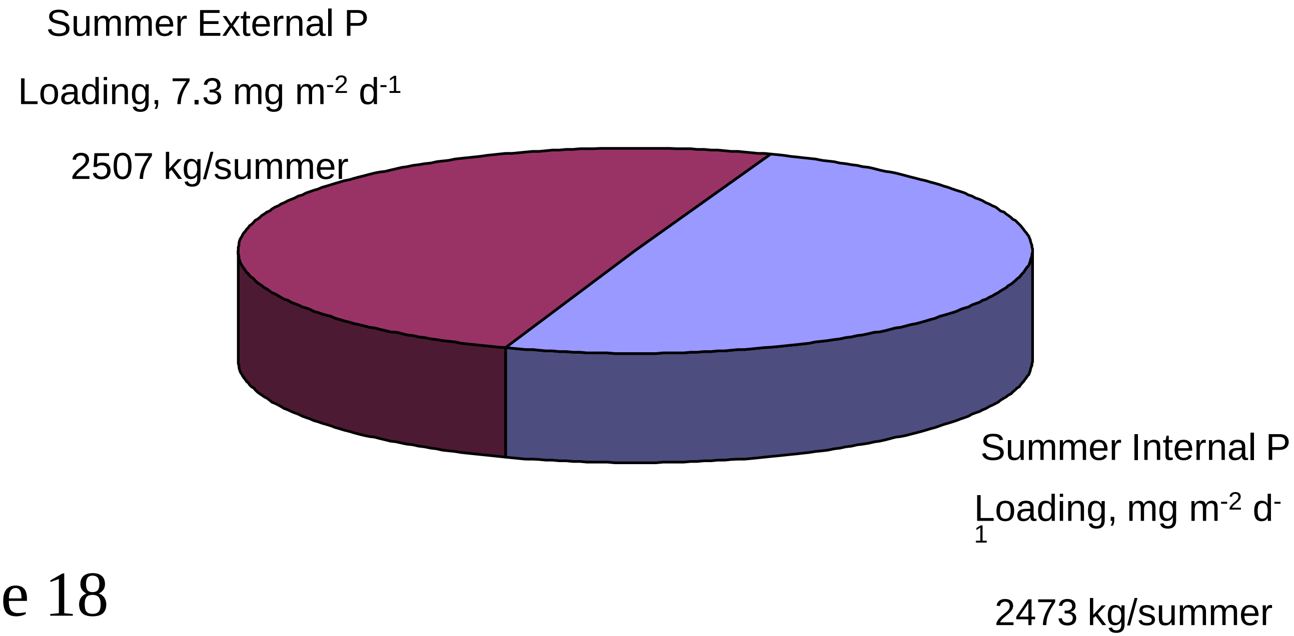


Figure 18

ESTIMATED BLOOM FREQUENCY
LAKE EAU CLAIRE - 1998
No Internal P Loading Management

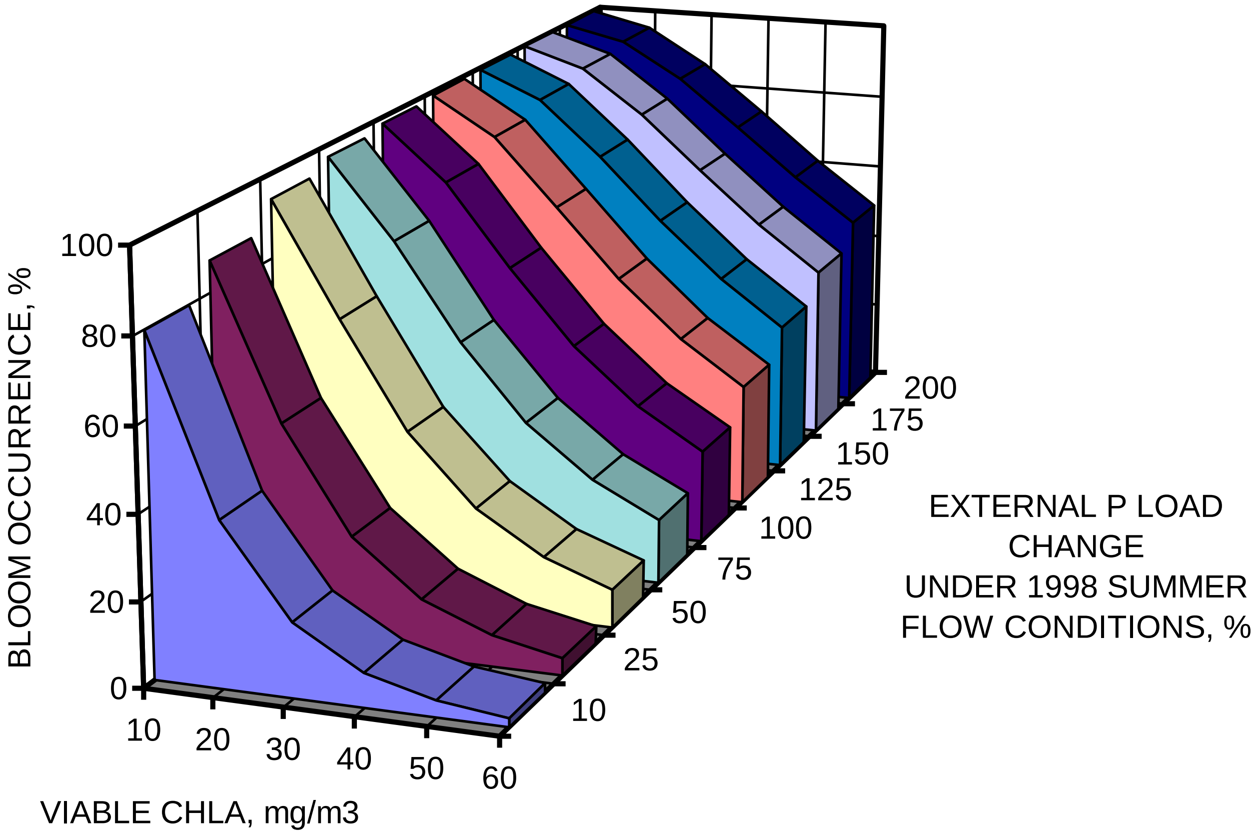
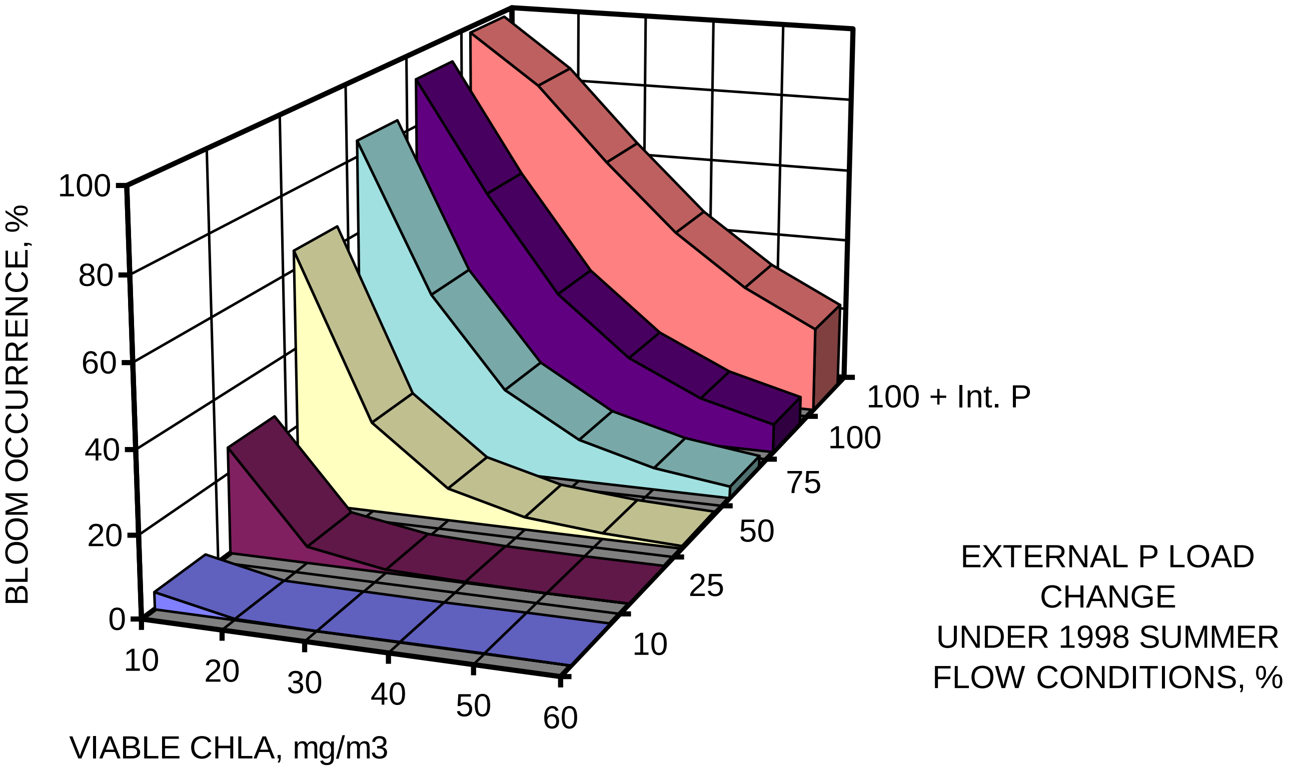


Figure 20



ESTIMATED BLOOM FREQUENCY
LAKE EAU CLAIRE - 1998
85 % Internal P loading Management

Figure 22