Limnological Investigations of Camelot, Sherwood, and Arrowhead Lakes, Wisconsin

by

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PREFACE

This study was conducted in response to a request from the Tri-Lakes Lake Association 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 the Tri-Lakes Lake Association, WI-DNR, and USAED, St. Paul. The study coordinator for WI-DNR was Mr. Mark Huzaga. The Section 22 coordinator for the USAED, St. Paul, was Mr. Terry Engel.

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EXECUTIVE SUMMARY

Hydrology

Several storms occurred throughout the study period, resulting in elevated inflow from Fourteen Mile Creek, and Leola and Unnamed Ditch. Storm-related inflows from these tributaries were greatest during June through early July and early September. Discharges from Camelot, Sherwood, and Arrowhead dams were elevated during precipitation events in June-July and early September, and during the Winter draw-down (October- February) and Spring runoff (March) periods. On an annual basis, all lakes exhibited an hydrologic budgetary imbalance ranging from +18% (Camelot Lake) to -14% and -10% for Sherwood and Arrowhead Lakes, respectively. Positive imbalances (Camelot Lake) may be due to net groundwater recharge into the lake while negative imbalances (Sherwood and Arrowhead Lakes) may be attributed to net groundwater discharge (i.e., seepage) from the lake. On a summer basis (May-September), the residence time of water ranged from 48 days for Sherwood Lake to 63 days and 103 days for Camelot and Sherwood Lakes, respectively. Variations in the residence time between lakes were related primarily to lake volume (Arrowhead > Camelot > Sherwood).

Loading of sediment and nutrients

Annual loading of total suspended sediment (TSS), and total phosphorus (TP) were greatest for Fourteen Mile Creek. In contrast, Unnamed Ditch exhibited the greatest annual total nitrogen (TN) load. Average concentrations of TSS and TP were much greater for the inflows than the dam discharges, indicating net retention of these constituents in the three lakes. Camelot Lake retained most of the TSS and TP load generated from the three major tributaries. In contrast, Camelot Lake appeared to be a net source for TN while most of the TN was retained by Sherwood and Arrowhead Lakes. Most of the TN load was in the form of nitrate-nitrite-N (NO_2NO_3-N).

Mean rates of P release from sediments, measured in the laboratory, varied between 0.1 mg m^{-2} d^{-1} at the Arrowhead Dam Station to 8.3 mg m^{-2} d^{-1} at the Sherwood South Arm Station under anoxic conditions. Greatest rates under anoxic conditions were observed in Lower Camelot Lake (1.2 mg m^{-2} d^{-1}) and in the south arm (8.3 mg m^{-2} d^{-1}) and dam region (1.4 mg m^{-2} d^{-1}) of Sherwood Lake. For backwater stations, rates of P release from sediments under anoxic conditions ranged between 0.2 mg m^{-2} d^{-1} for Upper Camelot #2 backwater and 8.1 mg m^{-2} d^{-1} for Lower Camelot #3 backwater. Overall, the range in rates of P release under anoxic conditions are indicative of eutrophic (fertilized) sediments. In contrast, rates of P release from sediments under oxic conditions were near detection limits for most stations examined.

Lake water quality

As a result of apparently high retention (and sedimentation) of external P loads in Camelot Lake, average TP concentrations were low in the three lakes, relative to inflow concentrations, and the Wisconsin Trophic State Index (TSI) was near 50, indicative of mesoeutrophic conditions. One unusual (and as yet unexplainable) feature of average TP concentrations was a gradient of increasing concentration from Camelot to Arrowhead Lake (i.e., Arrowhead>Sherwood>Camelot). Average chlorophyll concentrations followed a similar pattern of increasing values. Overall, average summer chlorophyll concentrations were low for all lakes and the Wisconsin TSI for chlorophyll ranged between 52 (Camelot) and 58 (Arrowhead). Average Secchi transparency ranged between 1.5 and 2.2 m. Wisconsin TSI values for Secchi transparency ranged between 49 and 54, indicative of mesoeutrophic conditions. TSI values were within the mesoeutrophic range for backwaters stations monitored in Camelot and Sherwood Lakes.

Seasonally, average concentrations (over the upper 4 m water column) of chlorophyll (i.e., algal biomass) were low in the three lakes between April and early June and increased in August through September. During the algal bloom period in August-September, average concentrations of chlorophyll exceeded 30 mg/m^3 in Sherwood and Arrowhead Lakes. Average concentrations were much lower in Camelot Lake during this time period. Backwater regions of Camelot (i.e., Upper Camelot #2 and Lower Camelot #3) and Sherwood (i.e., Sherwood #6, #7, and #8) exhibited similar patterns in chlorophyll concentration as the main-stem stations. In general, backwater regions of both lakes exhibited low concentrations between April and June. Concentrations increased at these stations in August through September. Chlorophyll concentrations during this bloom period were greater in the backwaters examined in Sherwood Lake, compared to those backwaters examined in Camelot Lake.

Although main-stem stations in the Tri-Lakes system stratified during the summer period, dissolved oxygen depletion and the development of anoxic conditions in the bottom waters was minor, intermittent, and confined to the lower meter of the water column. No bottom water anoxia was detected Arrowhead Lake or in backwater stations. Thus, rates of P release from sediments were most likely driven by oxic conditions and probably had minimal impact on P flux to the Tri-Lakes system, based on laboratory results.

Modeled loading scenarios

We examined the impacts of both increased and decreased external TP loading on summer (May-September) lake response for the three lakes. External loads were varied between 25% and 200% of current (i.e., 2000) loading conditions. Annual external P loads (i.e., Fourteen Mile Creek, Leola Ditch, and Unnamed Ditch) were used in the calculation (versus seasonal loads). Camelot Lake exhibited the greatest response (and most sensitivity) to changes in P loading. Reducing external P loading by 50% resulted in an approximately 58% reduction on chlorophyll concentrations. In contrast, increasing external P loading by 50% resulted in an estimated 48% increase in chlorophyll concentration. These results suggested that managing external P loads will improve chlorophyll and Secchi transparency in Camelot Lake.

Since Camelot Lake appeared to trap most of the external P loading, modeled chlorophyll responses to changes in external P loading were less for Sherwood and Arrowhead Lakes, due to the moderating effects of Camelot Lake on TP concentrations. However, modeled chlorophyll response in Sherwood Lake, which receives discharges from Camelot Lake, appeared to be more sensitive to changes in external P loading than Arrowhead Lake, which is located downstream of Sherwood Lake. Changes in the estimated bloom frequency occurrence followed a similar pattern. Bloom frequency occurrence appeared to respond more dramatically to increases or decreases in external P loading in Camelot lake, followed by less sensitive responses in Sherwood and Arrowhead Lakes, respectively.

Implications for P management of the Tri-Lakes system

Causes for the unusual positive gradient in TP and chlorophyll from Camelot to Arrowhead Lake are not completely known, given that there are no apparent streams located downstream of Camelot Lake that could act as a source of external P. P release from sediment under anoxic conditions could contribute to TP concentration gradients between the lakes. However, it was low for sediments collected near Arrowhead Dam (0.1 mg m^{-2} d^{-1}), and higher for sediments collected near Sherwood Dam (1.4 mg m^{-2} d^{-}

^{1}) and Lower Camelot Dam (1.2 mg m^{-2} d^{-1}). In general, we did not detect prolonged or extensive periods of bottom water anoxia in any lake, suggesting that internal P loading via sediment was probably negligible. Other potential internal sources of P to Sherwood and Arrowhead Lakes, that we did not measure directly, include groundwater influxes, other bottom sediments or inundated soils in the lakes that we did not locate, and direct uptake of sediment P by algae.

Management of the watershed via BMP=s (Best Management Practices) to control P inputs will have a very positive impact on water quality conditions in the Tri-Lakes system. Reduction of P inputs and sediment will lessen the likelihood of algal blooms and lower the risk of development of bottom water anoxia and enhanced internal P loading from the sediments.

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 the Ti-Lakes system. 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 Fourteen Mile Creek, Leola Ditch, and Unnamed Ditch (Fig. 1) were monitored using continuous stage height recorders (ISCO Model 4120 or 4150). Stage elevations were converted to volumetric flow using a rating curve generated under different flow regimes. Pool elevation fluctuations were obtained from Gerald Bakus of the Tri-Lakes Lake Association and converted to discharges using rating tables developed by R.A. Smith and Associates (1992) for estimation of hydrological mass balance. Net residual was calculated according to the following hydrological mass balance:

Change in pool volume, m^3 *= (measured inflow + precipitation) - (measured outflow + residual flow)*

for estimation of net groundwater flux in each lake.

Grab samples from the three tributary inflows and the outflow at each dam (i.e., Upper Camelot, Lower Camelot, Sherwood, and Arrowhead Dams) were collected at tri-weekly intervals. Additional water samples were collected from Fourteen Mile Creek, Leola Ditch, and Unnamed Ditch using automated sampling procedures (ISCO model 3700 automated water samplers).

Water samples collected at various inflows and dam discharges were analyzed for the variables listed in Table 1. For total suspended sediment (TSS) 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 (TN) and phosphorus (TP) were predigested with potassium persulfate according to Ameel et al. (1993) before analysis. Water samples for analysis of soluble constituents were filtered through a 0.45 μm filter (Gelman Metricel) prior to analysis. TN, nitrate-nitrite-N (NO_2NO_3-N), ammonium-N (NH_4-N), TP, and soluble reactive phosphorus (SRP) were measured colorimetrically on a Lachat QuikChem automated water chemistry system (Zellweger Analytics, Lachat Div., Milwaukee, WI). Annual loadings by various external sources were estimated using the computer model *Flux* (Walker 1996).

LIMNOLOGICAL MONITORING

Sampling stations were established near the dam of Upper and Lower Camelot Lake, in the northern and southern arm and near the dam of Sherwood Lake, and near the dam of Arrowhead Lake (Fig. 1). Sampling stations were also established in backwater embayments located on Upper and Lower Camelot Lake (i.e., Upper Camelot #2 and Lower Camelot #3) and Sherwood Lake (i.e., Sherwood #6, #7, and #8;

Fig. 1). Average water column depths at the main-stem sampling stations during the ice-free period were as follows: Arrowhead Dam = 6.5 m; northern arm of Sherwood Lake = 4.1 m; southern arm of Sherwood Lake = 3.8 m; Sherwood Dam = 7.7 m; Upper Camelot Dam = 6.8 m; Lower Camelot Dam = 7.3 m. Average water column depths at the backwater sampling stations during the ice-free period were as follows: Upper Camelot #2 = 2.9 m; Lower Camelot #3 = 2.3 m; Sherwood #6 = 2.0 m; Sherwood #7 = 1.8 m; Sherwood #8 = 2.5 m. During the ice-free period, water samples were collected triweekly at 1-m intervals from the surface (i.e., 0.1 m) to the 3 m depth and at 2-m intervals from 4 m to within 0.5 m from the bottom for the water quality variables listed in Table 1 (see above section entitled AExternal Loadings and Discharges@ for analytical methodology on TSS, POM, TN, NO_2NO_3-N, NH_4-N, TP, and SRP). For soluble constituents (i.e., soluble reactive phosphorus), samples collected from anoxic water in the lake were filtered immediately without exposure to oxygen. 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. Secchi transparency was measured at each station to the nearest cm using an alternating black and white 10 cm Secchi disk. The Carlson Trophic State Index (Carlson 1977) was estimated using the computer program *Profile* and *Bathtub* (Walker 1996) using Secchi transparency values and total phosphorus and viable chlorophyll *a* concentrations determined over the upper 4 m of the reservoir. In addition, the Wisconsin Trophic State Index was estimated using equations described in Lillie et al. (1993).

The computer model *Bathtub* (Walker 1996) was also used as a management tool to forecast the trophic response of the Tri-Lakes system to reductions and increases in P loading. We used measurements of chlorophyll and total phosphorus weighted over the period May through September as average summer conditions. The computer program *Profile* (Walker 1996) was used to estimate weighted summer concentrations for input into *Bathtub*.

INTERNAL LOADINGS

Six replicate intact sediment cores were collected from the profundal sediments of stations located along the main-stem of the Tri-Lake system and in the backwater embayments located in Camelot and Sherwood Lakes (Fig. 1), for determination of rates of SRP release from the sediment. 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 SRP. Rates of P release from the sediment (mg m^{-2} d^{-1}) were calculated as linear changes in P 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.

RESULTS

HYDROLOGICAL CONDITIONS

Several precipitation events occurred during the study period in 2001 (Fig. 2). Events exceeded 1 inch eight times in April through June, once in August, and once in September. The greatest measured precipitation event (> 2 inches) occurred in early September (Fig. 2). Overall, monthly precipitation was greatest in June, exceeding 10 inches (Fig. 3). Monthly precipitation exceeded 5 inches in September and 3 inches in May, July, and August. Monthly precipitation exceeded 1 inch in March and April. Lowest monthly precipitation (< 1 inch) occurred in October and November.

Annual average measured flow was greatest for Fourteen Mile Creek and Leola Ditch (Table 2), while Unnamed Ditch exhibited a lower annual average flow of 0.22 cubic meters per second (cms). Peaks in daily flow at the three monitored inflow stations between mid-March and November coincided with peaks in precipitation events (Fig. 2), indicating storm runoff. Peaks in flow in late February and early March coincided with an early Spring snowmelt and runoff.

During the summer period between May and September, mean daily discharge from the three dams (Camelot, Sherwood, and Arrowhead) fluctuated primarily as a function of storm-related inflows, with peaks in dam discharge coinciding with peaks in precipitation and measured inflow (Fig. 4). During the same summer period, Sherwood Lake had the lowest hydraulic residence time, followed by Camelot and Arrowhead Lakes, respectively (Table 3). Thus, the equivalent of the summer volume of Camelot Lake was flushed 2.4 times, while the equivalent of the summer volume of Sherwood and Arrowhead Lakes were flushed 3.2 and 1.5 times, respectively, during the five month period. During spring snowmelt and the winter ice-covered period, dam discharge (and pool elevation) was adjusted to maintain winter drawdown conditions and to accommodate spring snowmelt runoff (Fig. 4). Winter declines in pool elevation were greatest in Camelot and Sherwood Lakes (Figs. 5-7).

The annual hydrologic budget for the 3 lakes is shown in Table 4. Camelot lake exhibited greater net annual outflow than inflow, suggesting the occurrence of net seepage of groundwater into the lake. In contrast, Sherwood and Arrowhead Lakes exhibited greater net annual inflow than outflow, suggesting the occurrence of net seepage out of these lakes.

SEDIMENT AND NUTRIENT SOURCES AND SINKS

External Loadings

Fourteen Mile Creek contributed the greatest annual loading of TSS, followed closely by Leola Ditch (Table 5). Unnamed Ditch exhibited the lowest measured annual TSS load (Table 5). Average concentrations of TSS were similar between the three tributaries, ranging between 19.6 and 22.8 mg/L.

Unnamed Ditch contributed the greatest TN load to the Tri-lakes system due, in large part, to high average concentrations of TN in the runoff (Table 5). NO_2NO_3-N comprised 78% of the annual TN load contributed by Unnamed Ditch, suggesting the occurrence of agricultural contributions to high TN. Although TN loading via Fourteen Mile Creek was equivalent to that of Unnamed Ditch, mean TN concentrations were lower, compared to Unnamed Ditch, and the NO_2NO_3-N component accounted for only 50% of the TN load from this tributary. Leola Ditch contributed the lowest TN load to the Tri-Lakes system and NO_2NO_3-N account for 40% of the TN load from this tributary. In contrast, organic N loading (not shown) was greatest for Fourteen Mile Creek and Leola Ditch (45% and 54%, respectively). Organic N loading via Unnamed Ditch represented only 20% of the total N loading from this tributary. NH_4-N concentrations and loads were low for all three tributaries.

TP Loading ranged between ~300 kg/y for Unnamed Ditch and ~600 kg/y for Fourteen Mile Creek. Average concentrations of TP were greatest for Fourteen Mile Creek, followed by Leola Ditch and Unnamed Ditch, respectively. SRP accounted for 11% or less of the TP load, indicating that particulate and organic P fractions dominated the TP load to the Tri-Lakes system.

In contrast to the relatively high concentrations of TSS and P in the inflows, concentrations and loads of these constituents were generally much lower in the discharge of Camelot, Sherwood, and Arrowhead Lakes (Table 5). In general, Camelot Lake retained ~94% and ~60% of the measured TSS and TP loading, suggesting the occurrence of sedimentation in Camelot Lake (Table 6). Of the TSS and TP load discharged from Camelot Lake to downstream reservoirs, less than 20% was retained in Sherwood and Arrowhead Lakes. Thus, Camelot Lake appeared to be a sink for most of the watershed-derived TSS and TP (Table 6).

TN exhibited an unusual pattern as Camelot Lake discharged ~ 46% more TN than could be accounted for by TN loading from the three tributaries. Thus, it appeared to be a source of TN to downstream reservoirs (Table 6). Most of the TN in the discharge (91%) of Camelot Lake was in a soluble form (NO_2NO_3-N; Table 5), suggesting it was derived from an internal (as yet unidentified) source within the lake. Thirty-eight to fifty percent of the TN (primarily as NO_2NO_3-N) discharged from Camelot Lake was retained in Arrowhead and Sherwood Lakes, respectively (Table 6).

Concentrations of TSS and TP in the inflows of the three tributaries appeared to exhibit a seasonal pattern, as they were elevated during inflow periods between March and May and September through November, and lower during the period June through August (Fig. 8). In contrast, TN and NO_2NO_3-N exhibited a strong inverse relationship between flow and concentration for the three tributaries (not shown). We did not observe seasonal variations in discharge concentrations from the three dams (i.e., Lower Camelot, Sherwood, and Arrowhead Dams).

Internal Loadings

Mean rates of P release from sediments, measured in the laboratory, varied between 0.1 mg m^{-2} d^{-1} at the Arrowhead Dam Station to 8.3 mg m^{-2} d^{-1} at the Sherwood South Arm Station under anoxic conditions (Table 7). Greatest rates were observed in Lower Camelot Lake and in the south arm and dam region of Sherwood Lake (Table 7). For backwater stations, rates ranged between 0.2 mg m^{-2} d^{-1} and 8.1 mg m^{-2} d^{-1}. Under oxic conditions, rates of P release from sediments were below detection for most stations examined (Table 7). The south arm of Sherwood Lake and backwater stations located in Lower Camelot (#2) and Sherwood (#7) Lakes exhibited very low detectable rates of P release (Table 7).

LIMNOLOGICAL CONDITIONS

Main-Stem Stations

Thermal stratification (i.e., warmer surface water overlying cooler bottom water) occurred at all main-stem stations between late June and late August (Figs. 9-11). In general, stratification appeared to be stronger in Upper Camelot Lake than in Lower Camelot Lake during the summer period, which is likely the result of segregation of Upper Camelot Lake from inflow and, thus, flushing influences. The epilimnetic depth in each lake during the summer stratified period ranged between 3.5 and 4.2 m. Periods of turnover occurred in April and late September through October at all main-stem stations.

During the stratified period, dissolved oxygen depletion occurred in the bottom waters of all main-stem stations (Figs. 12-14). However, the occurrence of anoxia occurred only intermittently during this period at several stations and the vertical extent of anoxia was confined to the bottom 1 to 2 m of the water column. Bottom water anoxia occurred at main-stem stations located in Upper and Lower Camelot Lakes for very short periods in June and August (Fig. 12). A brief period of bottom anoxia also occurred in Lower Camelot Lake in May (Fig. 12). In Sherwood Lake, bottom anoxia was observed in late August at the station located in the South Arm (Fig. 13). Bottom anoxia occurred near the dam of Sherwood Lake briefly in mid-July and late August

(Fig. 13). Bottom anoxia was not observed at the station located near the dam of Arrowhead Lake during the entire study period (Fig. 14).

Mean epilimnetic concentrations of chlorophyll for main-stem stations in the Tri-lakes system are shown in Figure 15. Over all stations, chlorophyll was lowest between April and mid-July and October through November (Fig. 15). Peaks in concentration occurred in August through September, coinciding with strong stratification. In Camelot Lake, chlorophyll peaks during that period were greatest in the lower arm. In contrast, all stations in Sherwood Lake exhibited similar concentration peaks during that period. Arrowhead dam exhibited a similar concentration peak in August through September (Fig. 15).

Concentrations of TP were elevated at all main-stem stations in late April through early May (Fig. 16), coinciding with periods of high spring inflow (Fig. 2). TP declined at all main-stem stations during the early summer period of high inflow (June-July), then generally increased in August-September in conjunction with peaks in chlorophyll, suggesting uptake by algae. Concentration declines during the June through July storm inflow periods may be attributed to dilution. Concentrations of TP also increased in Camelot Lake in October-November. In Sherwood and Arrowhead Lakes, TP declined slightly during that period.

Secchi transparency was generally lowest at all main-stem stations in August through September, in association with peaks in chlorophyll, suggesting algal-mediated light attenuation (Fig. 17). During April through July, it often exceeded 2 m at all main-stem stations. Greatest Secchi transparency values occurred in April in the north and south arms of Sherwood Lake.

In contrast to TP, TN concentrations exhibited peaks at all main-stem stations during the high inflow events in June (Fig. 18). Much of the TN during this period was in the form of NO_2NO_3-N (Fig. 19). Concentrations of TN and NO_2NO_3-N declined at main-stem stations from June peaks in late August through November (Figs. 18-19). NH_4-N was generally low at all main-stem stations throughout the study period (Fig. 20).

Overall, mean epilimnetic concentrations of chlorophyll and TP were lowest in Camelot Lake (i.e., average for combined Upper and Lower Camelot Lake; Table 8). Concentrations of these constituents exhibited a gradient of increasing concentration in downstream Sherwood and Arrowhead Lakes (Table 8). Secchi Transparency exhibited the opposite pattern, as it was lowest in Camelot and Sherwood Lakes and greater in Arrowhead Lake. Trophic state indices for chlorophyll, TP, and Secchi transparency ranged between 39 and 60 (i.e., both Carlson and Wisconsin indices), falling within the mesoeutrophic to eutrophic for all main-stem lakes (Table 8). Arrowhead Lake exhibited higher trophic state index values for the three constituents than the other lakes (Table 8).

Backwater Stations

Unlike main-stem stations, backwater stations generally did not exhibit strong thermal stratification during the summer months (Fig. 21). An exception occurred for backwater 2 of Upper Camelot Lake, where temporary stratification was observed in late August (Fig. 21). Due to the lack of summer stratification, dissolved oxygen concentrations did not decline in the bottom waters of the backwater stations monitored (Fig. 22). Dissolved oxygen concentrations remained above 6-8 mg/L in the water column of all backwater stations throughout the summer period.

Similar to patterns observed at main-stem stations, mean concentrations of chlorophyll were lower during the high inflow period of June through July and increased to a peak in August through September (Fig. 23). However, lower secondary peaks in chlorophyll occurred in early June at backwater #6 and #7 in Sherwood Lake. Overall, peaks in chlorophyll concentration were greatest in the Sherwood backwater regions, compared to those monitored in Camelot Lake. TP exhibited peaks in concentration in August-September at backwater stations (Fig. 24), coinciding with peaks in chlorophyll. These patterns suggested incorporation of TP by algae as biomass.

Secchi transparency values fluctuated between 1.4 and 2.7 m at the backwater stations between April and July (Fig. 25). Transparency declined at all stations during peak chlorophyll concentrations in August-September, then increased turn fall overturn in October-November.

Like patterns observed at main-stem stations, TN exhibited peak concentrations in conjunction with storm inflows in June and July (Fig. 26). Overall, NO_2NO_3-N was the dominant inorganic form of TN at all backwater stations (Fig. 27). NH_4-N comprised a negligible percentage of the TN (Fig. 28).

Over the summer (May-September) period, backwater stations monitored in Camelot Lake exhibited lower mean concentrations of chlorophyll and TP, and higher mean transparency values, than backwater stations monitored in Sherwood Lake (Table 9). Carlson trophic state index values ranged between 54.8 and 60.2 for chlorophyll at all backwater stations, suggesting moderately eutrophic conditions. Trophic state index values for other parameters also fell within the eutrophic range for all backwater stations (Table 9).

BATHTUB MODELING FOR THE SUMMER PERIOD OF 2000

External P loadings for Fourteen Mile Creek, Leola Ditch, and Unnamed Ditch, calculated over the entire year using the program FLUX (Table 5), were used as input for the model *Bathtub*. Since main-stem stations exhibited only brief periods anoxia, we assumed that internal P release from profundal sediments was regulated by oxygenated conditions and, thus, represented a negligible input to all lakes. The period May through September was used to estimate lakewide mean concentrations of chlorophyll and TP, and Secchi transparency for model input. Since different stations within a lake generally exhibited similar water quality trends, we did not segregate the lakes into arms, etc, for

Bathtub modeling. Instead, we estimated lakewide means of these constituents for each lake and segregated the Tri-Lakes system into a Camelot, Sherwood, and Arrowhead compartment for modeling purposes. In particular, it was difficult to segregate Camelot Lake into an Upper and Lower compartment for modeling purposes because there was no direct measured input to Upper Camelot Lake due to lack of defined streams, etc, flowing into the upper lake. Thus, inflows from Fourteen Mile Creek, Leola Ditch, and Unnamed Ditch were used as input to an area-averaged Camelot Lake that included both Upper and Lower Camelot Lake. Modeled discharge from Camelot Lake served as input to Sherwood Lake, while modeled discharge from Sherwood Lake served as input to Arrowhead Lake.

The uncalibrated BATHTUB model (Table 10) predicted that TP and chlorophyll should be greatest in Camelot Lake and decline in a step-wise manner in Sherwood and Arrowhead Lakes (i.e., Camelot > Sherwood > Arrowhead). This pattern was due primarily to the assumption that predicted deposition of P (via BATHTUB modeling) should follow a similar gradient from Camelot to Arrowhead Reservoir. As a consequence of predicted gradients in P concentrations, the uncalibrated model estimated that Secchi transparency should exhibit the opposite pattern, with transparency lowest in Camelot Lake and higher in downstream reservoirs. While this gradational pattern is often typical for reservoir series, measured concentrations in the Tri-Lakes system exhibited an unusual opposite pattern, necessitating adjustments in calibration coefficients (Table 11) to account for gradational differences between the lakes (i.e., Arrowhead > Sherwood > Camelot). While the reasons for these gradational differences between the lakes are not entirely known, they may be attributed to localized internal P inputs which we did not identify, including groundwater P. Finally, we did not include a separate groundwater P input as a part of the BATHTUB model, but rather adjusted model coefficients to account for unmeasured internal P inputs such as groundwater.

For BATHTUB modeling purposes, we varied external P loadings to simulate the impacts of both increased and decreased external P loads on the Tri-Lakes system (Fig. 29). In general, Camelot Lake exhibited the greatest response to changes in external P loading because it receives P directly from the tributary sources (Fig. 30). As P loading increased, simulated chlorophyll increased in a linear manner. A 50% increase in P loading resulted in a 48% increase in the estimated chlorophyll concentration of Camelot Lake. Conversely, a 50% decrease in P loading resulted in a 58% decrease in the estimated chlorophyll concentration of Camelot Lake. Estimated Secchi transparency increased as P loading to Camelot Lake was decreased (Fig. 30), due to simulated reduction in turbidity and chlorophyll. As P loading was increased, the opposite pattern occurred; Secchi transparency declined.

Sherwood Lake exhibited a similar chlorophyll response to external P loading changes as Camelot Lake (Fig. 31). However, because modeling coefficients were adjusted to account for unmeasured internal P loading to Sherwood Lake, responses to changes in external P loading were restricted to a smaller deviation from nominal external P loading conditions due to unmeasured internal P contributions to the lake that were apparently subsidizing algal production. For instance, simulated chlorophyll response ranged between 24.4 mg m^{-3} for a 200% increase in external P loading to 4.4 mg m^{-3} for a 75% decrease in external P loading (Fig. 31). A simulated 50% increase in external P loading to the Tri-Lakes system resulted in a projected 41% increase in chlorophyll in Sherwood Lake to 20.9 mg m^{-3} (Fig. 31). A simulated 50% decrease in external P loading resulted in a projected 37% decrease in chlorophyll in Sherwood Lake.

Arrowhead Lake simulations also produced a buffered response to changes in external P loading due to apparent internal P loadings that subsidized chlorophyll (Fig. 32). Thus, although chlorophyll increased and decreased as a result of simulated increases and decreases in external P loading, respectively, the percent change from nominal conditions was not as great, compared to Sherwood and Camelot Lakes. For instance, a 50% increase or decrease external P loading resulted in only ~20% change in chlorophyll, respectively.

The BATHTUB algal bloom frequency represents the probable length of the growing period that algae will exhibit a given chlorophyll concentration as a result of the external P loading rate (Fig. 33). For instance, under nominal external P loading conditions, Camelot Lake exhibited an estimated bloom frequency of > 10 mg m^{-3} for ~ 34% of the summer and > 20 mg m^{-3} for ~7% of the summer. Under nominal external P loading conditions, Sherwood and Arrowhead Lakes exhibited greater frequencies of bloom occurrence at higher chlorophyll concentrations due to apparent unmeasured internal P loads driving productivity in these reservoirs (Fig. 33). Sherwood Lake exhibited instances of algal blooms in the range of 30 mg m^{-3} over ~7% of the summer while Arrowhead Lake exhibited higher bloom frequencies of > 30 mg m^{-3} over 21% of the summer and 40 mg m^{-3} over 10% of the summer.

Simulated increases in external P loading resulted in increases in both the concentration and frequency of occurrence of algal blooms during the summer in all reservoirs (Fig. 33). Conversely, simulated decreases in external P loading resulted in decreases in both concentration and the frequency of occurrence of algal blooms in all reservoirs (Fig. 33). As with chlorophyll (see above), the magnitude of change in the frequency of occurrence and severity (i.e., concentration of chlorophyll) of algal blooms was greatest for Camelot Lake in response to changes in external P loading (Fig. 33). Responses to changes in external P loading were lower in magnitude for Sherwood and Arrowhead Lakes due to apparent internal P influences.

DISCUSSION

One of the surprising observations of this study was the occurrence positive gradients in the concentration of P and chlorophyll from Camelot to Arrowhead Lake, given that external tributary inflows (and P loads) entered the Tri-lakes system at Camelot Lake and internal fluxes of P from the sediment into the water column were negligible. Under these P input conditions, we expected the opposite pattern to occur due to retention of external P loads in Camelot Lake. Because substantial externally-derived P was trapped in the headwaters reservoir (i.e., Camelot Lake), much less of this P was available to downstream reservoirs for algal production. Thus, chlorophyll concentrations should have declined progressively in Sherwood and Arrowhead Lakes, relative to concentrations in Camelot Lake (i.e., Camelot>Sherwood>Arrowhead). The establishment of gradients of higher concentrations of TP and chlorophyll from Camelot to Arrowhead Lakes suggested that other internal P sources or internal recycling processes may be subsidizing chlorophyll in downstream reservoirs.

While we have not yet identified these P processes, additional sources of P to the system include groundwater fluxes. The hydrologic balance did not provide insight into the possible occurrence of net groundwater influx (i.e., influx-efflux) to Sherwood and Arrowhead lakes; however, gross groundwater influx (i.e., influx only) could still be an important component of the P economy of this system. Groundwater moving through sediments could result in the movement of P into the water column for uptake by algae. Additionally, regions of P-rich bottom sediments that we did not locate in the lakes could be contributing to internal P loads.

Seasonally, it appeared that the onset of algal blooms in the Tri-Lakes system coincided with a period of higher residence time (i.e., lower inflow) and the onset of autumn mixing (i.e., late August-September). However, there was no correspondence between periods of elevated P loading from measured internal or external sources and the development of an algal bloom. Inflow and P loading was nominal (i.e., before the

September storm)when the bloom first developed, and diffusion of P from sediments, measured in the laboratory, appeared to be negligible. Thus, external and internal sources of P flux that we measured probably did not stimulate the algal bloom. These results suggested that algae, perhaps, directly accessed P from the sediments for growth during this period. For instance, excystment of blue-green algal inocula residing in the profundal sediments and uptake of sediment P for growth would provide a mechanism of direct P transport to algae from an unmeasured P source (Osgood 1988). Mixing associated with breakdown of thermal stratification could also facilitate temporary exposure of algae directly to P associated with the sediment.

Overall, contributions of P to the system were dominated by Fourteen Mile Creek, followed closely by Leola and Unnamed Ditch. Interestingly, there was not a strong relationship between flow and concentration for any of the measured tributary inflows. Rather, changes in P concentration of the inflows appeared to follow a seasonal pattern, as concentrations were greater during the Spring and Autumn, and lower during the summer months. This pattern may be attributed to seasonal changes in land-use patterns in the watershed. In addition, NO_2NO_3-N concentrations were high and constituted a large percentage of the TN load to the system, indicating the occurrence of nitrification (i.e., conversion of ammonium to nitrate). High NO_2NO_3-N in the runoff may be related to oxidation of ammonia fertilizers originating from the watershed.

Although rates of P release from sediments collected at main-stem and backwater stations in the Tri-Lakes system were negligible under oxic conditions, they were elevated in Camelot and Sherwood Lakes under anoxic conditions and comparable to rates of P release from anoxic sediments measured for a variety of eutrophic lakes (Nürnberg et al. 1986). Mortimer (1941, 1942) demonstrated that under anoxic conditions, sediment phosphorus becomes disassociated with iron compounds, resulting in its release into the porewater and overlying water column. Accumulation of sediment-derived P in the bottom waters and transport to the surface for algal uptake has been demonstrated as an important mechanism resulting in algal blooms in other aquatic systems (Stauffer and Lee 1973; Larson et al. 1981; Kortmann et al. 1982). In the Tri-Lakes system, the occurrence of bottom water anoxia at both main-stem and backwater stations was minor, indicating that sediment-bottom water interactions were driven primarily by oxic conditions. Under these conditions, iron is oxidized and has a high binding affinity with P, resulting in inhibition of P diffusion into the overlying water column. Thus, fluxes of P from sediments in the Tri-Lakes system were probably minor during the summer due to primarily oxygenated conditions in the bottom waters.

Overall water quality conditions were good and fell within the mesoeutophic range for main-stem and backwater stations in the Tri-Lakes system (Lillie et al. 1993). Concentrations of chlorophyll were generally below 20 mg m^{-3} at all main-stem stations between April and July and October through November. Peaks in concentration occurred only in August and September, indicating a currently low bloom frequency occurrence for all lakes. As with chlorophyll and TP concentrations, there was a positive gradient of increasing frequency of algal bloom with Camelot Lake exhibiting the lowest bloom frequency, Sherwood exhibiting an intermediate bloom frequency, and Arrowhead exhibiting the greatest bloom frequency of the three lakes.

BATHTUB modeling results suggested that the three lakes are susceptible to deteriorating water quality conditions as external P loading is increased above current conditions. Model results suggested that both concentrations of chlorophyll, and greater frequency of occurrence of algal blooms of higher concentrations (resulting in lower transparency), will occur as external P loading increases. In contrast, the model suggested that decreases in external P loading will be accompanied by decreases in the concentration of chlorophyll and lower frequency of occurrence of algal blooms.

Modeling results also suggested that Camelot Lake was more sensitive to changes in external P loading than the other two lakes. This pattern may be attributed to two mechanisms that dampen the water quality responses of the downstream lakes. The first mechanism was driven by presumably unmeasured (probably internal) P loads that sustain algal productivity in the downstream lakes even though external P loading to Camelot Lake decreases. The second mechanism is retention of much of the external P load in Camelot Lake. Since Camelot Lake acts as a sink for external P loads, further increases in external P loading will be trapped by this lake, resulting in a dampening of P flux and, thus, chlorophyll response, to downstream lakes. A caveat to this scenario is identification and control of these unmeasured P sources to Sherwood and Arrowhead Lakes. If these sources can be controlled, both Sherwood and Arrowhead Lakes should respond more dramatically than current modeling result predict.

An indirect impact that we did not explore using BATHTUB is the likelihood that dissolved oxygen demand could increase as external P loading and storage of oxygen-demanding materials in the sediment increases. This scenario could aggravate dissolved oxygen demands in the bottom waters, leading to enhanced P recycling from the sediment via anoxic P release. This new internal source of P, in combination with greater external P loading, could exacerbate algal bloom frequencies in the Tri-lake system.

External phosphorus loading reduction via BMPs, development of vegetated shoreline buffer strips, and restoration of wetlands will be important avenues for controlling chlorophyll and the frequency of algal blooms in the Tri-Lakes system during the summer. An evaluation of the importance of groundwater flux and associated transport of P though the Tri-Lakes system will also be essential, as this mechanism could account for the unmeasured internal P load entering the Tri-Lakes region. If septic systems are leaching into the groundwater, additional P could be transported into the Tri-Lakes system for use by algae. Since the three lakes are densely populated with riparian dwellings, sources of P from overland runoff of fertilizers needs to be controlled as well.

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TABLES

Table 1. Variable list for tributary loadings

FLOW, cms
SUSPENDED SESTON, mg/L
POM, mg/L
TOTAL NITROGEN, mg/L
NITRATE-NITRITE-N, mg/L[1]
AMMONIUM-N, mg/L[1]
TOTAL PHOSPHORUS, mg/L
SOLUBLE REACTIVE PHOSPHORUS, mg/L[1]

Variable list for limnological monitoring.

WATER TEMPERATURE, °C
DISSOLVED OXYGEN, mg/L
PH
CONDUCTIVITY, µS/cm[2]
SECCHI TRANSPARENCY, cm
SUSPENDED SESTON, mg/L
POM, mg/L
TOTAL NITROGEN, mg/L
NITRATE-NITRITE-N, mg/L
AMMONIUM-N, mg/L
TOTAL PHOSPHORUS, mg/L
SOLUBLE REACTIVE PHOSPHORUS, mg/L
VIABLE CHLOROPHYLL *a*, µg/L

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[1] Only grab samples (i.e., at triweekly intervals) were analyzed for these constituents. Samples collected via automated equipment was analyzed for total constituents only.

Table 2. Average annual flow for Fourteen Mile Creek, Leola Ditch, and Unnamed Ditch for the year 2000.

Tributary	Annual Average Flow, cms
Fourteen Mile Creek	0.33
Leola Ditch	0.30
Unnamed Ditch	0.22

Table 3. Hydraulic residence times during the May-September period for Camelot, Sherwood, and Arrowhead Lakes.

Lake	Summer Hydraulic Residence time, d
Camelot	63
Sherwood	48
Arrowhead	103

Table 4. Hydrologic budget for Camelot (including Upper and Lower Lake), Sherwood, and Arrowhead Lakes for the year 2000.

Reservoir	Hydrologic Source	Annual Average Flow (cms)	Residual (% of total flow)
Camelot			
	Inflows[1]	0.852	
	Outflows[2]	1.040	
	Change in Reservoir Storage	0	
	Residual	0.188	18%
Sherwood	Inflow	1.040	
	Outflow	0.900	
	Change in Reservoir Storage	0	
	Residual	-0.140	-13.5%
Arrowhead	Inflow	0.900	
	Outflow	0.809	
	Change in Reservoir Storage	0	
	Residual	-0.129	-10.1%

[1] Fourteen Mile Creek, Leola Ditch, and Unnamed Ditch

[2] Upper and Lower Camelot Dams

Table 5. Summary statistics for annual external loads and discharges. CV represents the coefficient of variation.

Tributary	TSS			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
Fourteen-Mile Creek	2.4×10^5	22.5	0.086	27614	2.615	0.064	594	0.057	0.071
Leola Ditch	2.2×10^5	22.8	0.098	24660	2.594	0.064	442	0.046	0.056
Unnamed Ditch	1.3×10^5	19.6	0.111	27941	4.093	0.019	302	0.044	0.102
Upper Camelot Dam	3.0×10^3	2.6	0.380	2637	2.093	0.040	19	0.016	0.329
Lower Camelot Dam	1.1×10^5	2.7	0.163	98752	3.002	0.024	516	0.013	0.132
Sherwood Dam	9.8×10^4	3.5	0.134	46901	1.647	0.086	428	0.015	0.076
Arrowhead Dam	9.2×10^4	3.6	0.160	29270	1.147	0.091	393	0.015	0.146

Table 5. Continued.

Tributary	$NO_2NO_{3\text{-}N}$			NH_4-N			SRP		
	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
Fourteen-Mile Creek	13865	1.313	0.227	1374	0.130	0.055	50	0.005	0.152
Leola Ditch	9869	1.038	0.193	1350	0.142	0.061	45	0.005	0.152
Unnamed Ditch	21743	3.188	0.093	745	0.109	0.034	32	0.005	0.116
Upper Camelot Dam	1826	1.450	0.106	55	0.044	0.330	2	0.002	0.183
Lower Camelot Dam	90319	2.227	0.045	2463	0.060	0.189	111	0.003	0.267
Sherwood Dam	24422	0.857	0.281	4396	0.155	0.322	103	0.004	0.255
Arrowhead Dam	13982	0.547	0.283	4338	0.169	0.310	69	0.003	0.117

Table 6. Estimated annual loads to each lake, retention of loads, and percent retention of loads. The percent retention represents the percent of the load that is retained in the lake.

Source	TSS			Total N			Total P		
	LOAD kg y^{-1}	RETENTION kg y^{-1}	RETENTION %	LOAD kg y^{-1}	RETENTION kg y^{-1}	RETENTION %	LOAD kg y^{-1}	RETENTION kg y^{-1}	RETENTION %
Measured Inflows	1787453			69478			1336		
Camelot Discharge	115064	1672389	93.6	101377	-31899	-45.9	537	799	59.8
Sherwood Discharge	98570	13151	11.8	46902	51833	52.5	429	88	17
Arrowhead Discharge	92520	6050	6.1	29330	17572	37.5	394	35	8.2

Table 7. Mean (∀ 1 standard deviation) rates of phosphorus release from the profundal sediments of various stations measured under oxic and anoxic conditions.

Main-stem Stations	Oxic Rate ($mg\ m^{-2}\ d^{-1}$)	Anoxic Rate ($mg\ m^{-2}\ d^{-1}$)
Upper Camelot	< 0.1	0.5 (0.7)
Lower Camelot	< 0.1	1.2 (1.6)
Sherwood North Arm	Could not collect sediment here	
Sherwood South Arm	0.1 (0.03)	8.3 (5.3)
Sherwood Dam	< 0.1	1.4 (0.5)
Arrowhead Dam	< 0.1	0.1 (0.1)
Backwater Stations	**Oxic Rate ($mg\ m^{-2}\ d^{-1}$)**	**Anoxic Rate ($mg\ m^{-2}\ d^{-1}$)**
Upper Camelot #2	< 0.1	0.2 (0.1)
Lower Camelot #3	0.3 (0.1)	8.1 (2.1)
Sherwood #6	< 0.1	1.9 (C)
Sherwood #7	0.1 (0.04)	3.6 (2.3)
Sherwood #8	< 0.1	1.9 (0.4)

Table 8. Estimates of Carlson and Wisconsin Trophic State Index (TSI) values for stations in main-stem regions of the Tri-Lakes syystem. Concentrations of chlorophyll *a* and total phosphorus (TP) and Secchi transparency represent means (CV) over the upper 4 m water column for the period May through September.

				Carlson TSI			WI TSI		
Lake	Secchi, m	Chla, µg/L	TP, µg/L	$\mathrm{TSI}_{\mathrm{SD}}$	$\mathrm{TSI}_{\mathrm{chla}}$	$\mathrm{TSI}_{\mathrm{TP}}$	$\mathrm{WTSI}_{\mathrm{SD}}$	$\mathrm{WTSI}_{\mathrm{chl}\backslash}$	$\mathrm{WTSI}_{\mathrm{TP}}$
Camelot	2.1 (0.05)	9.5 (0.14)	11 (0.13)	49	52	39	49	52	47
Sherwood	2.2 (0.16)	14.8 (0.19)	15 (0.15)	49	57	43	49	55	49
Arrowhead	1.5 (0.09)	21.9 (0.16)	24 (0.16)	54	60	54	54	58	53

Table 9. Estimates of Carlson and Wisconsin Trophic State Index (TSI) values for stations in backwater regions of the Tri-Lakes syystem. Concentrations of chlorophyll *a* and total phosphorus (TP) and Secchi transparency represent means over the entire water column for the period May through September.

					Carlson TSI			WI TSI	
Back-water	Secchi, m	Chla, µg/L	TP, µg/L	TSI_{SD}	TSI_{chla}	TSI_{TP}	$WTSI_{SD}$	$WTSI_{chl}$	$WTSI_{TP}$
UC2	2.0	12.8	13	50.0	55.6	41.2	50.3	54.1	48.0
LC3	1.8	11.8	18	51.5	54.8	45.8	51.8	53.5	50.5
SW6	1.7	16.5	27	52.3	58.1	51.7	52.6	56.0	53.7
SW7	1.4	20.5	33	55.1	60.2	54.6	55.3	57.6	55.2
SW8	1.7	17.5	25	52.3	58.6	50.6	52.6	56.4	53.1

Table 10. A comparison of observed versus estimated values for the uncalibrated reservoir-in-series BATHTUB model. Asterisks indicate significant differences between observed and estimated values (t-test; $p < 0.05$).

Lake	Variable	Observed		Estimated	
		Mean	CV	Mean	CV
Camelot	Total P, mg/L	0.011*	0.13	0.025	0.45
	Chlorophyll, mg/m^3	9.5*	0.14	10.7	0.44
	Secchi Transparency, m	2.1	0.05	2.0	0.40
Sherwood	Total P, mg/L	0.015*	0.15	0.021	0.45
	Chlorophyll, mg/m^3	14.8*	0.19	8.4	0.71
	Secchi Transparency, m	2.2*	0.16	3.4	0.63
Arrowhead	Total P, mg/L	0.024*	0.16	0.015	0.46
	Chlorophyll, mg/m^3	21.9*	0.16	5.2	0.69
	Secchi Transparency, m	1.5*	0.09	4.0	0.58

Table 11. Calibration coefficients and models used in BATHTUB for the reservoir-in-series model.

	Calibration Coefficients		
Model	Camelot	Sherwood	Arrowhead
Phosphorus Model: 2nd Order Decay	0.44	0.69	1.60
Chlorophyll Model; P, Light, Turbidity	2.31	2.27	2.01
Dispersion Model: Fisher Numeric	1.00	1.00	1.00

FIGURE CAPTIONS

Fig. 1. Map of the Tri-lakes region water and sediment sampling stations.

Fig. 2. Variations in precipitation and flow from Fourteen Mile Creek, Leola Ditch, and Unnamed Ditch between January and December, 2000.

Fig. 3. Total monthly precipitation in the Tri-Lakes region between March and November, 2000. Precipitation in the form of snowfall is not included.

Fig. 4. Variations in total measured inflow (i.e., Fourteen Mile Creek, Leola Ditch, and Unnamed Ditch) and dam discharges from Camelot (i.e., both Upper and Lower Lake), Sherwood, and Arrowhead Lakes between January and December, 2000.

Fig. 5. Variations in pool elevation of Lower Camelot Lake between January and December, 2000.

Fig. 6. Variations in pool elevation of Sherwood Lake between January and December, 2000.

Fig. 7. Variations in pool elevation of Arrowhead Lake between January and December, 2000.

Fig. 8. An example of variations in mean daily flow and concentrations of total phosphorus (P) for Unnamed Ditch between January and December, 2000. Horizontal bars represent the averaging periods and mean total P concentrations used to calculated loading.

Fig. 9. Contour plot of seasonal and vertical variations in temperature at stations located in Upper and Lower Camelot Lake.

Fig. 10. Contour plot of seasonal and vertical variations in temperature at stations located in Sherwood Lake.

Fig. 11. Contour plot of seasonal and vertical variations in temperature at the station located in Arrowhead Lake.

Fig. 12. Contour plot of seasonal and vertical variations in dissolved oxygen at stations located in Upper and Lower Camelot Lake. The blackened areas represent periods of bottom water anoxia (dissolved oxygen < 2 mg/L).

Fig. 13. Contour plot of seasonal and vertical variations in dissolved oxygen at stations located in Sherwood Lake. The blackened areas represent periods of bottom water anoxia (dissolved oxygen < 2 mg/L).

Fig. 14. Contour plot of seasonal and vertical variations in dissolved oxygen at the station located in Arrowhead Lake.

Fig. 15. Seasonal (April through November) variations in mean concentrations of epilimnetic chlorophyll (upper 4 m) at stations located in Camelot, Sherwood, and Arrowhead Lakes.

Fig. 16. Seasonal (April through November) variations in mean concentrations of epilimnetic total phosphorus (P; upper 4 m) at stations located in Camelot, Sherwood, and Arrowhead Lakes.

Fig. 17. Seasonal (April through November) variations in Secchi transparency at stations located in Camelot, Sherwood, and Arrowhead Lakes.

Fig. 18. Seasonal (April through November) variations in mean concentrations of epilimnetic total nitrogen (N; upper 4 m) at stations located in Camelot, Sherwood, and Arrowhead Lakes.

Fig. 19. Seasonal (April through November) variations in mean concentrations of epilimnetic nitrate-nitrite-nitrogen (NO_2NO_3-N; upper 4 m) at stations located in Camelot, Sherwood, and Arrowhead Lakes.

Fig. 20. Seasonal (April through November) variations in mean concentrations of epilimnetic ammonium-nitrogen (NH_3-N; upper 4 m) at stations located in Camelot, Sherwood, and Arrowhead Lakes.

Fig. 21. Contour plot of longitudinal and vertical variations in temperature for backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

Fig. 22. Contour plot of longitudinal and vertical variations in dissolved oxygen for backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

Fig. 23. Seasonal (April through November) variations in mean concentrations of chlorophyll at backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

Fig. 24. Seasonal (April through November) variations in mean concentrations of total phosphorus (P) at backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

Fig. 25. Seasonal (April through November) variations in Secchi transparency at backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

Fig. 26. Seasonal (April through November) variations in mean concentrations of total nitrogen (N) at backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

Fig. 27. Seasonal (April through November) variations in mean concentrations of nitrate-nitrite-nitrogen (NO_2NO_3-N) backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

Fig. 28. Seasonal (April through November) variations in mean concentrations of ammonium-nitrogen (NH_4-N) backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

Fig. 29. External P loading variations used in BATHTUB simulations. External phosphorus loading was increased or reduced relative to nominal external total phosphorus loading conditions that occurred during the year 2000.

Fig. 30. Estimated changes in total phosphorus (P), chlorophyll, and Secchi transparency in Camelot Lake 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 year 2000.

Fig. 31. Estimated changes in total phosphorus (P), chlorophyll, and Secchi transparency in Sherwood Lake 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 year 2000.

Fig. 32. Estimated changes in total phosphorus (P), chlorophyll, and Secchi transparency in Arrowhead Lake 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 year 2000.

Fig. 33. Estimated changes in the frequency of algal bloom occurrence of different concentrations of chlorophyll in Camelot, Sherwood, and Arrowhead Lakes versus different external phosphorus loading conditions. External phosphorus loading was increased or reduced relative to nominal loading conditions that occurred during 2000.

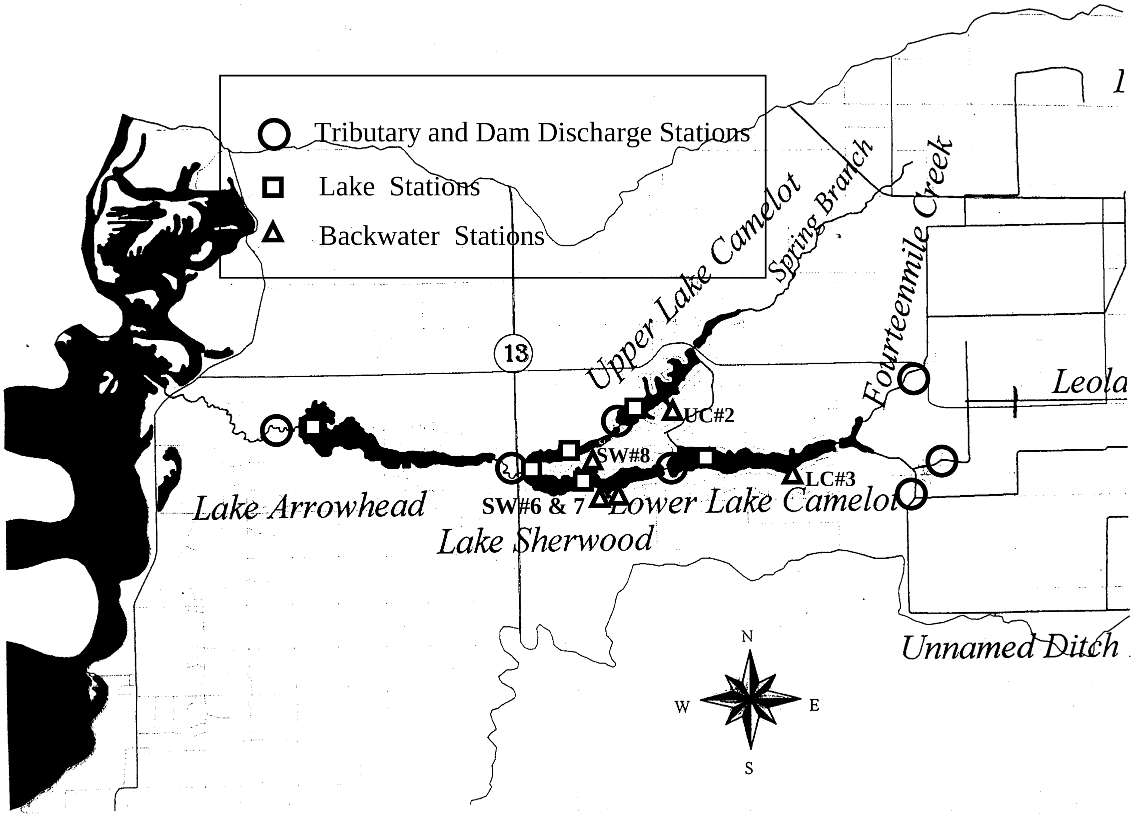


Fig. 1. Map of the Tri-lakes region water and sediment sampling stations.

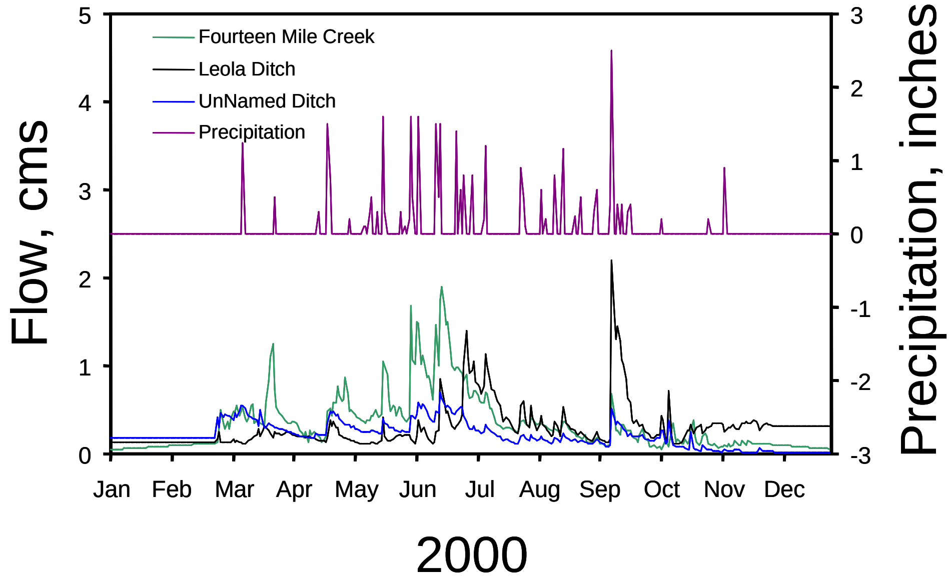


Fig. 2. Variations in precipitation and flow from Fourteen Mile Creek, Leola Ditch, and Unnamed Ditch between January and December, 2000.

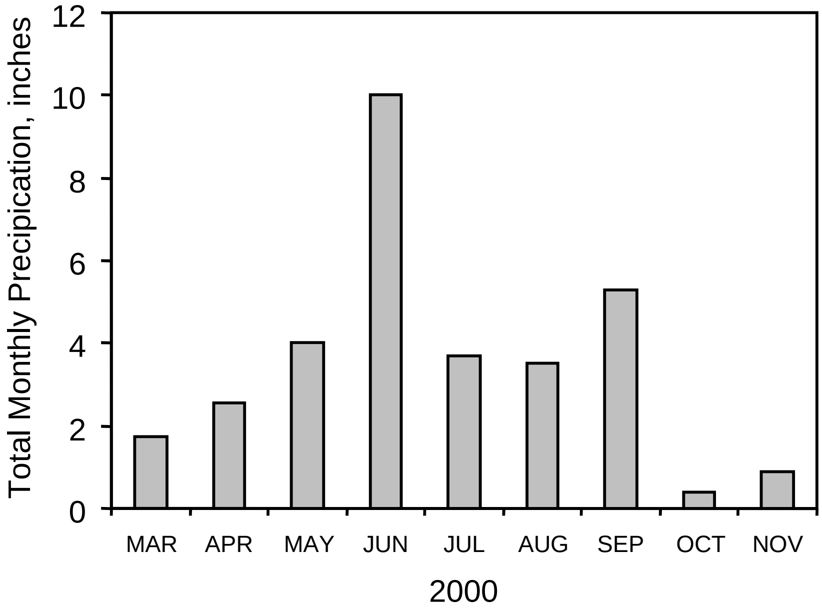


Fig. 3. Total monthly precipitation in the Tri-Lakes region between March and November, 2000. Precipitation in the form of snowfall is not included.

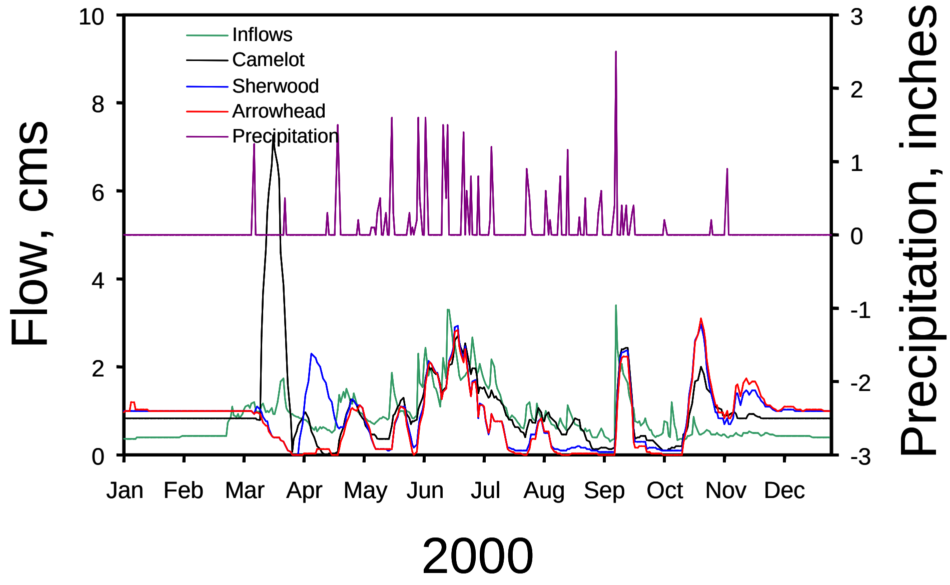


Fig. 4. Variations in total measured inflow (i.e., Fourteen Mile Creek, Leola Ditch, and Unnamed Ditch) and dam discharges from Camelot (i.e., both Upper and Lower Lake), Sherwood, and Arrowhead Lakes between January and December, 2000.

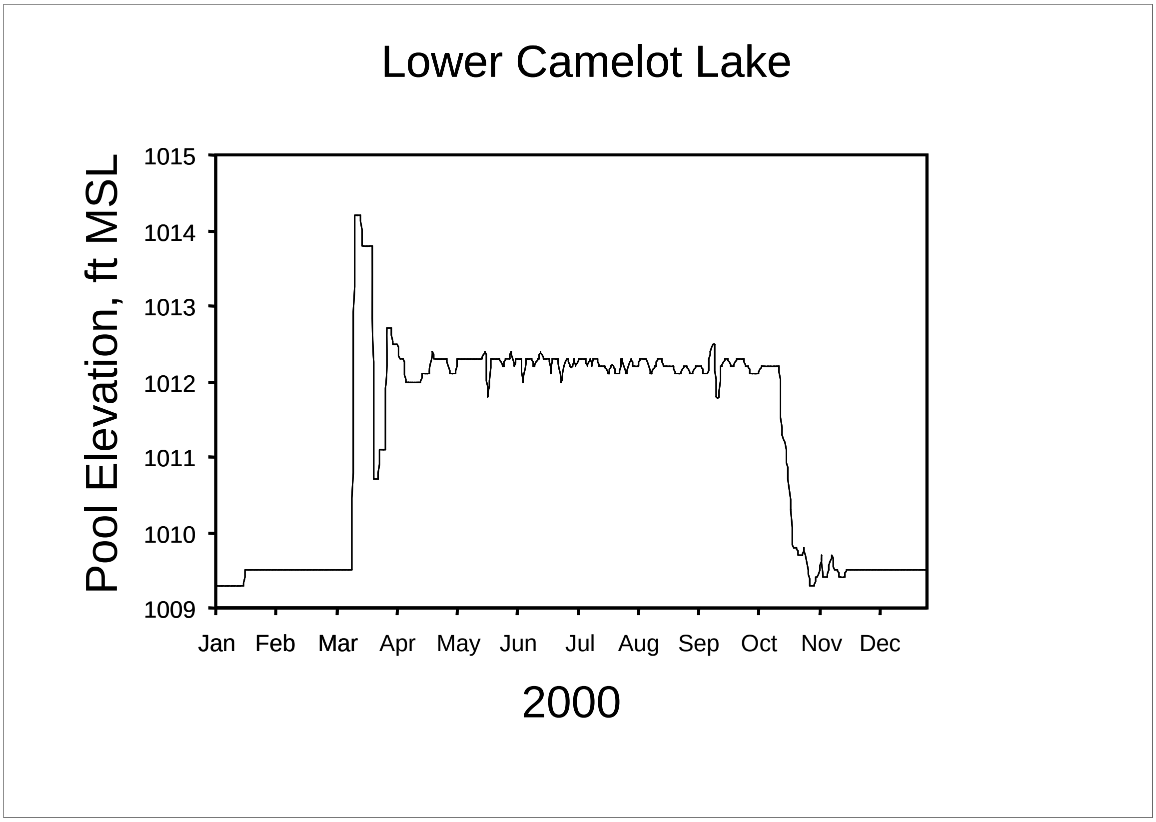


Fig. 5. Variations in pool elevation of Lower Camelot Lake between January and December, 2000.

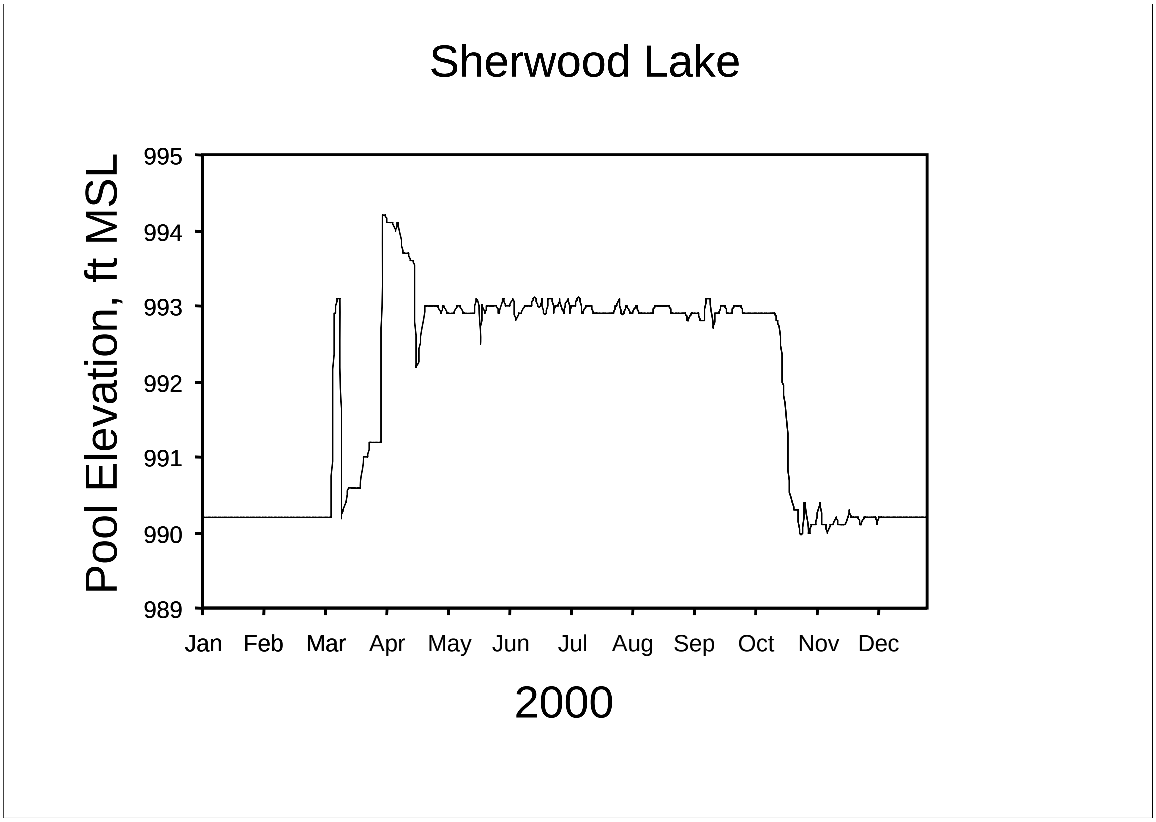


Fig. 6. Variations in pool elevation of Sherwood Lake between January and December, 2000.

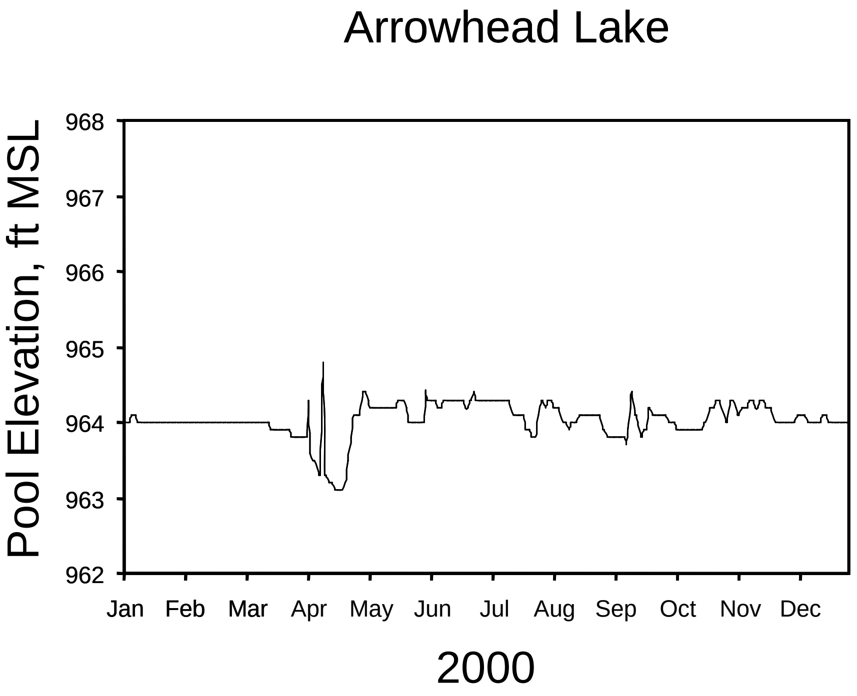


Fig. 7. Variations in pool elevation of Arrowhead Lake between January and December, 2000.

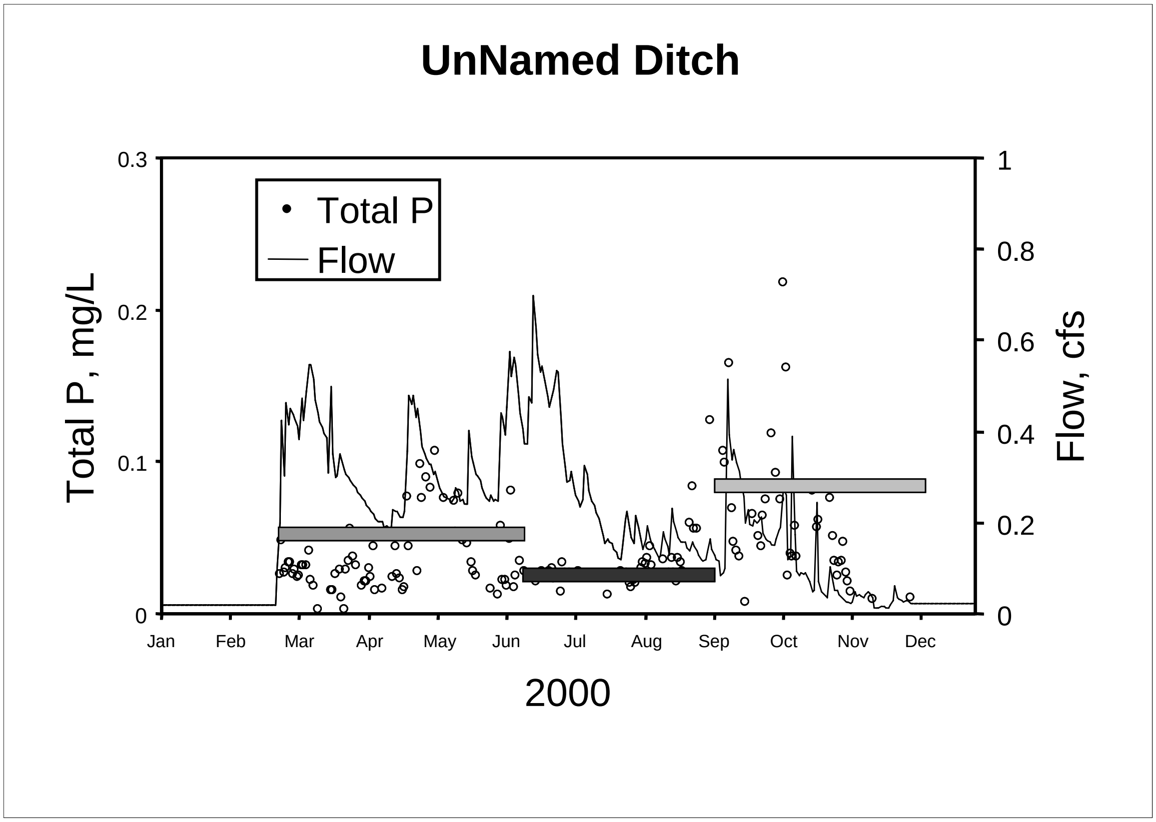
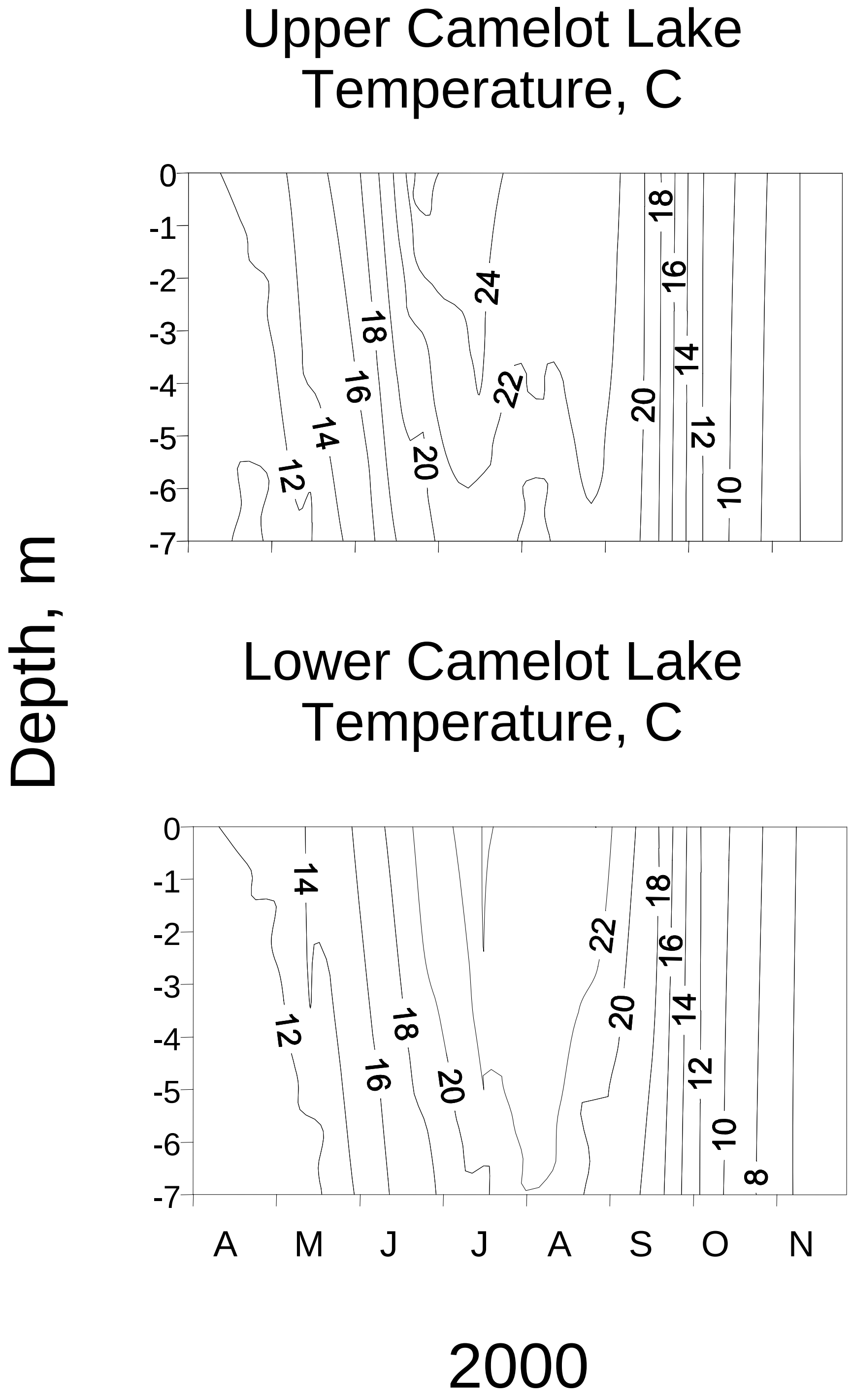


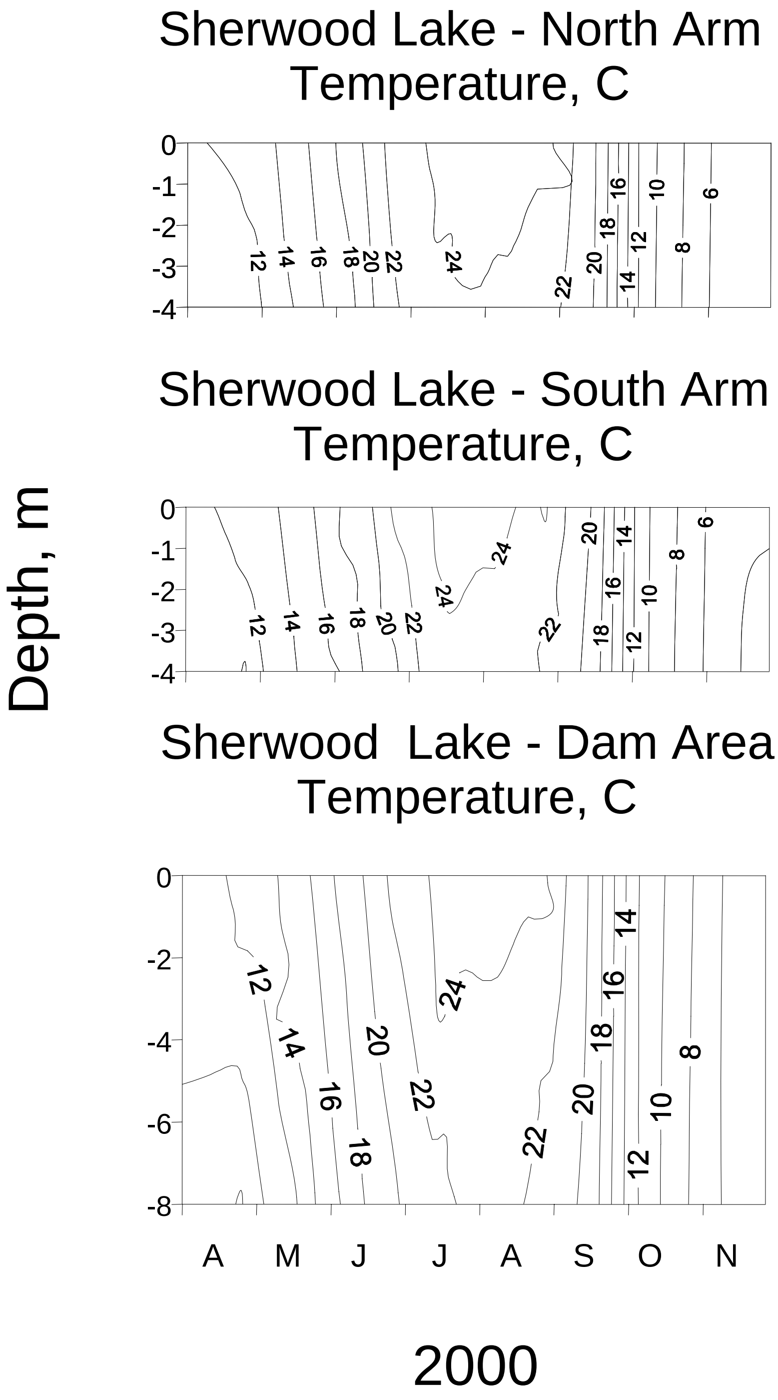
Fig. 8. An example of variations in mean daily flow and concentrations of total phosphorus (P) for Unnamed Ditch between January and December, 2000. Horizontal bars represent the averaging periods and mean total P concentrations used to calculated loading.



Upper Camelot Lake
Temperature, C

Lower Camelot Lake
Temperature, C

Fig. 9. Contour plot of seasonal and vertical variations in temperature at stations located in Upper and Lower Camelot Lake.


Sherwood Lake - North Arm Temperature, C

Sherwood Lake - South Arm Temperature, C

Sherwood Lake - Dam Area Temperature, C

Fig. 10. Contour plot of seasonal and vertical variations in temperature at stations located in Sherwood Lake.

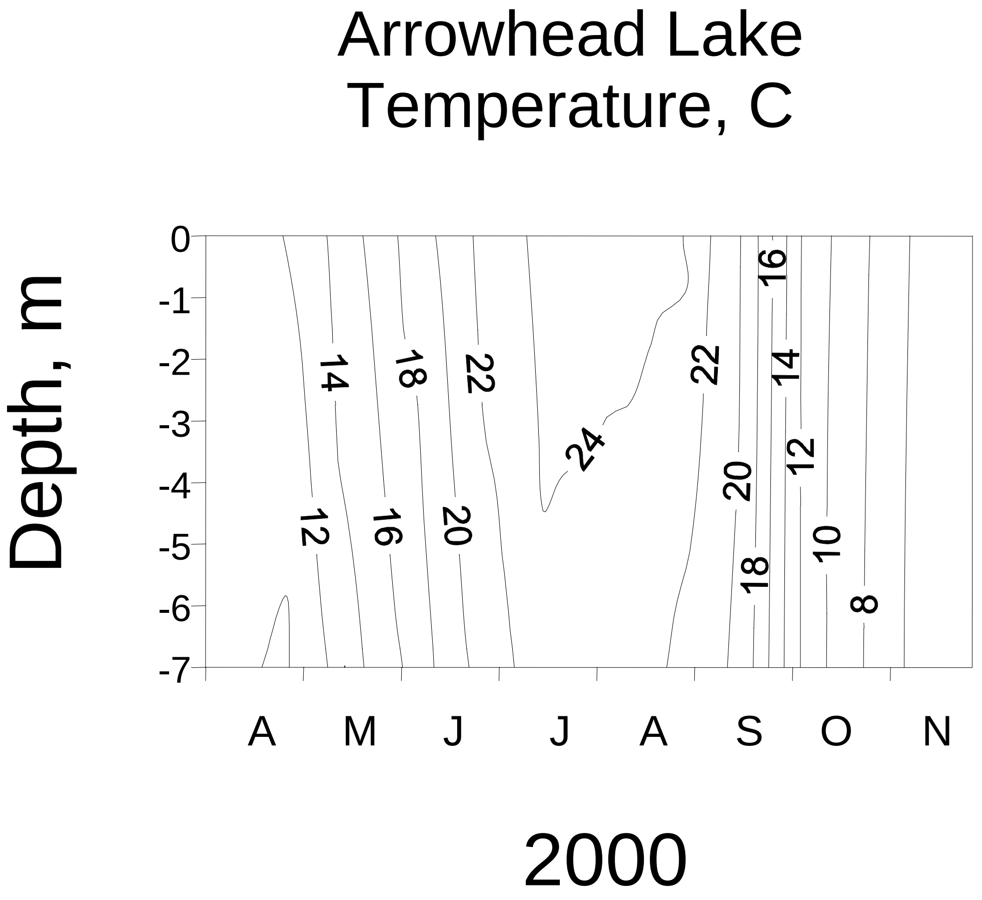


Fig. 11. Contour plot of seasonal and vertical variations in temperature at the station located in Arrowhead Lake.

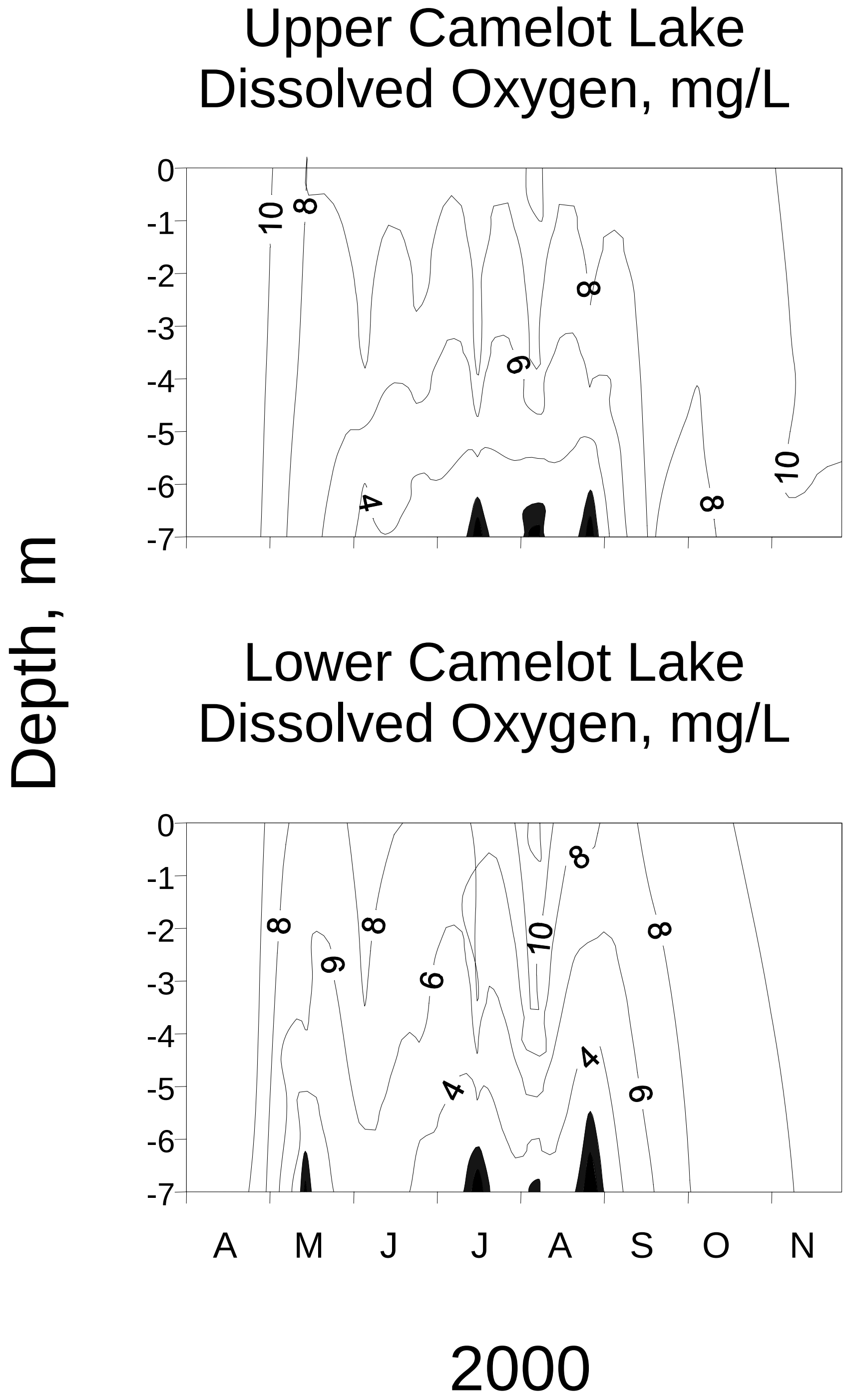
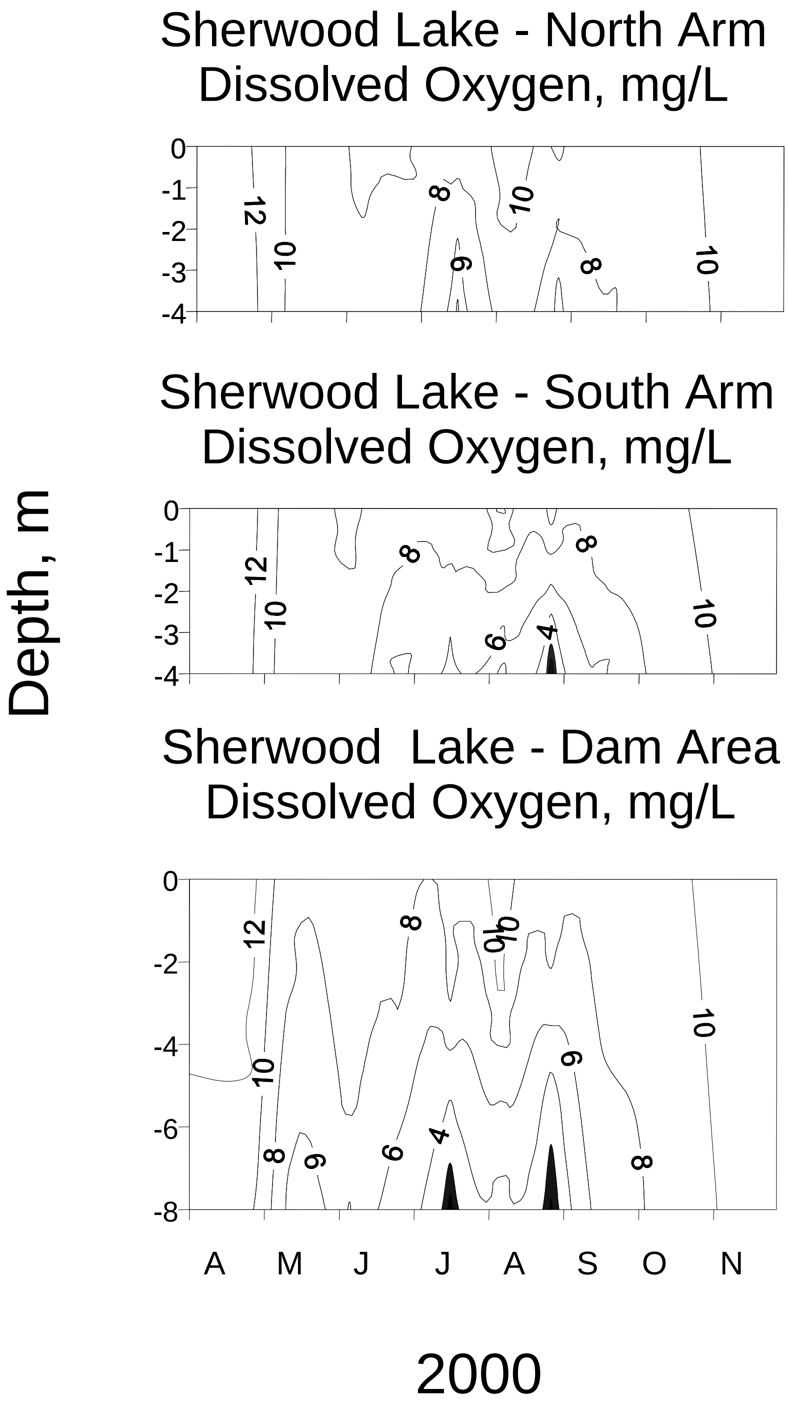


Fig. 12. Contour plot of seasonal and vertical variations in dissolved oxygen at stations located in Upper and Lower Camelot Lake. The blackened areas represent periods of bottom water anoxia (dissolved oxygen < 2 mg/L).



Sherwood Lake - North Arm
Dissolved Oxygen, mg/L

Sherwood Lake - South Arm
Dissolved Oxygen, mg/L

Sherwood Lake - Dam Area
Dissolved Oxygen, mg/L

Fig. 13. Contour plot of seasonal and vertical variations in dissolved oxygen at stations located in Sherwood Lake. The blackened areas represent periods of bottom water anoxia (dissolved oxygen < 2 mg/L).

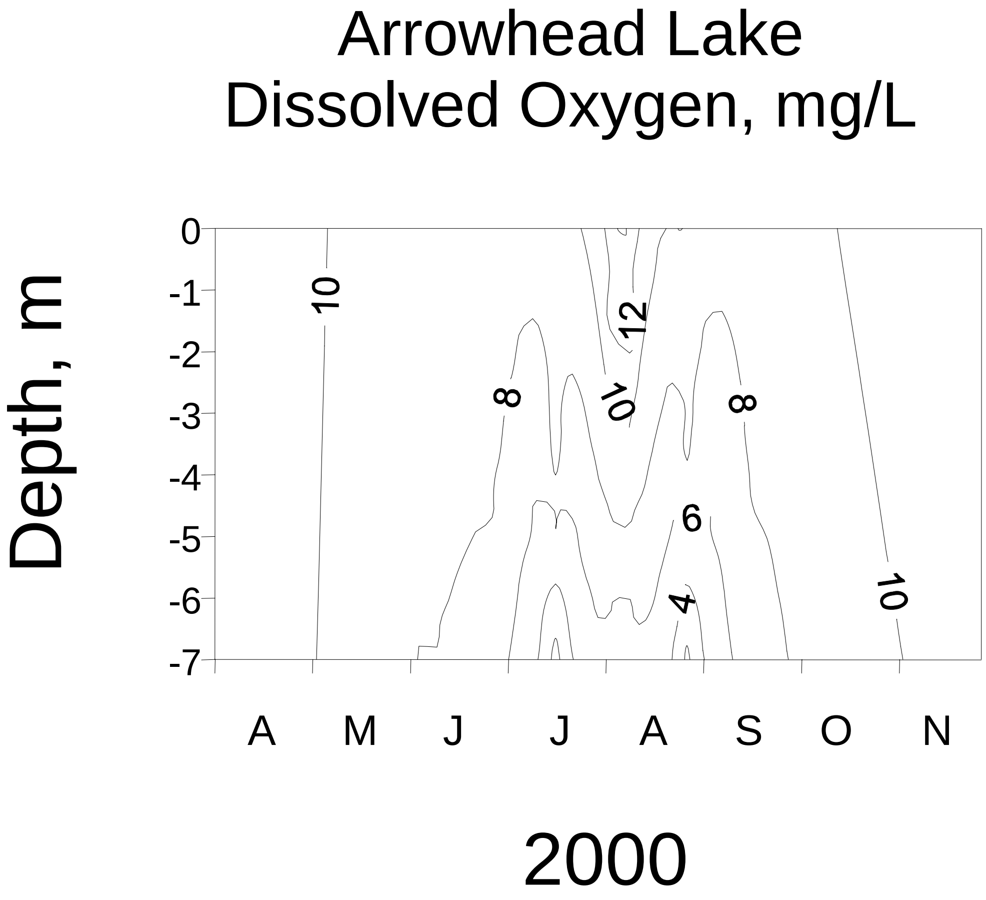


Fig. 14. Contour plot of seasonal and vertical variations in dissolved oxygen at the station located in Arrowhead Lake.

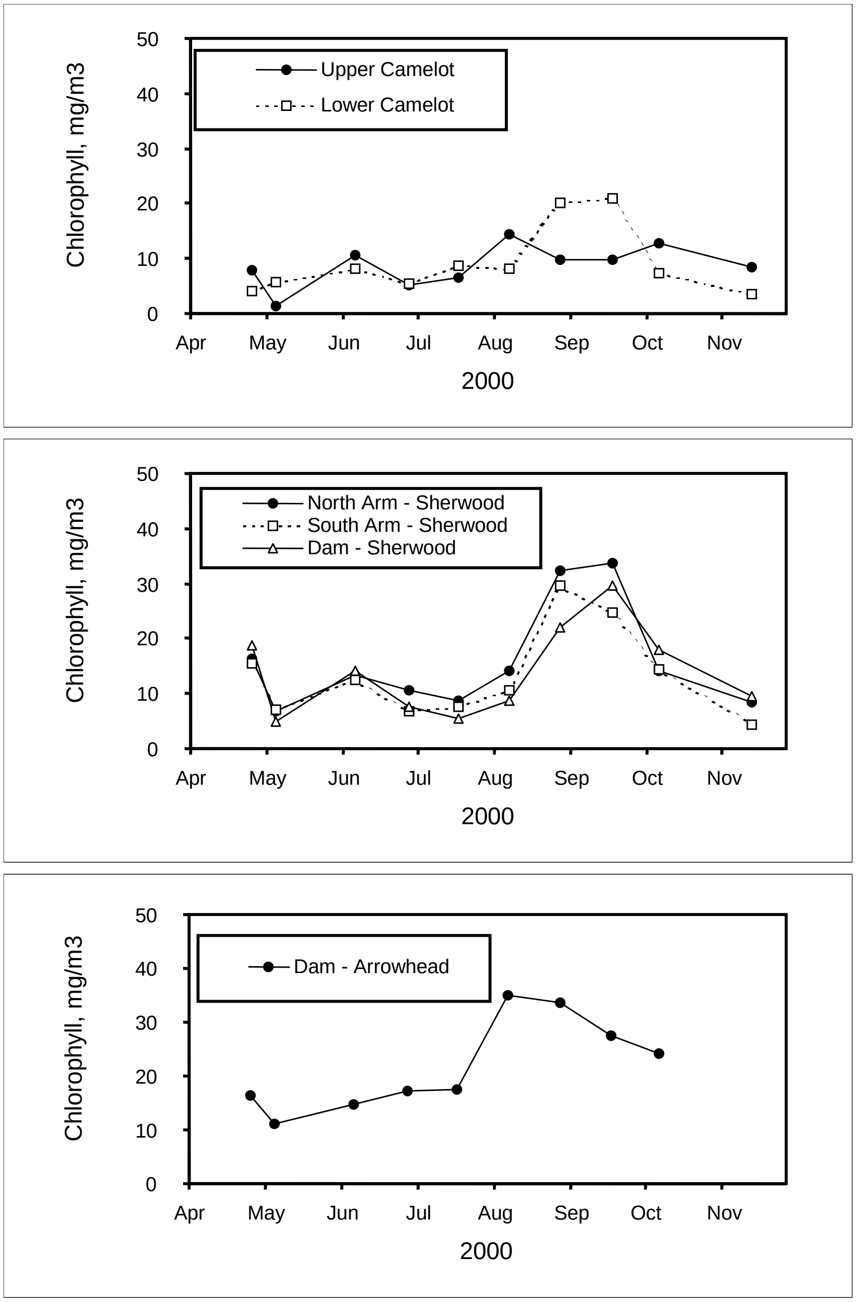


Fig. 15. Seasonal (April through November) variations in mean concentrations of epilimnetic chlorophyll (upper 4 m) at stations located in Camelot, Sherwood, and Arrowhead Lakes.

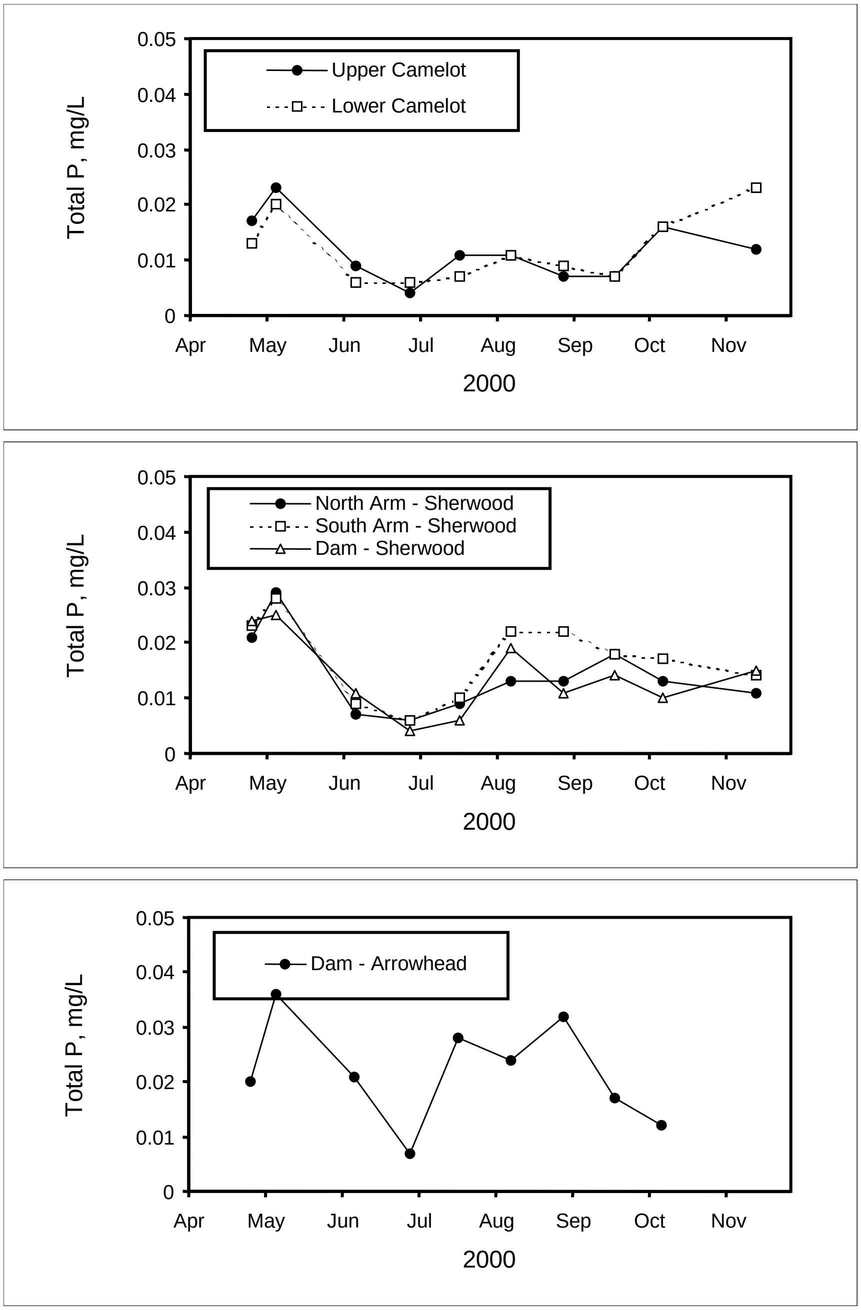


Fig. 16. Seasonal (April through November) variations in mean concentrations of epilimnetic total phosphorus (P; upper 4 m) at stations located in Camelot, Sherwood, and Arrowhead Lakes.

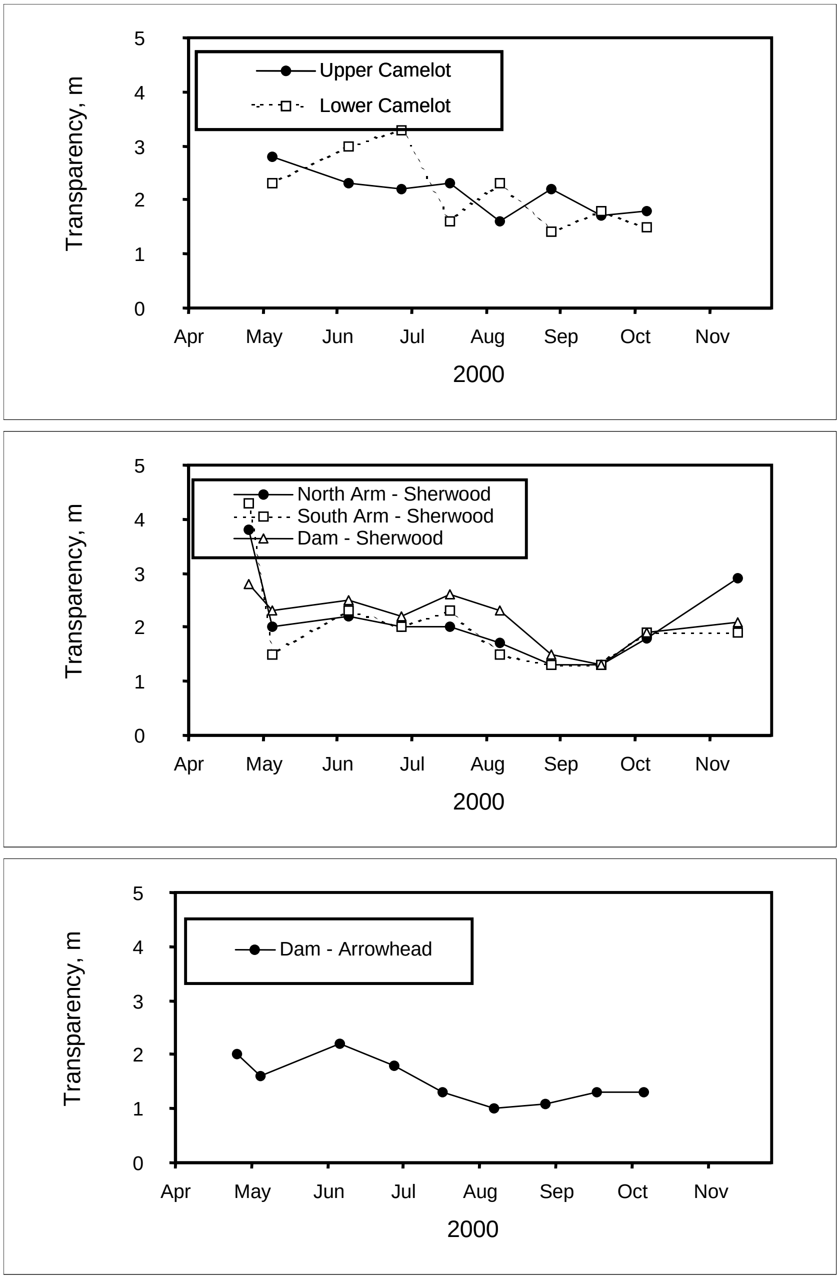


Fig. 17. Seasonal (April through November) variations in Secchi transparency at stations located in Camelot, Sherwood, and Arrowhead Lakes.

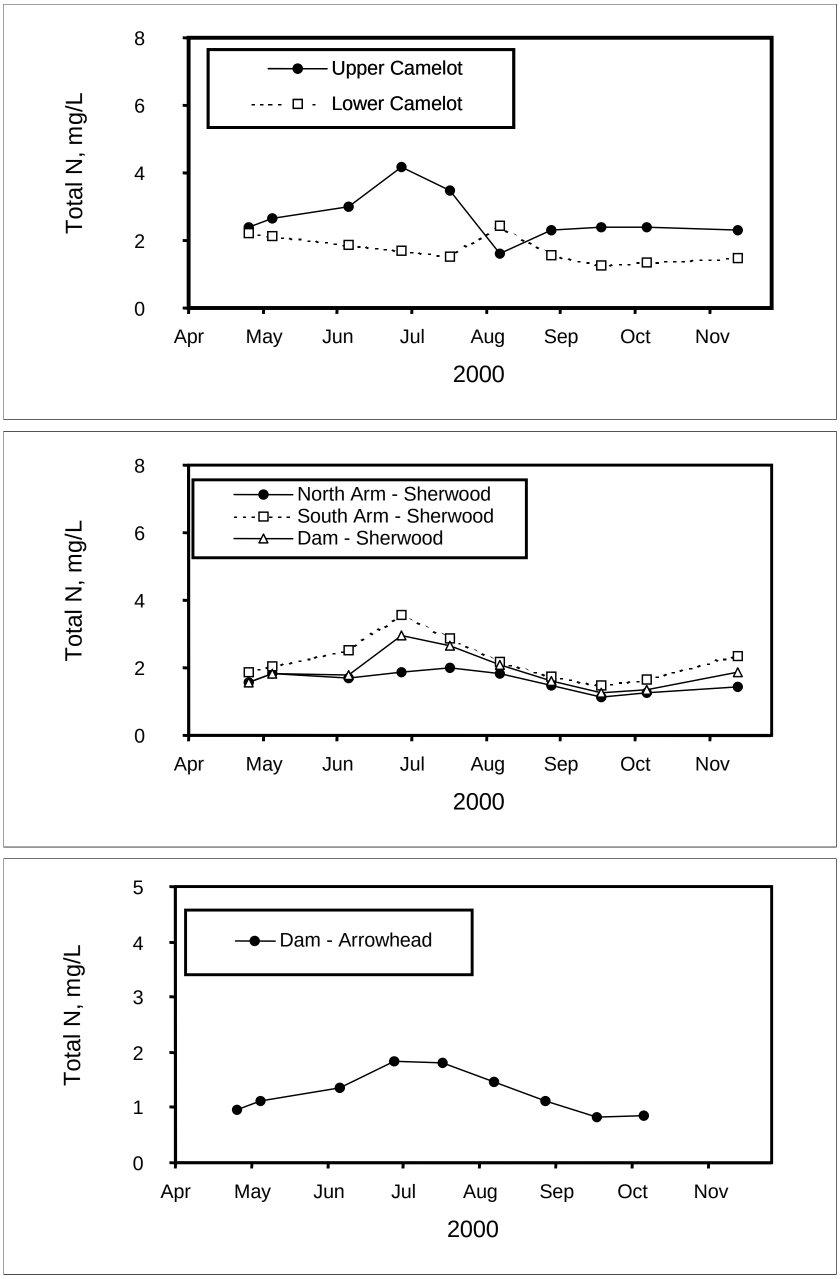


Fig. 18. Seasonal (April through November) variations in mean concentrations of epilimnetic total nitrogen (N; upper 4 m) at stations located in Camelot, Sherwood, and Arrowhead Lakes.

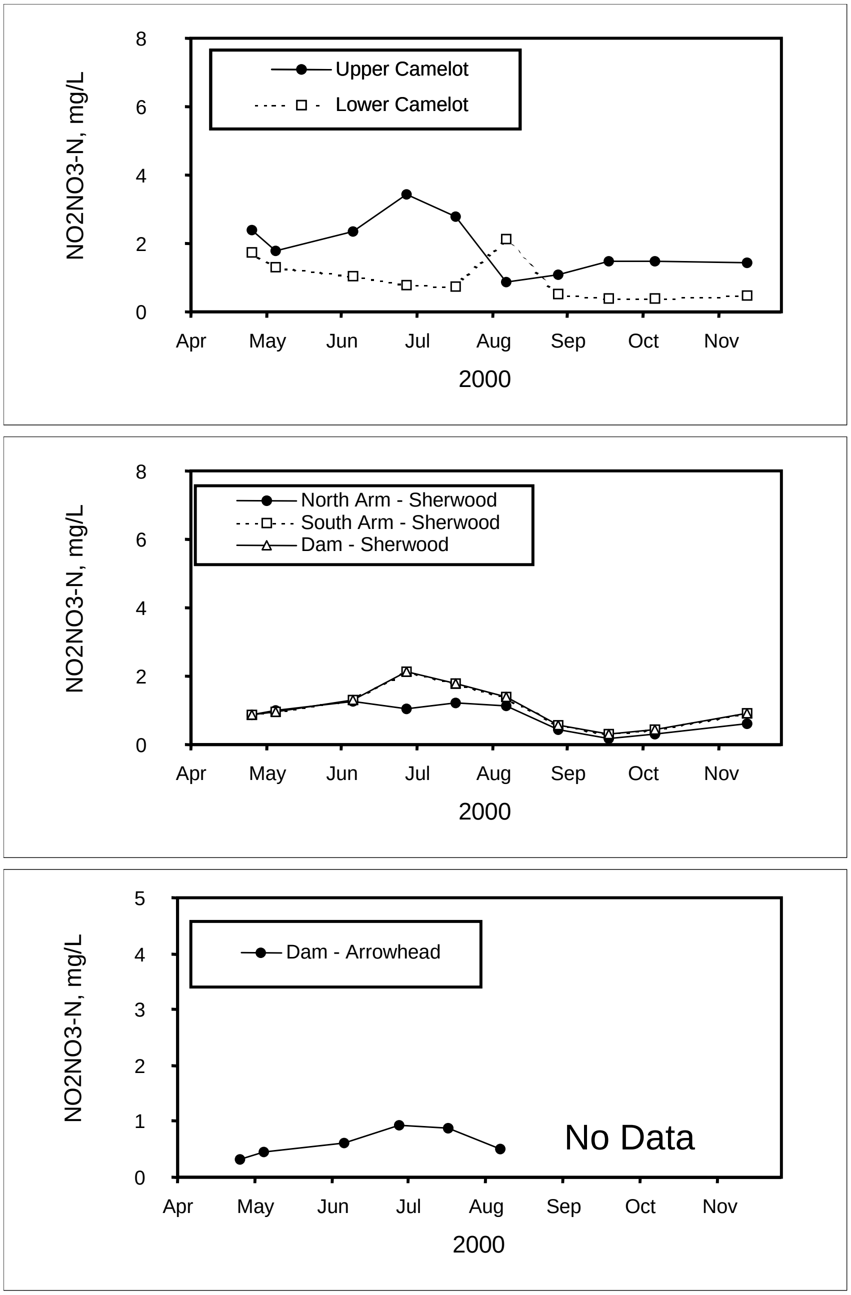


Fig. 19. Seasonal (April through November) variations in mean concentrations of epilimnetic nitrate-nitrite-nitrogen (NO_2NO_3-N; upper 4 m) at stations located in Camelot, Sherwood, and Arrowhead Lakes.

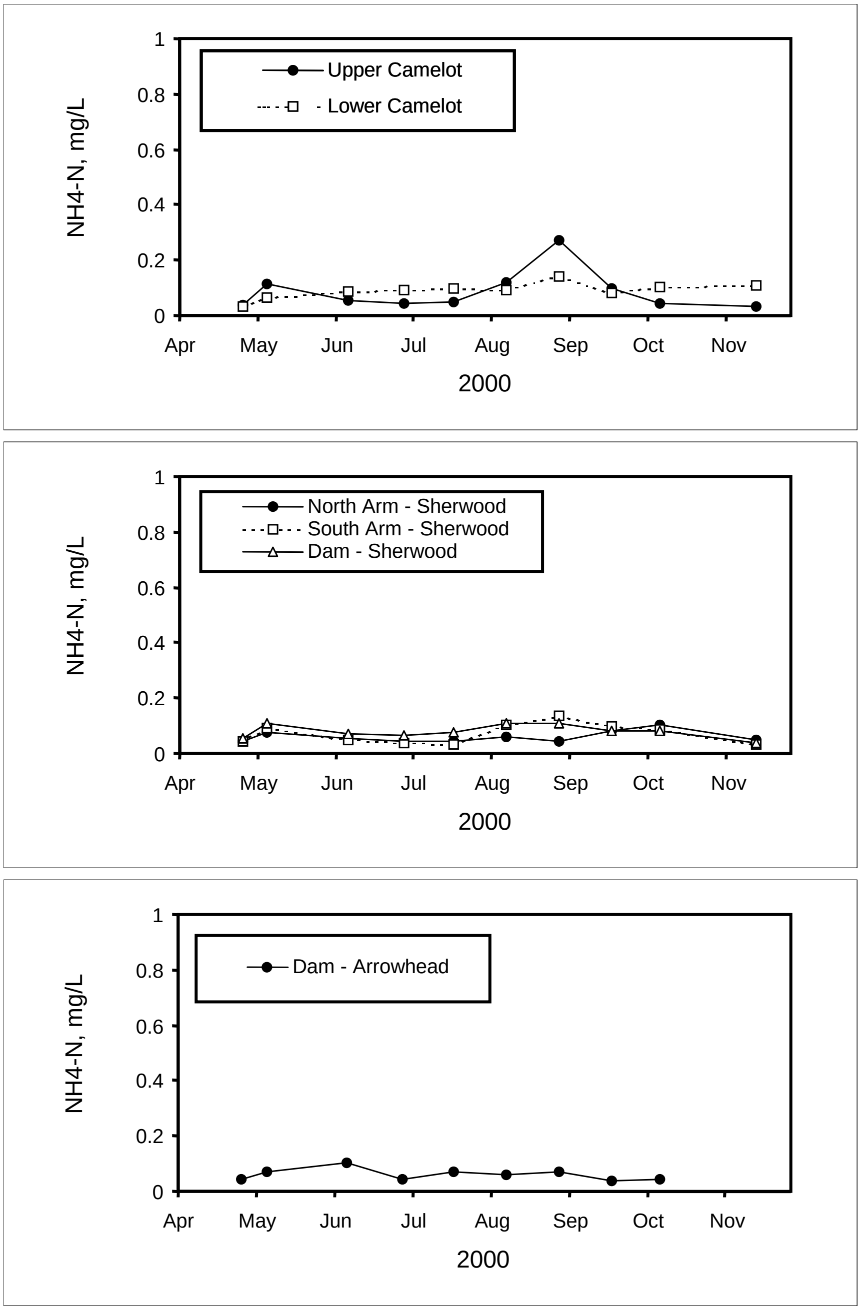


Fig. 20. Seasonal (April through November) variations in mean concentrations of epilimnetic ammonium-nitrogen (NH_3-N; upper 4 m) at stations located in Camelot, Sherwood, and Arrowhead Lakes.

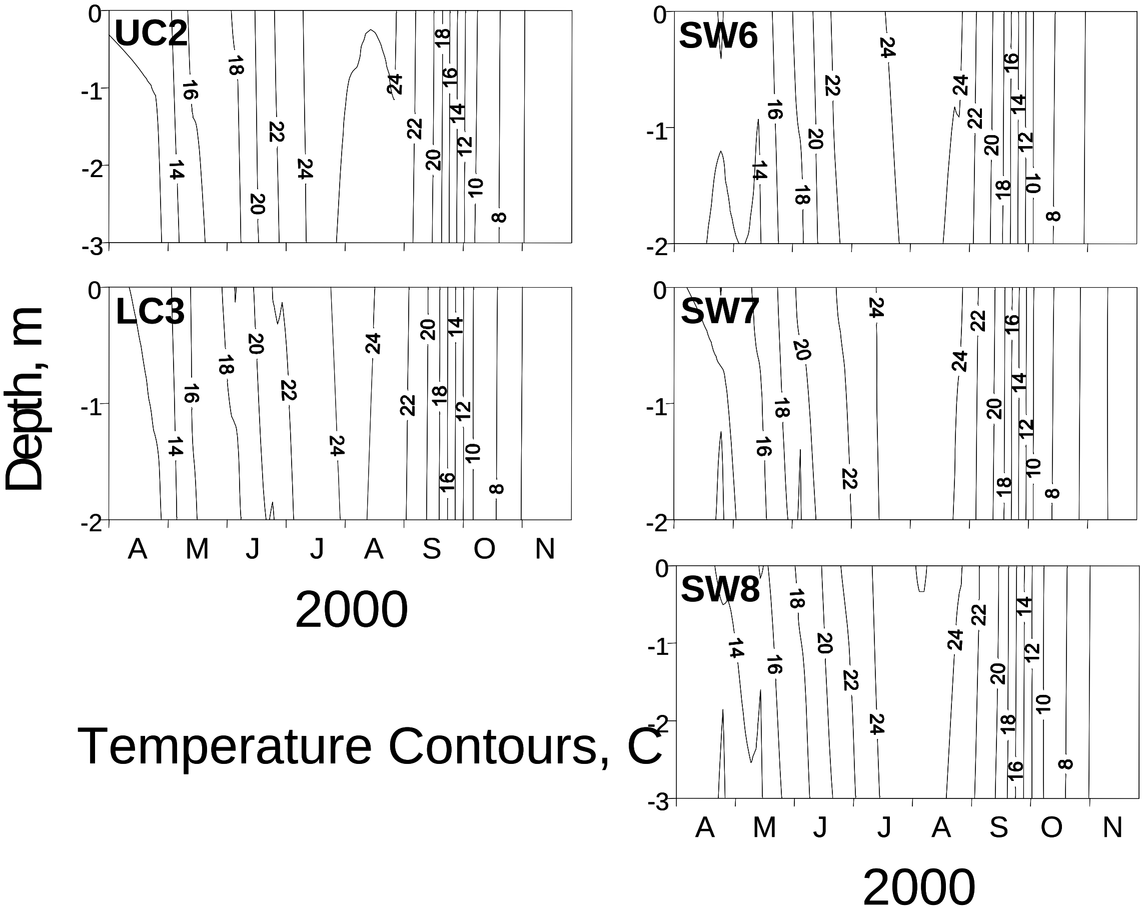


Fig. 21. Contour plot of longitudinal and vertical variations in temperature for backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

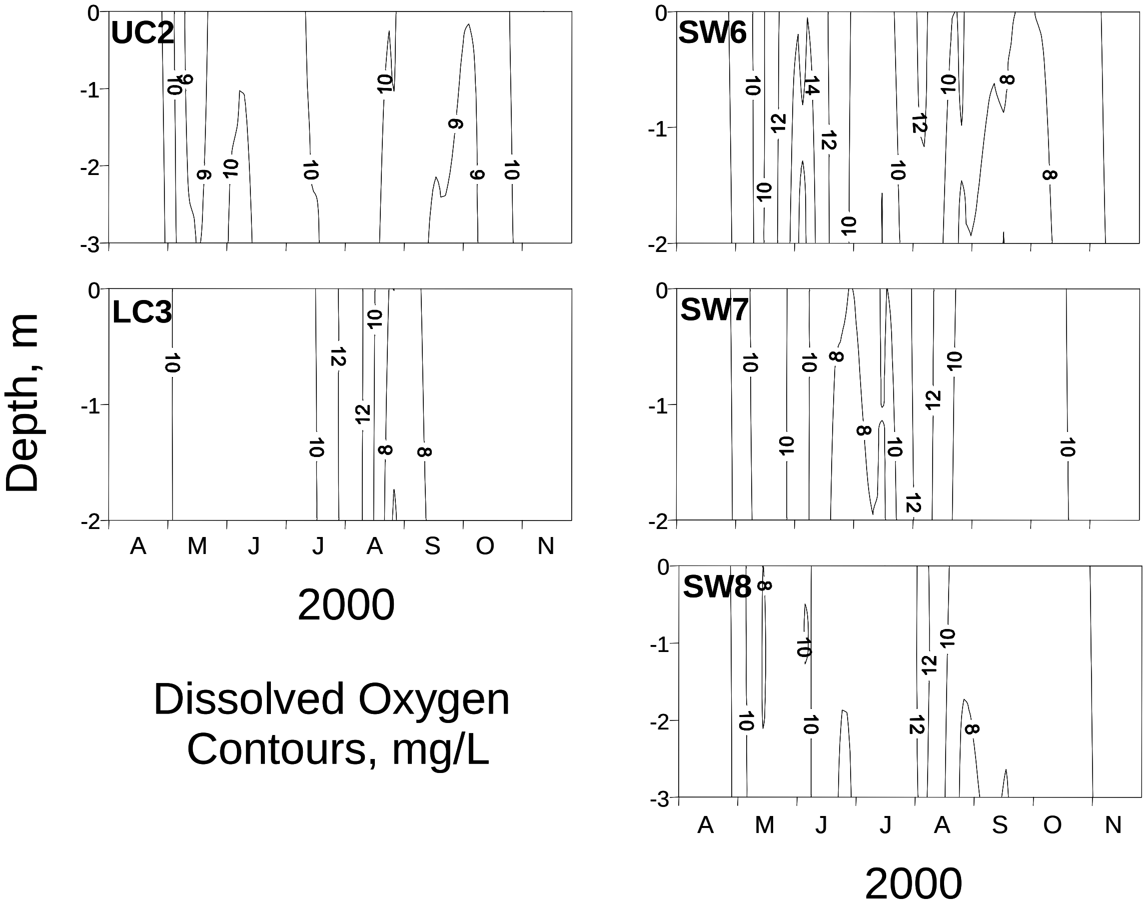


Fig. 22. Contour plot of longitudinal and vertical variations in dissolved oxygen for backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

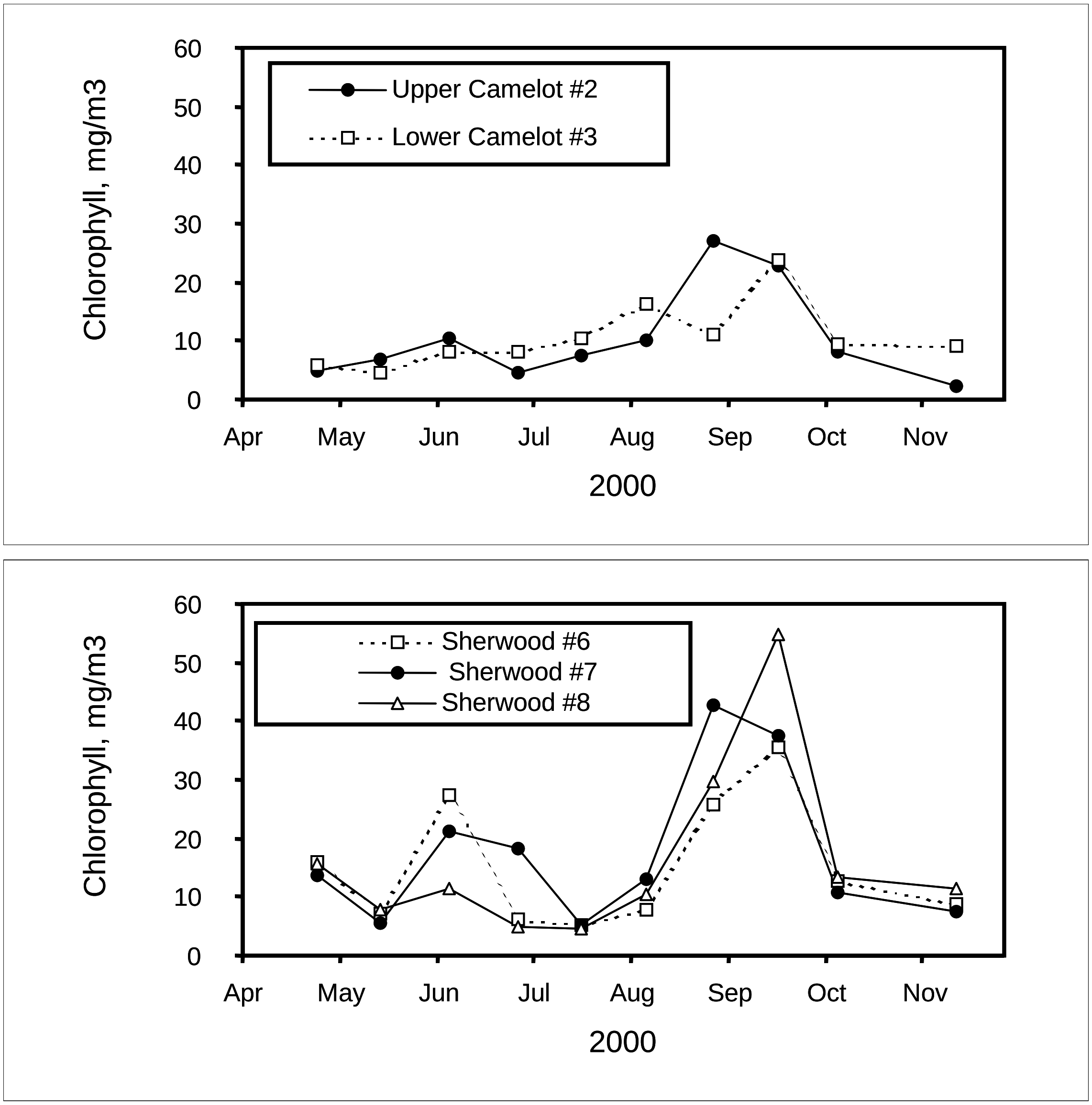
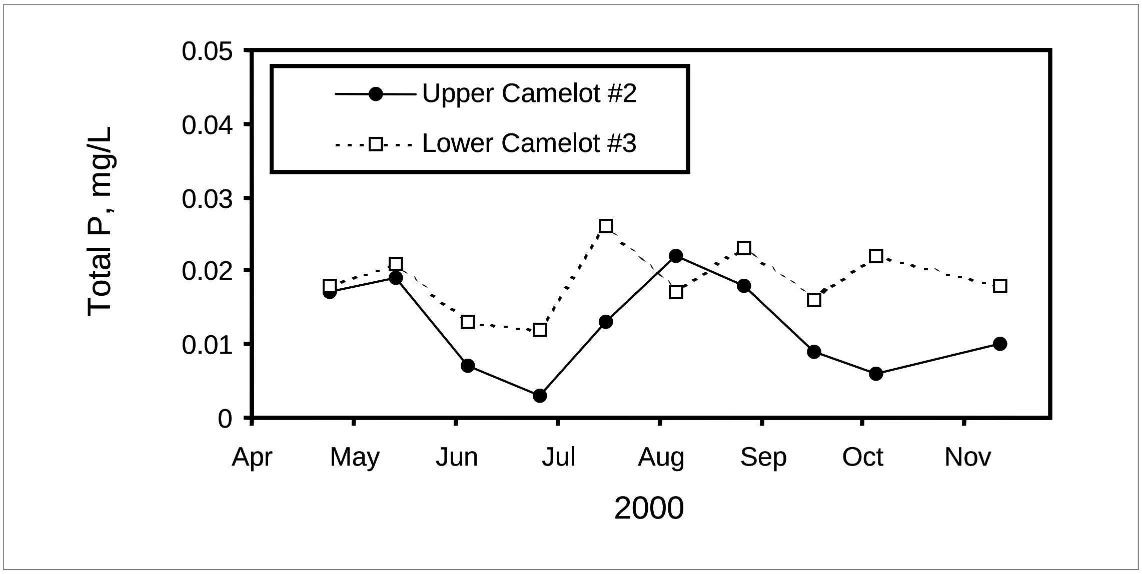


Fig. 23. Seasonal (April through November) variations in mean concentrations of chlorophyll at backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.



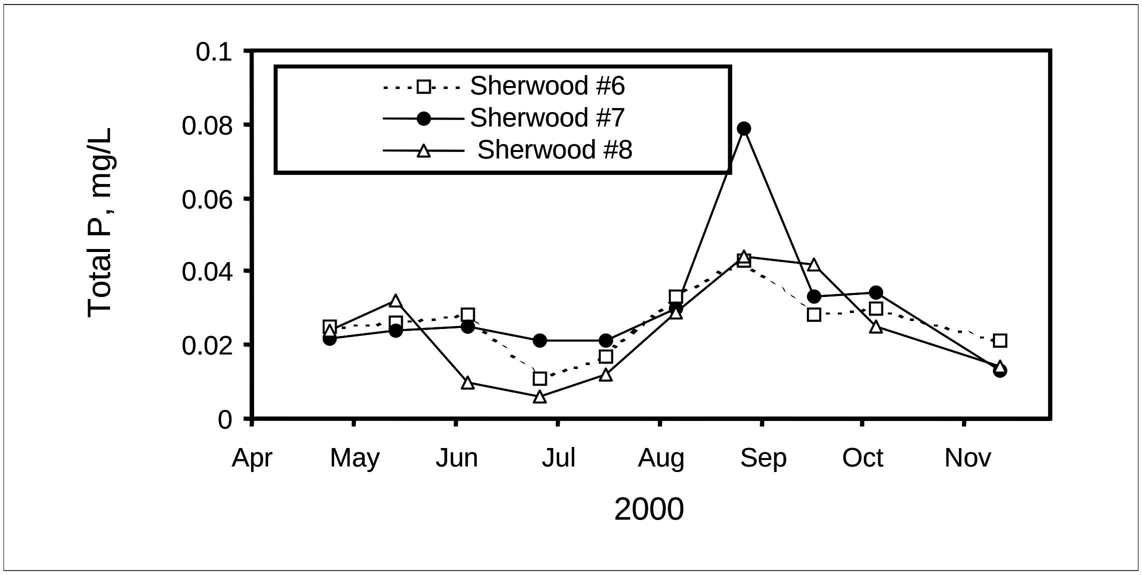


Fig. 24. Seasonal (April through November) variations in mean concentrations of total phosphorus (P) at backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

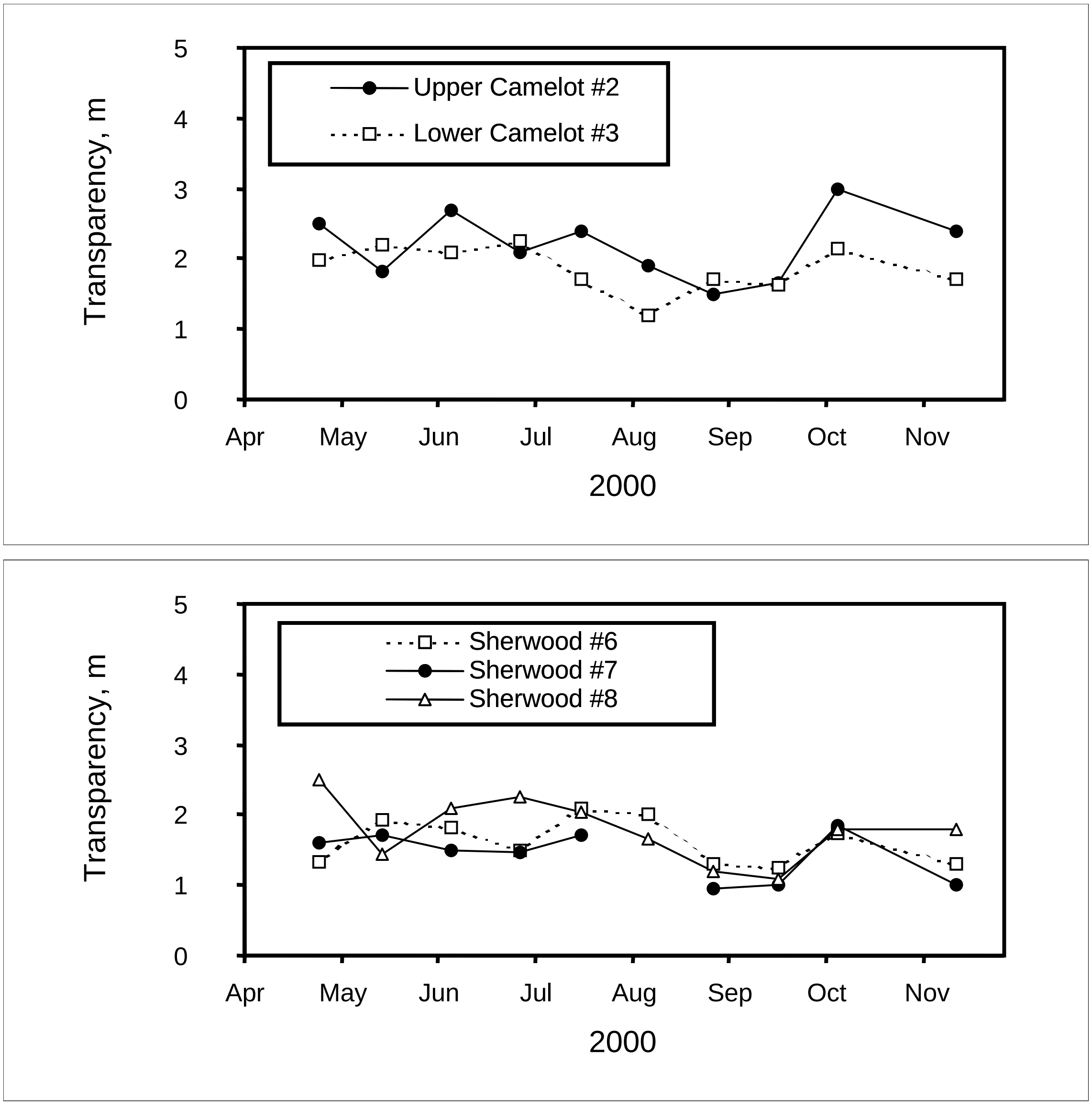


Fig. 25. Seasonal (April through November) variations in Secchi transparency at backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

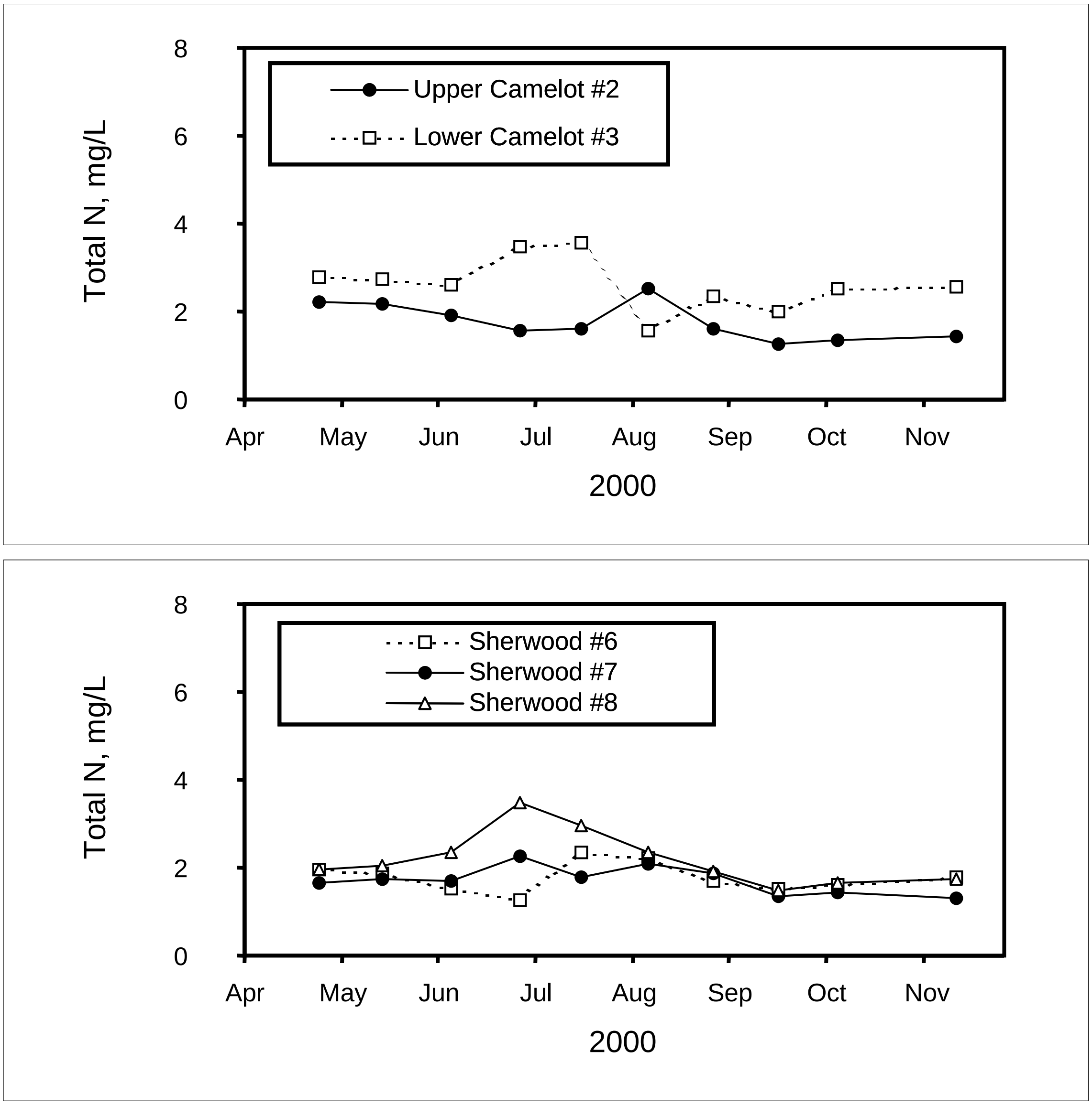


Fig. 26. Seasonal (April through November) variations in mean concentrations of total nitrogen (N) at backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

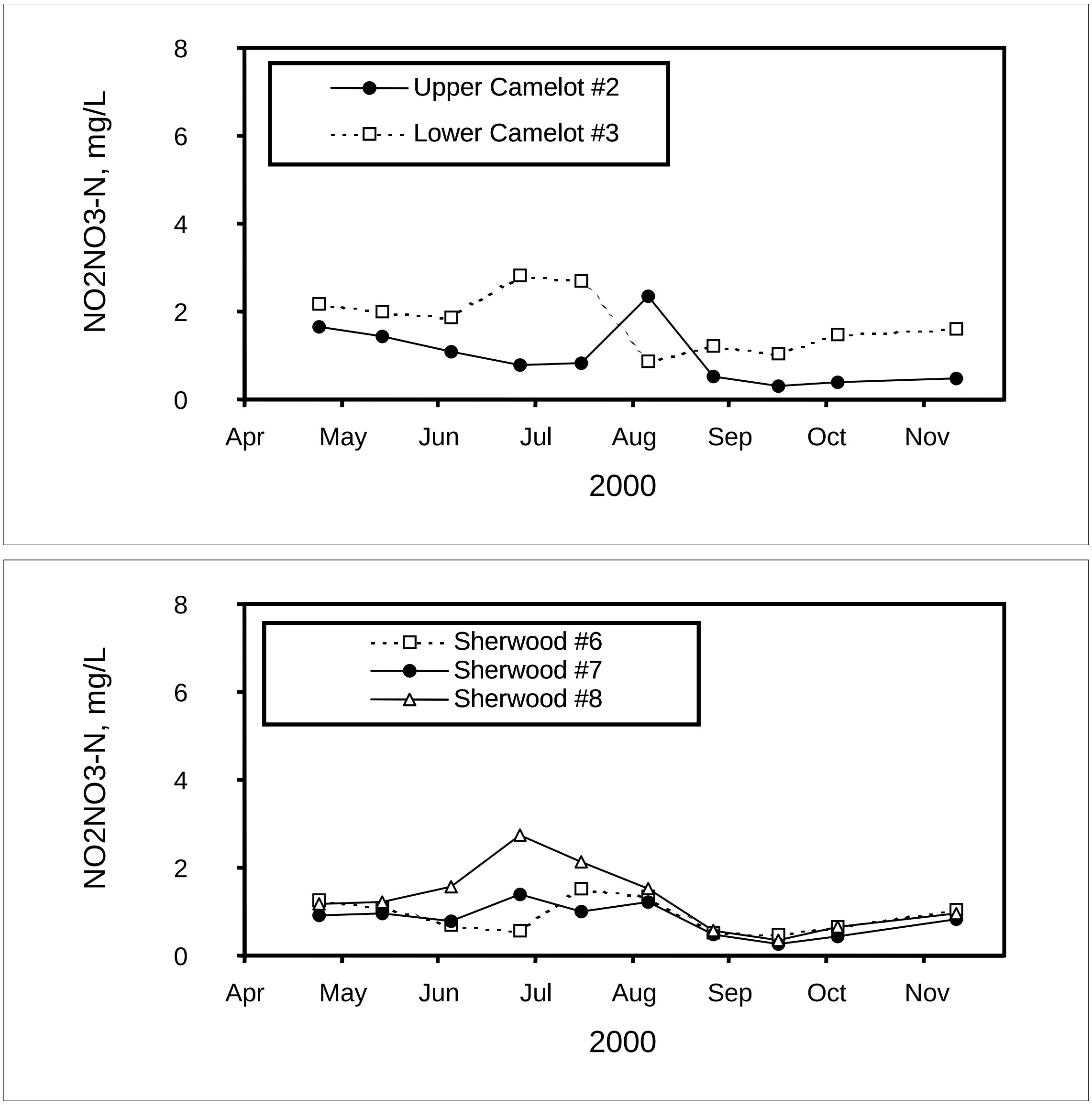


Fig. 27. Seasonal (April through November) variations in mean concentrations of nitrate-nitrite-nitrogen (NO_2NO_3-N) backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

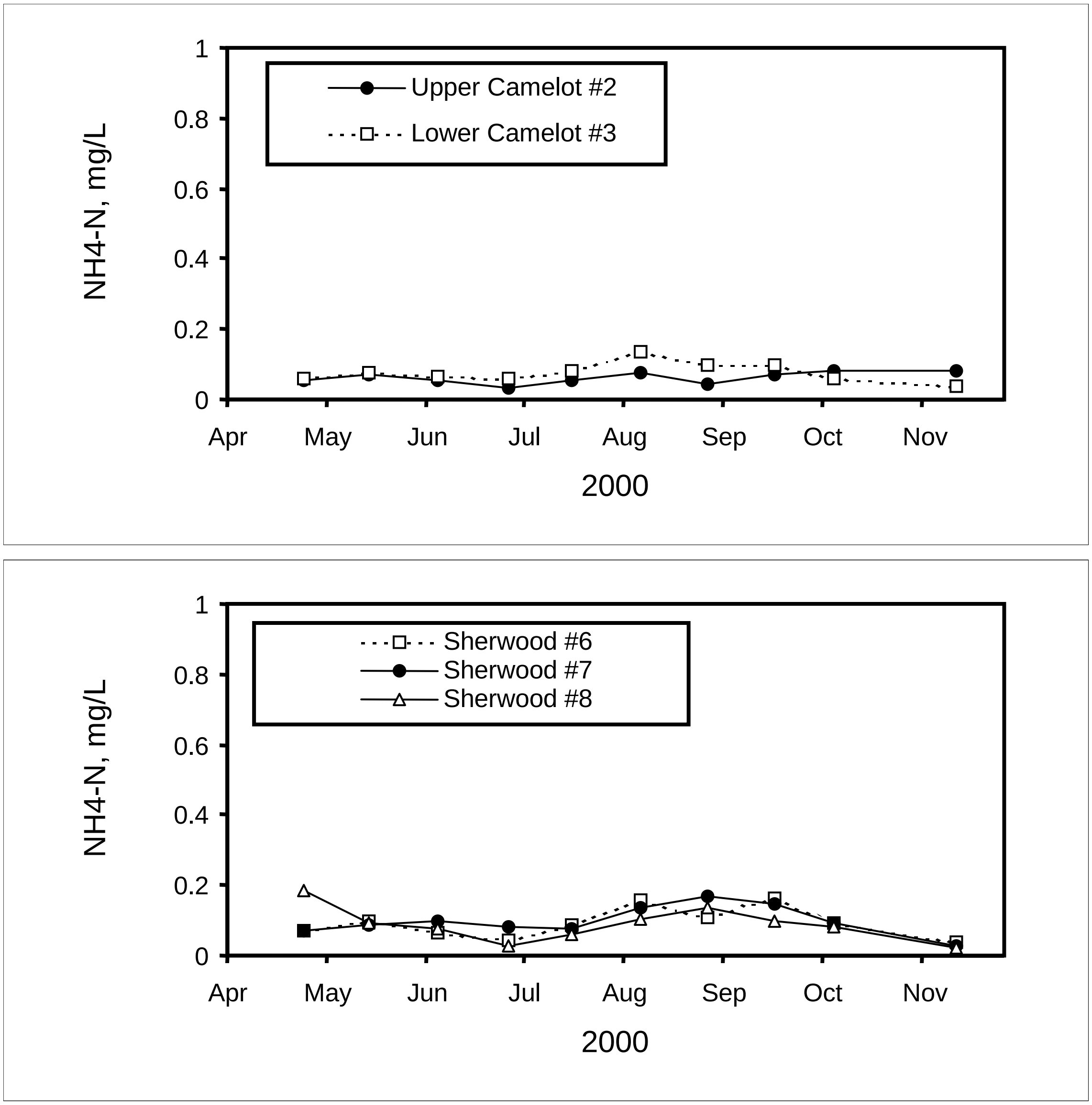


Fig. 28. Seasonal (April through November) variations in mean concentrations of ammonium-nitrogen (NH_4-N) backwater stations located in Upper and Lower Camelot Lake (UC and LC) and Sherwood (SW) Lakes.

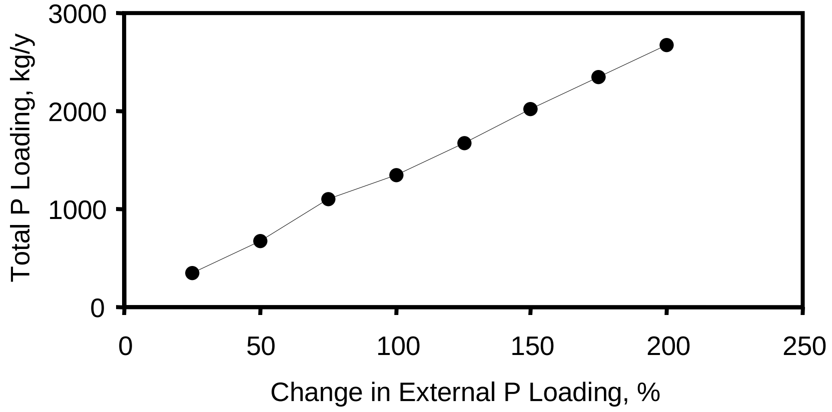


Fig. 29. External P loading variations used in BATHTUB simulations. External phosphorus loading was increased or reduced relative to nominal external total phosphorus loading conditions that occurred during the year 2000.

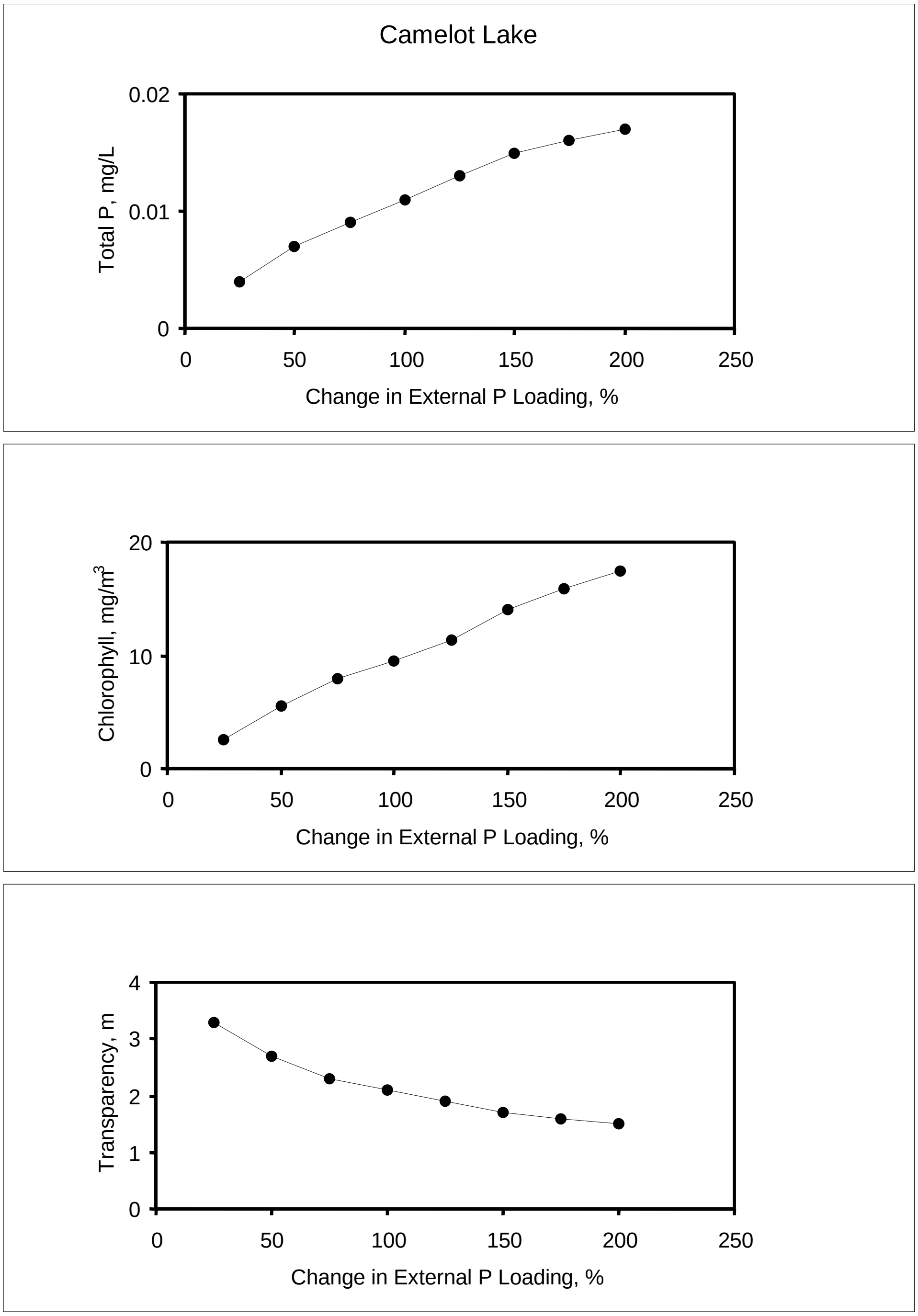


Fig. 30. Estimated changes in total phosphorus (P), chlorophyll, and Secchi transparency in Camelot Lake as a function of external phosphorus loading increases or decreases. External phosphorus loading was increased or reduced relative to nominal external total phosphorus loading conditions that occurred during the year 2000.

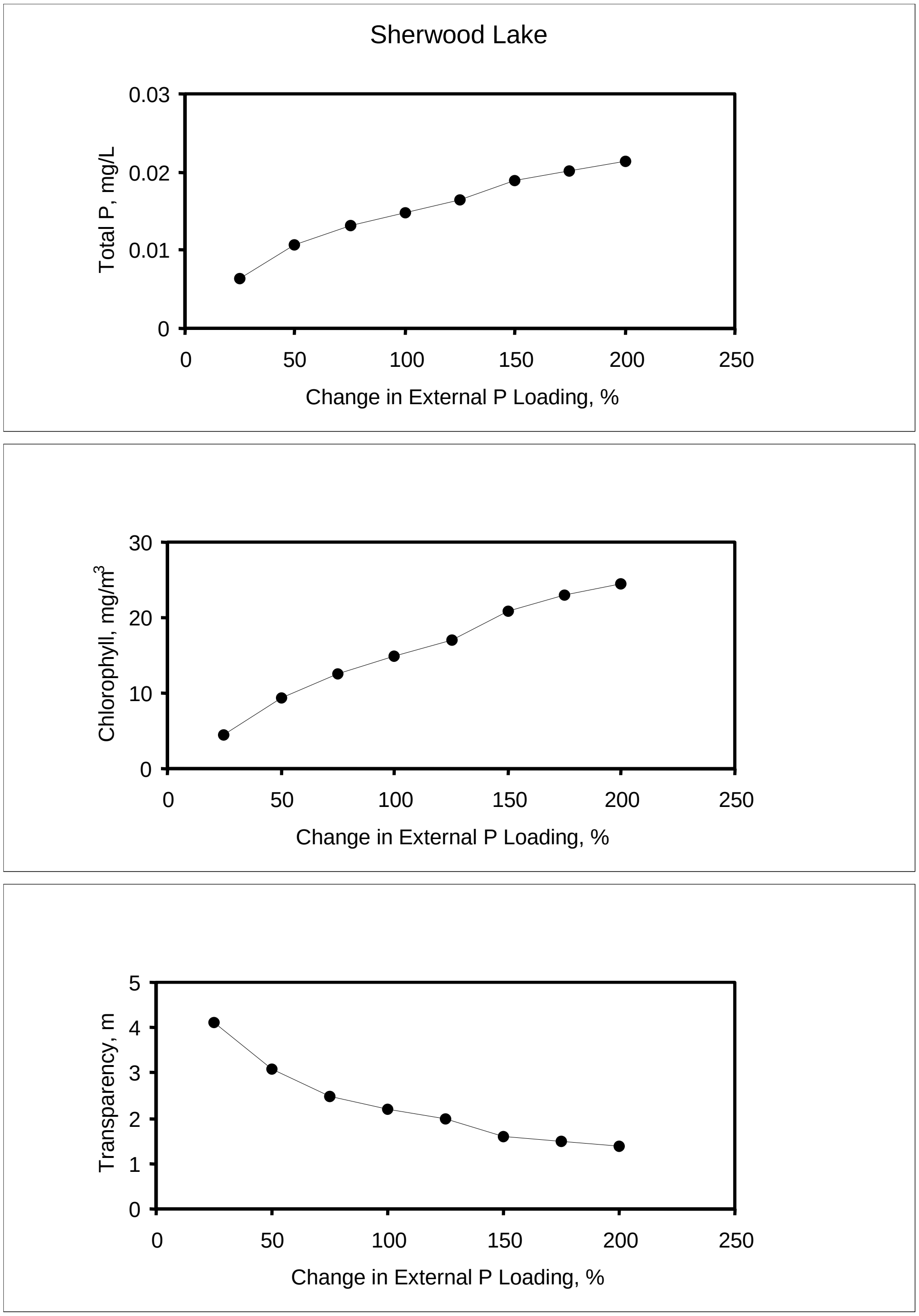


Fig. 31. Estimated changes in total phosphorus (P), chlorophyll, and Secchi transparency in Sherwood Lake as a function of external phosphorus loading increases or decreases. External phosphorus loading was increased or reduced relative to nominal external total phosphorus loading conditions that occurred during the year 2000.

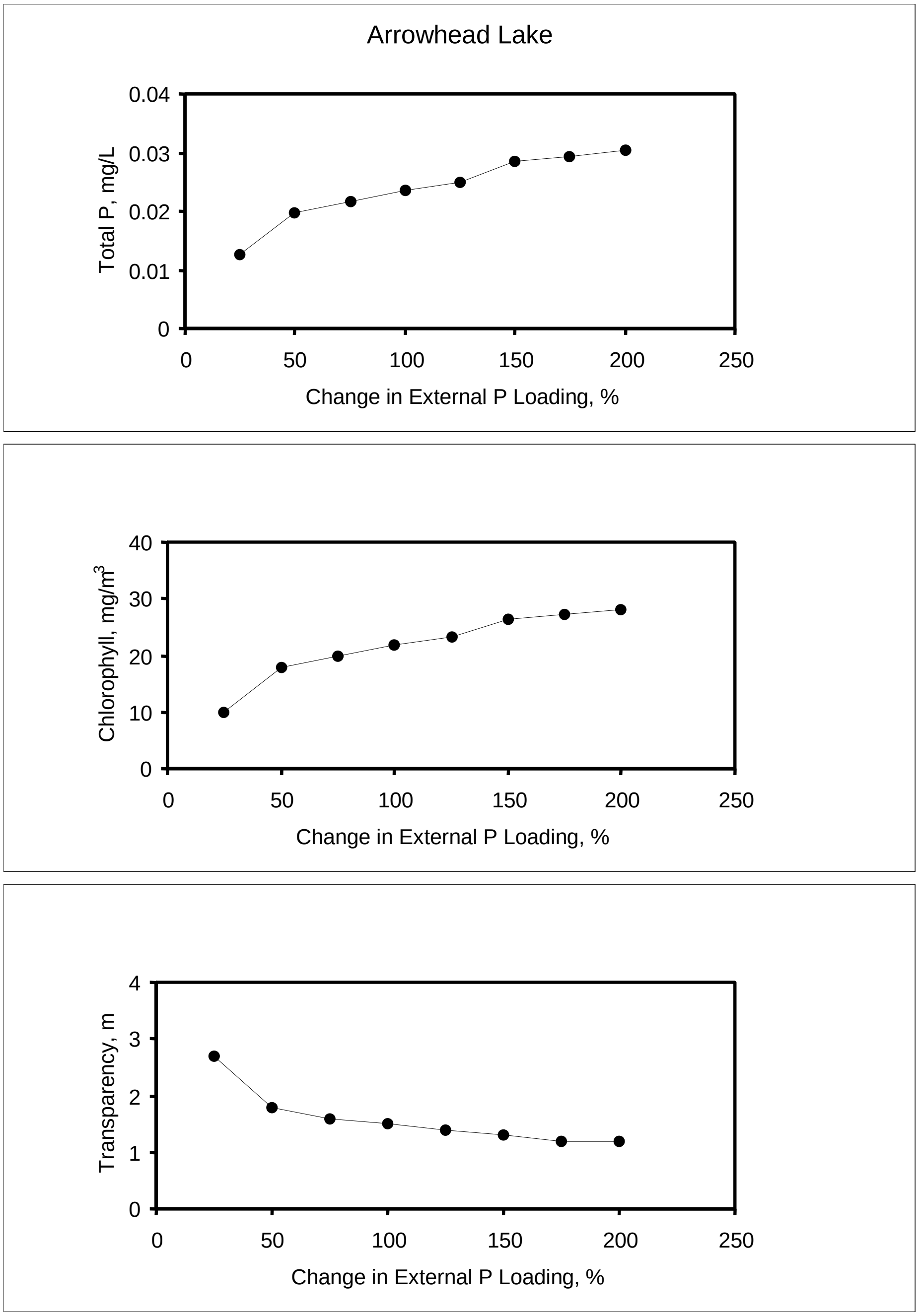
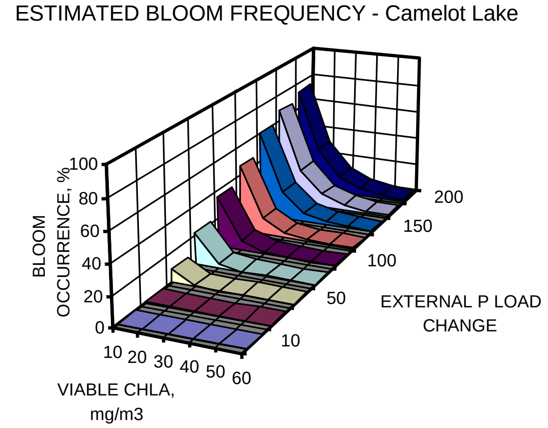
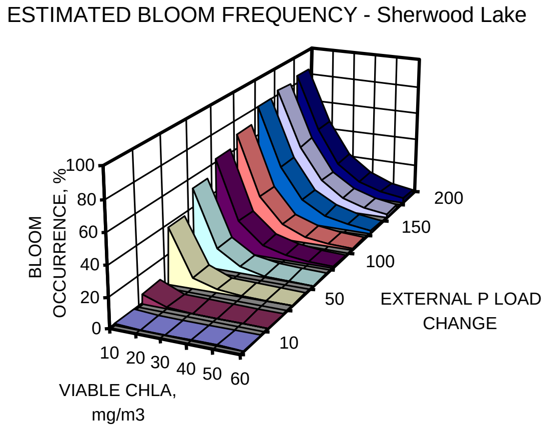


Fig. 32. Estimated changes in total phosphorus (P), chlorophyll, and Secchi transparency in Arrowhead Lake as a function of external phosphorus loading increases or decreases. External phosphorus loading was increased or reduced relative to nominal external total phosphorus loading conditions that occurred during the year 2000.





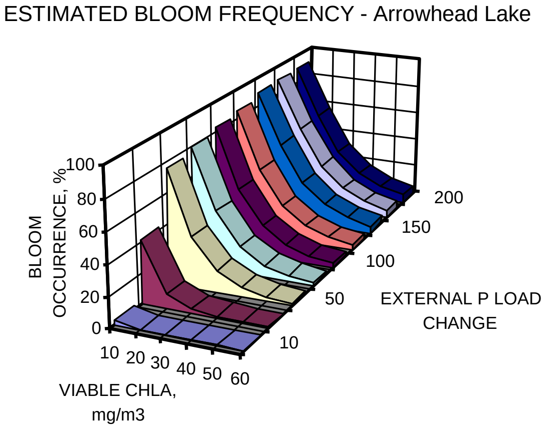


Fig. 33. Estimated changes in the frequency of algal bloom occurrence of different concentrations of chlorophyll in Camelot, Sherwood, and Arrowhead Lakes versus different external phosphorus loading conditions. External phosphorus loading was increased or reduced relative to nominal loading conditions that occurred during 2000.