FEASIBILITY OF AQUATIC PLANT CONTROL IN LAKE LAWRENCE, THURSTON COUNTY, WASHINGTON USING TRIPLOID GRASS CARP (*Ctenopharyngodon idella* Val.)

Phase 1 Baseline Study

by

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EXECUTIVE SUMMARY

The purpose of this research was to assess the feasibility of using sterile triploid grass carp to control nuisance growths of aquatic macrophytes in Lake Lawrence, Thurston County, Washington State. Integral to this feasibility assessment is the prediction of the potential impacts of grass carp grazing on water quality and fish production.

The aquatic macrophyte (plant) community in Lake Lawrence was dominated by *Nymphaea* sp., *Elodea canadensis*, *Potomogeton praelongus*, and *Vallisneria americana*. Maximum seasonal biomass during the summer of 1989 was 1,010 g m^{-2}.

The aquatic plants in Lake Lawrence did not form extensive surface canopies, or associated localized degradation of water quality that has been seen in other Pacific Northwest lakes with more extensive vegetative cover. Dissolved oxygen concentrations in the sub-surface water were apparently increased by the patchy, sub-surface growth of plants.

Mixing of the bottom waters (hypolimnion) into the upper part of the lake (epilimnion) over the summer may have supplied the limiting nutrient, phosphorus, to phytoplankton (algae) near the surface. Growth and photosynthesis by phytoplankton (algae) appeared to be a much more serious water quality concern in Lake Lawrence than the aquatic macrophytes.

The highest densities of largemouth bass were associated with the aquatic macrophytes, suggesting a beneficial relationship with the plants. Also the present degree of plant cover in Lake Lawrence (approximately 38%) is reported to be optimal for largemouth bass production (Wiley et al. 1984a). Growth rates and survival of the planted rainbow trout suggest that aquatic macrophytes are not interfering with the Washington Department of Fisheries stocking program. Feeding experiments indicated that many of the nuisance plants in Lake Lawrence were quite palatable to grass carp. Additionally, water temperatures were high enough to allow effective grass carp grazing. Four stocking rates from 9,045 fish to 12,940 fish were calculated to provide Lake Lawrence managers a range of options to choose from depending on their management objectives.

Recommendations

Levels of aquatic plants in Lake Lawrence do not appear to be detrimental to water quality, and may have actually contributed to improving the aquatic habitat. The largemouth bass fishery would probably not respond favorably to large reductions of the vegetated areas of the lake. If the management goals for Lake Lawrence are to preserve or improve this fishery, large scale removal of the aquatic plants should not be implemented. Selective removal of plants, such as around docks and swimming areas, could potentially be carried out without adversely impacting the warmwater fish populations. Littoral regions (such as in the weedy cove) can be restructured to enhance recreation, potentially without sacrificing biological diversity by fragmenting areas of dense vegetation with selective removal of plants (Engel 1985).

If the management goals are to improve water skiing and boating, more plants should probably be removed. It is essential that the user groups and management agencies concerned with Lake Lawrence clearly define their goals prior to the implementation of any specific course of action.

If the decision is made to selectively remove plants from Lake Lawrence around swimming areas, docks, and boat launches, we feel that other control methods, such as harvesting or bottom barriers may be more suitable than grass carp. The amount and areas of plant removal can be closely controlled with mechanical methods, and habitat for fish and wildlife can be maintained. The degree and location of plant control obtained with grass carp is less predictable.

A significant number of grass carp managers polled in a world-wide survey stated that algae populations increased following the stocking of grass carp. Since algae may be more of a water quality concern in Lake

Lawrence than the aquatic macrophytes, use of grass carp may accelerate this problem.

If the removal of macrophytes over the whole area of the lake is acceptable, then grass carp may be an attractive, economical option. The palatability of the nuisance plant species, and the water temperatures of the lake are suitable for grass carp grazing. However, the results of grass carp stocking are often unpredictable and the potential of eradicating all submergent aquatic plants should be acknowledged. If grass carp are chosen as the plant control technique, we recommend the most conservative of the four stocking rates, 9,045 fish. If the desired results are not obtained within four years, supplemental plant control may be provided as needed and/or the stocking rate can be gradually increased.

PROJECT SUMMARY

Study Site

Lake Lawrence is a 137.38 hectare lake located 10 km south of Yelm in Thurston County, Washington. The lake has a maximum depth of 7.6 m, a volume of 1.907×10^8 cubic meters and drains to the Deschutes River (Wolcott 1965). The lake supports both a trout and spiny-ray fishery, as well as boating, water-skiing, and swimming activities. Aquatic macrophytes cover much of the shoreline or littoral habitat surface area of Lake Lawrence, and include species of aquatic submergent macrophytes that are common nuisances to lakes in the Pacific Northwest, Potamogeton and Elodea.

Research Objectives

Aquatic plants are important components of freshwater ecosystems, oxygenating the water through photosynthesis and providing habitat, food, and breeding sites for many organisms (Gangstad 1978; Seagrave 1988; Kimmel 1988). However, when plants reach high densities, they lose many of their positive attributes. Plant mats formed from excessive growth can degrade habitat by lowering dissolved oxygen content in underlying waters and raising pH to levels that are unacceptable to many fish and invertebrate species (Frodge et al. 1991).

Low dissolved oxygen levels under the canopy can also encourage the internal loading of phosphorus (Frodge 1990).

Overabundance of aquatic plants can also result in stunted populations of centrarchids and reduced production of piscivorous gamefish. This results from a high rate of centrarchid reproduction, combined with the inability of large fish to feed effectively on smaller, stunted individuals in dense weed beds. Wiley et al. (1984a) presented a model based upon trophic dynamics that predicted the production of largemouth bass was highest when macrophyte cover was about 40% of the surface of the littoral habitat. Additionally, human activity is restricted by dense stands of aquatic vegetation. Skiing, boating, swimming, and fishing are best suited to lakes with moderate to low densities of macrophytes.

Phase 1 research was conducted in 1989 to evaluate (1) if aquatic plants were exerting deleterious effects on the water quality and the fish production in Lake Lawrence and (2) if yes, would grass carp be an effective tool for reducing the nuisance plant infestations.

If management agencies decide grass carp are to be stocked, this study provides information important for their use including: biomass and species composition of the plant community, the feeding preferences of the grass carp, and the water temperature regime. A grass carp stocking rate was also calculated with the objective of controlling, but not eradicating all macrophytes from the lake.

MAJOR FINDINGS

Effects of Plant Communities on Lake Lawrence Water Quality

Some areas of Lake Lawrence had dense beds of aquatic macrophytes which formed surface canopies, and were associated with reductions in water quality (particularly reduced dissolved oxygen concentrations). However in 1989, these areas were limited in size. Most of the vegetated area of the lake had sub-surface patches of submergent macrophytes that were associated with increased sub-surface dissolved oxygen concentrations.

The absence of wide-spread deleterious impacts of the plants on water quality were attributed to the limited horizontal distribution of a solid plant canopy and the buffering effect of littoral water mixing with the adjacent open water areas of the lake. Thus, the argument of improving the dissolved oxygen levels in the littoral habitat by controlling aquatic macrophytes is inappropriate for supporting a plant control program.

On the contrary, phosphorus levels in Lake Lawrence were relatively high. The rapid removal of the aquatic macrophytes by grass carp grazing could contribute to the existing excessive growths of phytoplankton and blue green algae by contributing to the phosphorus concentrations in the lake. The high levels of phosphorus and resulting phytoplankton blooms may be associated with the establishment of an anoxic hypolimnion in the spring, and its gradual mixing with the surface water during the summer. However, the accelerated rate of organic sedimentation caused by the annual die off of aquatic plants and late summer hypolimnion oxygen depletion is an concern that has not been addressed but may support the argument for reductions of plants.

Fish Populations

Lake Lawrence was found to support a small but fast growing population of largemouth bass. The growth rates and maximum size of largemouth bass, along with their density and population structure suggest that production is not being detrimentally affected at present macrophyte densities. In fact, the highest densities of largemouth bass were associated with beds of aquatic macrophytes, suggesting a beneficial relationship with the plants, which agrees with the water quality findings for these plant beds. Also the present degree of plant cover in Lake Lawrence (38%) is reported to be optimal for largemouth bass production (Wiley et al. 1984a). As in Lake Conroe, Texas, the removal of aquatic macrophytes in

Lake Lawrence may cause a temporary decline in sportfishing success because there will be less plant bed edge habitat to concentrate bass for the anglers.

The largest number of warmwater fishes occurred in the highly vegetated west basin, whereas population densities as a whole were relatively low, suggesting that these species were limited by the extent of vegetated habitat. The west basin supported 73% of the juvenile and 46% of the adult largemouth bass, 40% of the brown bullhead, 51% of the yellow perch, and 67% of the pumpkinseed, while comprising less than 25% of the total surface area of the lake.

Lake Lawrence also supports a fishery for planted rainbow trout. The growth and survival of the rainbow trout in Lake Lawrence is managed by the Washington Department of Wildlife by periodic rotenone treatments to reduce competition with other fish species. The last treatment in 1985 was considered successful and the present growth rate and survival of the trout suggest that aquatic macrophytes are not interfering with this program. More open water in the littoral zone may enhance rainbow trout growth and survival. The central area of the lake is too deep to be colonized by aquatic macrophytes and the aerobic portion of the water column will continue to be used by the rainbow trout.

Wildlife Populations

There are populations of waterfowl, muskrats, otters, beavers, and other animals that utilize Lake Lawrence. Bald eagles have been observed on the lake. The importance of the aquatic plants in Lake Lawrence to this wildlife is unknown, and the Washington Department of Wildlife or U.S. Fish and Wildlife Service should be asked for an opinion.

Recreational Observations

There is substantial recreational boating activity on Lake Lawrence for skiing, fishing and other recreational purposes. The aquatic plants occupy some of the most desirable areas of the lake for water skiing and often are a nuisance to shore based activities such as fishing, swimming, and boat launching. A primary argument for controlling aquatic macrophytes is that more lake area will be opened for such activities. However, there are potential conflicts between the different recreational user groups in the lake, for instance, those supporting water skiing and bass fishing activities. A management plan needs to be developed to allocate adequate space to the various users to conduct their activities without severely disrupting each other. The development of such a plan must address the primary areas of the lake which would be targeted for aquatic plant control. It should also take into account the fact if the plants are removed, the current use by bass fishermen would probably be replaced by water skiing and fishing for rainbow trout.

The decision to removed aquatic plants is complex and will involve compromises by several different interest groups. The aquatic plants in Lake Lawrence are abundant but not so extensive as to cause obvious detrimental impacts to the fish, wildlife, or water quality, and on the contrary may be beneficial. The plants are also limited to specific locations where they exclude specific, but highly popular activities. Thus, we see that the decision to implement a plant control program must come from a management plan developed by the recreational users and approved by the management agencies.

Evaluation of Grass Carp as a Plant Control Technique

If the decision is made to control aquatic plants in Lake Lawrence, an effective plant control technique must be chosen. Using grass carp for aquatic plant control has both advantages and disadvantages when compared to other plant control techniques. We found several potential advantages to using grass carp to control the nuisance plants in Lake Lawrence. The submergent plant community, consists primarily of *Potamogeton* spp., *Vallisneria americana*, and *Elodea canadensis*, which are palatable to grass carp. Additionally, the lake's water temperature during the aquatic plant growing season is high enough (> 20 C) to allow intensive grazing by the fish. Grass carp tend to be much less expensive than other methods of macrophyte control. A comparison of macrophyte control methods for Devils Lake, Oregon demonstrates that grass carp, even when stocked at the high densities required in the Pacific Northwest are very economical. Grass carp are also a low maintenance and a reversible management strategy.

There are also several potential negative consequences of using grass carp as opposed to other plant control techniques. Grass carp commonly take between 2-5 years to control aquatic plant populations. Since grass carp are a biological control, the result of their stocking is less predictable than that which might be obtained by removing plants by mechanical or chemical methods. Since stocking rate predictions are not accurate enough at present to insure a desired degree of control, the decision to stock the fish must accept the possibility of no-control or eradication of all aquatic plants. Additionally, grass carp are difficult to remove once they are stocked, so the results of stocking could last for ten years or more. Grass carp avoid area of heavy human activity (Swanson 1986), so control may not occur in swimming areas, around docks or in boat launching areas until palatable plants are eaten elsewhere. Grass carp may also accelerate the growth of nuisance algae populations, especially the blue-greens.

CHAPTER 1. BASELINE WATER QUALITY AND THE EFFECTS OF AQUATIC MACROPHYTES ON LAKE LAWRENCE

Introduction

Aquatic macrophytes are recognized as having important influences on the physical and chemical environment and littoral biota (Carpenter and Lodge 1986), and at high densities have created problems due to their abundance (Grace and Wetzel 1978). Extensive covers of floating or emergent plants shelter the surface from wind, reduce turbulence and aeration, restrict mixing, and promote thermal stratification (Environmental Protection Agency 1972). The development of surface canopies of aquatic macrophytes can have severe detrimental effects on dissolved oxygen (DO), pH, and internal loading of phosphorus (P) from the sediments (Frodge 1990). It is also widely accepted that the effect of aquatic macrophytes on productivity in a lake largely depends upon macrophyte density, cover, and biomass (Wetzel 1983, Welch et al. 1988). Many authors have suggested that the effects of aquatic macrophytes on both productivity and water quality are related to the standing crop and percent of the lake volume covered (Howard-Williams and Allanson 1981; Canfield et al. 1983; Shireman et al. 1985).

The influence of aquatic macrophytes on the water quality of a lake also appears to be dependent on the size and morphometry of the lake. Small, shallow lakes that have most of the bottom within the photic zone (the zone of light penetration and photosynthesis) and are sheltered from the wind are more likely to develop extensive surface canopies and exhibit pronounced water quality responses (Dale and Gillespie 1977; Schreiner 1980; Frodge 1990). Deeper lakes, with a greater wind fetch and a larger ratio of open water to vegetated area appear to be buffered from the effects of macrophyte beds, and do not exhibit widespread changes in water quality.

Where excessive growths of aquatic macrophytes create nuisance conditions, grass carp (*Ctenopharyngodon idella* Val.) have been stocked to remove or reduce high densities of these plants (Van Dyke et al. 1984; Allen and Wattendorf 1987; Bonar et al. 1989). An understanding of the functional role of aquatic macrophytes in this lake is required to hypothesize about potential ecological changes associated with the reduction of the plant biomass. The objectives of the water quality monitoring in Lake Lawrence were: (1) to examine the baseline water quality, particularly as habitat for fish, (2) to determine whether the water quality was influenced by the macrophytes in the lake, and (3) to discuss potential changes in water quality associated with the reduction of the plants by triploid grass carp.

Methods

Investigations on water-macrophyte interactions in Lake Lawrence began in April 1989. A minimum of 15 sites were sampled synoptically with sampling of aquatic macrophytes (Chapter 4). Temperature, DO, and pH and conductivity were measured from the surface to the bottom at 0.25 m intervals with a Hydrolab 5000. The Hydrolab was calibrated prior to each sampling trip. Winkler titrations were used to calibrate DO, and standard solutions for pH and conductivity. Resolution for DO was 0.01 mg l^{-1}, and for pH 0.01 pH units.

Water samples for chemical analysis were taken from the surface and about 5 cm above the sediment water interface using a Van Dorn bottle, or SCUBA. Samples were collected in pre-washed 500-ml plastic Nalgene bottles, with one sample filtered through a 0.45 um millipore filter. The unfiltered sample was frozen at 15^{o}C upon return to the laboratory, and the membrane-filtered water was stored at 5^{o}C.

Total phosphorus (TP) in unfiltered surface and bottom samples was measured after digestion (Valderrama 1978). soluble reactive phosphorus (SRP) in filtered surface and bottom water was preserved with $HgCl_2$. Both

TP and SRP were determined using the ascorbic acid single reagent technique (APHA et al. 1985) with a spectrophotometer equipped with a 10 cm cell.

Differences in water temperature, pH, DO, and conductivity between the east basin (main lake) and the west basin (small cove) were tested by a fixed effects analysis of variance (ANOVA), with area and depth treated as fixed effects. These areas correspond to the sampling stations established by the Thurston County Health Department monitoring program. Water quality data was obtained for 1974, 1975 and 1981 from the Washington State Department of Ecology Water-Supply Bulletin 42, Data on Selected Lakes in Washington (1976; 1980) and the Thurston County Health Department for the years 1986 through 1988 (unpublished data).

Results

There were no significant differences between the measured water quality parameters in the east basin and the smaller west basin. Information on the annual variability and seasonality of the water quality in Lake Lawrence was obtained by comparing data collected in this study (1989) with data from previous years. Temperatures were not significantly different between the years when data was available (Table 1), but each year exhibited a definite seasonal cycle, with summer surface means between 20-25 ^{o}C, and lows in the winter of around

5 ^{o}C (Figures 1 and 2). In both 1988 and 1989 the difference between surface and bottom temperatures was greatest in mid- to late-spring, and during the summer there was a gradual warming of the deeper water. Surface and bottom temperature differences in the west basin appeared to persist somewhat longer than in the east basin in 1988 and 1989. Temperatures in September 1987, 1988, and 1989 showed very little change from the surface to the bottom, indicating that during these years Lake Lawrence was not stratified in late summer.

Conductivity also showed both seasonal and depth changes. Seasonal highs occurred in mid-summer during 1988 and 1989, although 1989 conductivity was nearly twice as high as in 1988. Conductivity data for 1988 and 1989 were collected by different investigators, but data from 1987 was higher than 1988 and comparable to conductivity recorded in 1989 (Table 1; Figures 3 and 4). In April 1989, surface conductivity was slightly lower and more variable than the rest of the water column, but by summer, this difference had disappeared (Table 2). Mean bottom conductivity was much higher than the rest of the water column in the spring, and at a few sites in summer, but by September there was essentially no difference in conductivity from the surface to the bottom.

The pH also varied seasonally and with depth, with low pH in late fall to early spring of around 6, to summer maxima of > 8 (Table 2; Figures 5 and 6). Vertical change was more complicated, with the highest summer pH ($\geq$ 8) at depths of 2-4 m. During spring and summer, before the stratification broke down, pH at 5-6 m decreased to winter minima of near 6. The range of pH between May and October was 6.0-9.83.

Dissolved oxygen concentrations at depths < 3 m were typically $\geq$ 10 mg l^{-1} during the entire year (Figures 7 and 8). Dissolved oxygen in deeper areas (5-6 m) changed seasonally, with concentrations equal to those at the surface during mixed conditions (Table 2). During the April and May stratification periods of both 1988 and 1989, DO concentrations at depth $\geq$5 m were reduced in both the west and east basins. In 1988, low DO persisted in the east basin until September, while concentrations in the west basin began to increase in July. In 1989, low DO concentrations in both basins again occurred in late spring, but by September DO concentrations at 6 m were $\geq$8 mg l^{-1} and not different from at the surface.

Water Quality-Aquatic Plant Associations

Examination of vertical profiles from both shallow ($\leq$ 2 m) and deep areas help explain some of the variability in the water quality measurements. Most of the macrophytes grew in what was defined as shallow water (<2.0 m), deeper areas were defined as sites with depth >2.0 m.

Deep water sites were thermally stratified in the spring (Figure 9). Water temperatures were between 20-25 ^{o}C from 0-2 m and decreased to 10-15 ^{o}C at the bottom. Readings from three sites in the middle of the main lake, or West Basin, did not change with depth, and temperature remained around 17 ^{o}C throughout the water column. In July, temperature decreased gradually with depth, from around 22 ^{o}C at the surface to around 15 ^{o}C at the bottom (>3.5 m). In September, temperature was nearly uniform from the surface to the bottom at around 20 ^{o}C.

Temperature in shallow areas varied more than in the deeper sections of the lake, both with depth and between individual sampling sites (Figure 10). Water temperature was typically cooler beneath floating leafed macrophytes, and slightly warmer within the upper portions of the canopies of the submergent plants.

Dissolved oxygen concentrations in the deeper sections of the lake (Figure 11) were associated with the vertical stratification of the temperature. While the thermocline was not distinct on the temperature profiles, the difference between epilimnetic and hypolimnetic DO concentrations was distinct. In spring, the thermocline developed around 2.5 m at a temperature change from about

16-18 °C. Beneath the thermocline, DO concentrations decreased, and in several instances the bottom water was anoxic. Dissolved oxygen concentrations in the deeper sites of the east basin apparently did not thermally stratify and did not show mid-water changes in DO concentration.

In July, DO concentrations increased to near 10 mg l^{-1} in the water column from 2.5 to 4.25 m, as the thermocline migrated deeper with the erosion of the hypolimnion. Below 4.25 m, where temperature decreased from around 20 to 18 °C, and DO concentration decreased and were often near zero. In September, DO concentrations were uniform from the surface to the bottom at around 8-9 mg l^{-1}. A few sites 3-4 m deep exhibited mid-water DO maxima, coinciding with the tops of sub-surface submergent macrophyte beds.

The shallow areas of the lake had much more variable vertical distributions of DO, which appeared to be associated with the type of plant cover, amount of open water, floating leafed, or submergent, that occurred at the sampling site (Figure 10). Sites with floating leafed macrophytes had low sub-surface DO throughout the sampling period (<1-2 mg l^{-1}). Concentrations of DO 0.5-1.0 m beneath these plants were often less than half of the concentrations at the surface, and several sites were anoxic at 1.0 m.

Sites with submergent macrophytes had high subsurface DO (10-15 mg l^{-1}), which corresponded with the depth of the majority of their photosynthesizing biomass. The difference between bottom DO concentrations beneath floating leafed (0-4 mg l^{-1}) and submergent macrophytes (10-17 mg l^{-1}) was greatest during September, the same time DO concentrations in the deeper water were uniform from the surface to the bottom (8-9 mg l^{-1}; Figures 10 and 11).

Shallow open water sites had DO concentrations around 9-11 mg l^{-1} in April, 7-9 mg l^{-1} in July and 9 mg l^{-1} in September. In most of the shallow open water sites, surface DO was equal to, or only slightly higher than at the bottom (Figure 10).

Between April and September, pH also exhibited slight variations with depth (Figure 12). In the deep areas in April, surface pH was between 6 and 8, while near 6 at the bottom. In July, surface pH was slightly higher (7.5-8.5), and only beneath 5 m was pH $\leq$ 6. In September, pH was near 8 from the surface to the bottom at 6 m.

In the shallow water areas, pH was higher in open water and submergent species sites than in areas with floating leafed macrophytes (Figure 13). Submergent macrophyte sites had slightly higher pH associated with the tops of the sub-surface plant beds, while surface and bottom pH in open water and floating leafed sites was nearly uniform.

Conductivity in the deeper parts of the lake also varied with depth, and corresponded to the thermal stratification in the lake (Figure 14). At the surface, conductivity was between 90-105 usiemens in April, between 115-120 usiemens from 0.25-2.5 m, and below 2.5 m increased to as high as 175 usiemens. Mixed sites in east basin did not have increased conductivity below 2.5 m. In July conductivity was uniform from the surface to around 5.0 m at 120-125 usiemens. Below 5.0 m conductivity increased to nearly 175 usiemens. In September, conductivity was uniform throughout the water column at 125-135 usiemens.

In the shallow water sites, conductivity increased from April through September, as it did in the deeper sections of the lake (Figure 13). Most of the shallow sites had relatively uniform conductivity with depth.

Phosphorus

Surface concentrations of TP were not significantly different between years where data was available , but were different at the bottom ($p<0.01$; Table 3; Figure 15). Surface concentrations ranged from 7-55 ug/l, with mean TP concentration in 1989 (23.68 ug l^{-1}) approximately equal to 1987 (22 ug l^{-1}), and lower than in 1974 (35 ug l^{-1}) or 1975 (33 ug l^{-1}). The highest mean bottom concentrations occurred in 1975 (77 ug l^{-1}). Mean bottom TP concentration in 1989 (58 ug l^{-1}) was higher than 1988 (42 ug l^{-1}), or 1987 (37 ug l^{-1}). The highest TP concentration in 1989 (136 ug l^{-1}) was exceeded only in 1975 (290 ug l^{-1}).

Concentrations of SRP at the surface were different between the years data was available ($p<0.001$; Table 3; Figure 16). Minimum concentrations for all years were between 1-4 ug l^{-1}, and maximum concentrations were observed in 1987 (14 ug l^{-1}) and 1989 (9 ug l^{-1}). Mean surface SRP were highest in 1987 (8.1 ug l^{-1}) and 1989 (4.7 ug l^{-1}), and both these years were significantly higher than 1974, 1975, 1986, or 1988. Bottom SRP concentrations were not significantly different between these years, with the highest concentrations in 1975 (15.5 ug l^{-1}) and 1989 (10.7 ug l^{-1}).

In 1989, TP surface concentrations were low in the spring, highest in July, and then decreased again in September-October (Table 4; Figure 17). At the bottom, maximum TP concentrations occurred in spring, coinciding with the period of low concentrations of DO. The seasonal pattern in 1989 was similar in both basins.

Concentrations of SRP in 1989, at both the surface and bottom had the highest concentrations in June and July. Bottom concentrations were consistently higher than at the surface, with the difference most pronounce in June and July and less so in May and September (Table 4; Figure 18).

Chlorophyll a

There was no significant difference in the mean chlorophyll a concentrations between the years when data was available (Table 3; Figure 19). Minimum values were all between 2-4.5 ug l^{-1}. The highest mean concentration observed (26.8 ug l^{-1}), and the highest concentration (53 ug l^{-1}) were both observed were in 1975 . All of the other years for which data is available were very similar (10-11 ug l^{-1}), with 1989 concentrations (13.7 ug l^{-1}) slightly higher (Table 4; Figure 19).

Discussion

Water quality in Lake Lawrence was monitored primarily to evaluate fish habitat quality, particularly how the water quality was associated with the growths of aquatic macrophytes. For most of the sampling period, the lake had water quality suitable for both the stocked rainbow trout (O. mykiss) and largemouth bass (M. salmoides).

The aquatic macrophytes in Lake Lawrence were primarily rooted submergents which did not form surface canopies. Development of dense surface canopies is a primary factor associated with decreased water quality conditions (Frodge et al. 1991). Surface mats developed in only limited areas in this lake, and the diffuse, sub-surface macrophytes were not associated with poor water quality. In only a very few areas of Lake Lawrence, primarily the southern end, were densities of macrophytes sufficiently high to result in significant reductions in dissolved oxygen concentrations or increased pH.

In the shallow portions of the lake (1-3 m), where rooted submergent aquatic macrophytes did not form surface canopies, the plants were associated with increased sub-surface DO. Persistence of open surface water and growing, photosynthesizing plants within the water column also contributed to higher mid-water column DO concentrations in Bull Lake, in Ellensburg, Washington, which was a much smaller and more heavily vegetated lake (Frodge et al. 1991). Similar mid-water DO maxima near the growing tips of the plant beds were reported by Dubay and Simmons (1979).

The basin morphometry of Lake Lawrence probably also influenced the distribution and density of the plants, which were generally most dense in depths under 2.5-3.0 m. The large open areas and fetch allowed wind to mix most of the lake. The increased mixing of the littoral water with the pelagic water appeared to dampen the effects patches of macrophytes had on the water quality.

The dominant physical cycle in Lake Lawrence was the development of thermal stratification of the lake in late spring after mixed conditions during the winter. The thermocline in April 1989 was at 2.5 m, with the maximum epilimnetic temperatures (23-25^{o}C) of the sampling period. The hypolimnion was anoxic over a large area during this period, probably because of the biological oxygen demand of organic material in the sediments. Conductivity in the hypolimnion, which is closely proportional to the ionic content of the water, increased as DO decreased.

The depth of the thermocline in April was not uniform over the entire lake. In the middle of the main lake, where exposure to the wind was greatest, temperature and DO were mixed to below 4 m. Also, the thermocline nearer shore, and, in areas more protected from the wind, was at 2.5 m. By mid-July, the thermocline had moved downward to 4.25 m, and the hypolimnion was restricted to the lower 2 m of the lake. In the epilimnion the water was mixed and temperature, DO, pH, and conductivity were nearly uniform, while below the thermocline pH and DO remained lower, and conductivity higher. By September, the entire water column was thoroughly mixed. Temperature, DO, pH, and conductivity were nearly uniform through the entire water column. Conductivity of the epilimnion increased as the bottom waters were mixed with the epilimnion.

This erosion of the hypolimnion was probably due to wind mixing and the unstable thermal stratification of the water column. At the warm temperatures at which stratification developed in Lake Lawrence, thermal resistance to mixing is low. The energy supplied by the wind was apparently sufficient to thoroughly mix the lake by September by downward erosion of the thermocline. The oxygen content at the sediment water interface is the most conspicuous feature regulating exchange of P between the sediments and the water (Li et al. 1972; Wetzel 1983). In many lakes, anoxic release of P over short periods of time exceeds aerobic release by an order of magnitude or more (Bostrom et al. 1982). Development of anoxic conditions over large parts of the sediments of Lake Lawrence probably resulted in sediment release of phosphorus, and may have accounted for increases in the surface phosphorus concentrations in Lake Lawrence.

Larsen et al. (1981) showed that erosion of the thermocline and mixing of hypolimnetic waters into the epilimnion by storm events could significantly increase the phosphorus concentration of the photic zone, and result in increases in phytoplankton production.

It is possible that the springtime anoxic conditions in the hypolimnion of Lake Lawrence resulted in the observed increases in phosphorus. The subsequent mixing of these waters with the epilimnion in summer could provide an almost continuous source of phosphorus, supporting the high level of phytoplankton production noted in Lake Lawrence.

In Lake Lawrence, the pelagic area is much larger than the colonizable littoral zone, which is dominated by rooted submerged species. These plants apparently oxygenated the lower portion of water column, and may have contributed to the maintenance of an oxidized barrier at the sediment water interface. Removal of these submergent macrophytes by any method, mechanical, chemical or by grass carp, may reduce inputs of oxygen to the bottom water and increase the volume of the lake with low DO.

There was no stratification in the shallow open-water areas comparable to what was observed in the deeper sections of the lake. Localized vertical stratifications in temperature, DO concentration, pH and conductivity were associated with beds of aquatic macrophytes. The lower sub-canopy temperature and DO concentrations beneath the canopies of floating leafed plants were similar to observations in several other Pacific Northwest lakes (Frodge et al. 1991).

Concentrations of DO and pH in the submergent plant beds were highest at the tops of the plants. At sites where the growth was restricted to near the bottom, DO was 2-5 mg l^{-1} higher than concentrations at the surface. Surface pH and DO concentrations above these submergent plant beds were similar to open water sites. Where submergents grew at medium depth (1-2 m), pH and DO maxima often occurred in the middle of the water column.

Maintenance of an oxygenated environment in the vegetated areas of Lake Lawrence may contribute to the maintenance of suitable habitat for fish, and may inhibit the additional release of P from the sediments. Removal of a large proportion of these plants could eliminate this sub-surface input of oxygen, resulting in degradation of fish habitat and possible elimination of the oxidized sediment barrier. Increasing anoxic areas in the lake will have a negative effect on the nutrient balance, which could lead to nuisance phytoplankton production, or reduced quality of the recreational fishery in Lake Lawrence.

In shallow lakes with limited allochthonous inputs of P and low flushing rates, the importance of sediment P cycled through aquatic macrophytes can be important and should be considered in restoration of these types of lakes (Landers 1982). Littoral macrophytes are expected to play an important role in nutrient dynamics in lakes where the ratio of colonizable littoral zone area to the pelagic zone area is large (Howard-Williams and Allanson 1981). In Lawrence Lake approximately 35% of the bottom and 10% of the surface is covered by aquatic macrophytes (DOE 1980).

Phytoplankton probably represents a larger water quality problem than the relatively low densities of aquatic macrophytes in Lake Lawrence. The macrophytes in Lake Lawrence did not form extensive surface canopies, and the areas where surface canopies formed and water quality was degraded were small. The relatively low vegetated littoral to open-water pelagic ratio in Lawrence Lake was apparently sufficient to minimize widespread macrophyte associated water quality changes, which have been observed in smaller more vegetated lakes (Frodge et al. 1990).

Restoration of Lake Lawrence should involve reductions of phosphorus (P) concentrations, which will potentially reduce the problem associated with high phytoplankton concentrations. Removal of the aquatic macrophytes by any of the accepted methods will probably lead to increases in phosphorus concentration. In several lakes in which external P loading from the watershed was reduced, internal P loading from the sediment was sufficient to maintain high P concentrations and associated nuisance conditions in the lake (Bostrom et al. 1982). If the springtime stratification and anoxic hypolimnia continue to develop, and are entrained into the photic zone of the upper water column, the high concentrations of phosphorus and phytoplankton will continue.

CHAPTER 2. POPULATION AND COMMUNITY STRUCTURE OF LAWRENCE LAKE FISHES.

Introduction

Warmwater fish communities such as that of Lake Lawrence typically utilize nearshore habitat from spring through autumn for spawning, feeding, and rearing. Aquatic macrophytes are generally confined to the shallow nearshore areas of lakes where sufficient sunlight can penetrate to the bottom and promote growth. Since both warmwater fishes and aquatic macrophytes utilize similar regions of the lake during the critical growing season, the interaction of littoral flora and fauna become a major concern when the density of aquatic macrophytes increases or decreases. As macrophyte densities change, the question becomes whether the change is beneficial or deleterious to the fish community.

The interaction of macrophytes and fish can be complex. At low to intermediate densities, aquatic macrophytes provide vertical relief and three-dimensional structure which fish use for cover. Wiley et al. (1984a) advanced the hypothesis that the biomass of insectivorous centrarchids (e.g., pumpkinseed *Lepomis gibbosus*, bluegill *Lepomis macrochirus*) increased linearly as macrophyte density increased. Wiley et al. (1984a) also hypothesized that the biomass of piscivorous fish (e.g., largemouth bass *Micropterus salmoides*) should increase with increasing macrophyte densities to a maximum at some intermediate density (i.e., 30% to 40% coverage of the littoral area) beyond which further macrophyte growth would inhibit their foraging efficiency and reduce the biomass of predators that could be supported in this habitat. Frodge (1990) proposed and supported an alternative mechanism for reductions of both insectivorous and piscivorous fishes when macrophyte densities were high and surface canopies formed. He showed that under dense canopies of aquatic macrophytes, dissolved oxygen concentrations often fell below the minimum tolerance level for most fishes. Although increasing densities of aquatic macrophytes potentially increase the physical structure available to support fish, this additional habitat might become unusable due to the associated degradation of water quality.

The relative abundance, size, and age structure of fish populations are good indicators of habitat quality. Good growth implies sufficient food availability, and good representation of each age class suggests a stable population structure in equilibrium with its environment. The relative abundance or density of the fish population is a measure of the productivity of the system. We will use these biological characteristics to assess the quality of the fish in Lake Lawrence, with particular emphasis on largemouth bass, the primary self-sustaining sport fish of interest in this system.

Methods

We collected fish samples with an electrofishing boat (Smith-Root model GPP-5.0) on the nights of June 14-16, 26-27, and July 7-8, 1989. The entire shoreline of the lake was sampled each night, but catches were recorded separately from the west and east basins of the lake. Specimens were weighed (nearest g), measured (nearest mm), and largemouth bass were tagged with either a Floy spaghetti tag (for fish $\geq$ 200 mm) or fin clipped (right pectoral fin). A subsample of the largemouth bass were stomach pumped to provide material for stomach content analysis.

Scale samples were removed from behind the pectoral fin for age and growth studies. Age and size of fish at the time of each annulus formation were determined from scale pattern analysis.

We estimated the population size of large ($\geq$ 200 mm) and small (< 200 mm) largemouth bass in the two basins using the Schnabel multiple mark-recapture method (Ricker 1975).

Predation by largemouth bass on fish prey was estimated using a bioenergetics model (Hewett and Johnson 1987) in conjunction with data from stomach analysis, and population and growth estimates of the largemouth bass population, and lake temperatures. Rice and Cochran

(1984) demonstrated that this model computed estimates of cumulative consumption that were within 10% of estimates generated entirely from field data.

Results

Fish Community Structure

The electrofishing samples in Lake Lawrence included largemouth bass (16%), brown bullhead (40%), yellow perch (30%), and pumpkinseed (12%; Figure 20). Rainbow trout were stocked annually and comprised 2% of the electrofishing catch, but were considered relatively invulnerable to electrofishing in the lake. Warmouth bass and rock bass were both captured, but each comprised less than 1% of the total catch.

Largemouth Bass

The total largemouth bass population was small with only 223 (95% confidence interval from 136 to 384) adults ($\geq$ 200 mm) and 1,175 (430 to 2938) juveniles. The relatively small weedy west basin contained 73% of the juvenile and 46% of the adult largemouth bass populations.

The size distribution of largemouth bass ranged from 30 mm to 510 mm. Fish of the size corresponding to 2-year olds were absent (Figures 20 and 21) indicating that this yearclass failed to recruit to the fishery, whereas 6-year olds were the dominant cohort, comprising 48% of the adult population. Growth was rapid and continued to 2,008 g by age 7, the oldest largemouth bass encountered (Figure 21).

The largemouth bass in Lake Lawrence has low population density (Table 5), but fast growth (Table 6) when compared with other populations in Pacific Northwest lakes.

Largemouth bass larger than 100 mm were highly piscivorous in Lake Lawrence. From largemouth bass stomach samples taken in early July, fish prey comprised 87% of the stomach contents by weight for largemouth bass between 100 mm and 200 mm, and 98% to 100% of the diet of largemouth bass larger than 300 mm. Most of the identifiable fish prey were young-of-the-year brown bullhead, followed by yellow perch (Table 7). Prey size was not correlated (r^2 = 0.05) with predator size over the size range of predators examined (128 mm to 371 mm). The mean sizes of brown bullheads, yellow perch, and unidentified fish found in the stomachs of largemouth bass were 28 mm, 46 mm, and 33 mm, respectively. Insects (12%) and other invertebrates (1%) were relatively unimportant to yearling largemouth bass during July, and even less so for the older year classes (Table 7).

The annual predation rate by yearling and older largemouth bass, based on the population structure observed in 1989 was estimated to be 1.9 metric tons of fish and 0.3 metric tons of invertebrates. These predation rates corresponded to daily ration sizes that were 58% of the maximum daily ration for yearlings, declining to 27% of the maximum for the oldest year class. These values bracket the range of ration sizes (30% to 40% of maximum ration) generally observed for largemouth bass feeding in the wild (Cochran and Adelman 1982; Hewett and Johnson 1987). If this level of predation was directed at only one yearclass of one prey species, it would equate to 4.1×10^{7} underyearling yellow perch, 1.6×10^{5} yearling yellow perch, 1.9×10^{5} underyearling brown bullheads, 9.6×10^{6} underyearling pumpkinseed, or 1.5×10^{5} yearling pumpkinseed.

Brown Bullhead

Three distinct size modes, centered at 30 mm, 130 mm, and 290 mm, were evident in the brown bullhead population (Figure 20). That the largest size group was the most abundant in the catch suggests that the younger year classes were not as vulnerable to the electrofishing gear. Forty percent of the brown bullheads sampled were captured in the west basin.

Yellow Perch

Two distinct size modes, centered at 50 mm and 120 mm, were present in the catch (Figure 20). Only the larger size class of yellow perch were recruited to the electrofishing gear. Fifty-one percent of the yellow perch sampled were captured in the west basin.

Pumpkinseed

Only one distinct size mode, at about 120 mm, was evident for the pumpkinseed population (Figure 20). However, length at age analysis revealed that this size mode contained three year classes (age 1-3) with their mean length at age ranging from 91 mm to 118 mm (Figure 22). Pumpkinseed grew relatively rapidly during their first year, and increased their weight during the second year, but grew very little thereafter. Compared with other populations, pumpkinseed in Lake Lawrence grew more quickly initially, but quit growing at an earlier age (Table 8). Sixty-seven percent of the pumpkinseed sampled were captured in the west basin.

Other Species

Three size modes of rainbow trout, centered at 90 mm, 310 mm, and 454 mm, were present in the electrofishing samples. Only 24% of the rainbow trout sampled were taken in the west basin.

Three warmouth bass and five rock bass were also captured, all but one of the former and all of the latter were captured in the west basin.

Discussion

Lake Lawrence contains relatively low densities of both game fish and forage fish relative to other warmwater lakes in the Pacific Northwest. The high growth rates of largemouth bass (and initial growth by pumpkinseed) are probably more a function of low population densities than of the productivity of the lake. That the largest catches of all warmwater fishes occurred in the weedy west basin, whereas population densities as a whole were relatively low, suggests that these species might be limited by the availability of the complex habitat offered by aquatic macrophytes (Cooper and Crowder 1979). This pattern is consistent with the relationship of macrophyte density to the biomass of piscivorous and insectivorous centrarchids hypothesized by Wiley et al. (1984a). Although Lake Lawrence macrophyte cover is 38%, which corresponds well with Wiley et al. (1984a) optimal of 40%, our data suggests that the densities of plants are slightly lower than what is needed for optimal yields of both largemouth bass and forage fishes. The macrophyte density in Lake Lawrence was too low for Frodge's (1990) habitat compression hypothesis to be applicable.

The level of piscivory was very high in Lake Lawrence in comparison with other Pacific Northwest lakes with higher densities of aquatic macrophytes (Washington

Cooperative Fish and Wildlife Unit, unpublished data). Low densities of aquatic macrophytes allow predators to forage efficiently, whereas higher densities inhibit piscivory (Cooper and Crowder 1979; Crowder and Cooper 1979; Savino and Stein 1982; Wiley et al. 1984a). The species composition and size range of prey consumed by largemouth bass probably changes seasonally because of changes in the relative abundance, availability, and vulnerability of prey. Therefore, data on prey composition in the diet gathered during just one month should be used cautiously. Nonetheless, the relatively low amount of cover available for juvenile fish probably leaves the juveniles of all species vulnerable to predation by largemouth bass throughout the growing season.

The fast growth of largemouth bass in Lake Lawrence was probably the result of the high proportion of fish prey in their diet. The high energy density of fish flesh could support the high growth rates observed for this population at a ration size that was almost half of what would be required if invertebrates were a large component of the diet. Since the estimated daily ration sizes (feeding mostly on fish) agreed with literature values for largemouth bass feeding in the wild, this lends further support to the conclusion that the largemouth bass in Lake Lawrence fed almost exclusively on fish.

The tremendous predation capacity (1.9 metric tons of fish consumed per year) estimated for a relatively small population of largemouth bass suggests that predation might be controlling the abundance and structure of the fish community in Lake Lawrence. Since the density of cover mediates the efficacy of predation, the structure and dynamics of the fish population suggest that fish production in Lake Lawrence is limited by the amount of suitable cover available for some or all critical life stages (spawning, incubation, or rearing) of the populations.

CHAPTER 3. RESULTS OF A CREEL SURVEY OF THE LAWRENCE LAKE FISHERY

Introduction

Angler surveys were made at Lake Lawrence in 1989 to: (1) characterize the sport fishery prior to the introduction of grass carp as a baseline for later comparisons, and (2) estimate fish mortality due to the sport fishery so that it can be accounted for when interpreting the effects of plant control on the fish populations. Specific objectives were to measure annual harvest, fishing effort, and harvest per angler-hour (C/f); to measure species, age, and size composition of the sport harvest; and to determine seasonal and daily use patterns that may be useful for planning future surveys.

Methods

Data Acquisition

A fixed access point survey design (Malvestuto 1983) was used to measure angler effort and C/f per angler-trip. Most angler interviews and instantaneous boat-counts were done by a biologist located at the boat launch, with supplementary sampling by boat to obtain interviews from shore anglers around the lake.

The survey schedule was based on a stratified random sampling design with effort divided between morning (8 AM to 2 PM) and afternoon (2-6 PM), weekday and weekend, and early season (April 23 to July 15) and late season (July 16 to September 10) strata. Sampling was conducted on approximately 2 weekend days and 1 weekday per month, resulting in 17 days of surveys over the fishing season (Table 9). Angler counts were made on an hourly basis during the early portion of the season, and every two hours during the latter portion.

Anglers were asked how long they had fished, whether their trip was complete, how many were in their group, and whether they had fished from shore or a boat. The biologist identified and enumerated fish that were harvested and recorded this information along with interview responses on a computer keypunch form. When possible, fish were also weighed and measured and scales were obtained for aging. Scales were mounted on gummed paper, pressed on acetate cards, and ages were determined using a microfiche reader according to methods described in Bagenal and Tesch (1978).

Data Analysis

Interview data were keypunched directly from field forms to computer files at the University of Washington School of Fisheries data entry services. A MS-DOS compatible microcomputer equipped with the SPSS-PC statistical package was used to manipulate and analyze data.

Effort was estimated for each sampling stratum, and these estimates were summed to arrive at an annual total. C/f was calculated as the ratio of harvest to effort according to the total ratio estimator method (Malvestuto 1983), and was also estimated individually for each sampling stratum. Harvest was estimated as the product of effort and C/f for individual species and all species combined. Confidence limits of harvest and effort estimates were calculated using the delta method of variance propagation (Seber 1973). Equations for these calculations follow:

$$E_{....} = \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \sum_{m=1}^{n} (F_{ijkm}/n)\ K_{ijk}$$

$E_{....}$ = annual effort (angler-hours).

F = instantaneous angler count.

K = an expansion factor equal to the total number of hours in a stratum.

i : 1, early season; 2, late season.
j : 1, weekday; 2, weekend.
k : 1, morning; 2, afternoon.
m : replicate number.
n : number of replicates (angler-counts) in a stratum.

$$H_{....} = \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \left(\sum_{m=1}^{n} C_{ijkm} / \sum_{m=1}^{n} f_{ijkm} \right) E_{ijk}$$

$H_{....}$ = annual harvest.

C = number of fish harvested by a group of anglers.
f = effort expended by a group (angler-hours).
E = total effort (angler-hours) in a stratum computed as described above.

i,j,k : same as above.
m : replicate number.
n : number of replicates (groups interviewed) in a stratum.

$$95\%\ CI(E_{....}) = E_{....} \pm 2\ SE(E_{....}) \quad \text{where}$$

$$SE(E_{....}) = \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} K^2 \ (var(\bar{F}_{ijk})/n_2)$$

$\bar{F}$ = mean angler count during a sampling stratum.
K = an expansion factor equal to the number of hours in a sampling stratum.
i,j,k : same as above.
n : number of replicates (angler-counts) in a sampling stratum.

$$95\%\ CI(H_{....}) = H_{....} \pm 2\ SE(H_{....}) \quad \text{where}$$

$$SE(H_{....}) = K^2 \ [((\bar{F}/\bar{f})^2 \ (var(\bar{C})/n_1)) + ((\bar{C}\ \bar{F}/(\bar{F}^2))^2 \ (var(\bar{f})/n_1)) + ((\bar{C}/\bar{f})^2 \ (var(\bar{F})/n_2))]$$

$\bar{F}$ = mean angler count during a sampling-stratum.

$\bar{C}$ = mean harvest per group during a sampling stratum.

K = an expansion factor equal to the number of hours in a sampling stratum.

$\bar{f}$ = mean angler-hours per group during a sampling stratum.

n_1 = number of angler groups interviewed in a sampling stratum.
n_2 = number of instantaneous angler counts in a sampling stratum.

Differences in harvest and angler effort among time strata were analyzed graphically and using analysis of variance (ANOVA) and non-parametric statistical tests

(Sokal and Rolhf 1981; Seigel and Castellan 1988). Data were log-transformed to normalize them before use in parametric ANOVA.

Results

Annual Harvest, Effort, and C/f Estimates

An estimated 24,195 angler-hours were expended to harvest 9,479 fish from Lake Lawrence during the 1989 fishing season (Table 10). Ninety-five percent confidence intervals were ± 14% of estimated effort and ± 13% of estimated harvest. Rainbow trout (Oncorhynchus mykiss) and brown bullhead (Ictalurus nebulosus) composed 85% and 13% of the harvest, respectively, and the remaining 2% of the harvest was made up of yellow perch (Perca flavescens) and pumpkinseed (Lepomis gibbosus). Overall C/f was 0.39 fish per angler-hour, and C/f for individual species ranged from 0.33 for trout to 0.01 for pumpkinseed. These harvest and C/f estimates were based on 162 angler interviews and a catch sample of 539 fish.

Seasonal Harvest, Effort, and C/f Estimates

Eighty-two percent of annual angling effort and 88% of annual harvest took place during the early season sampling period (April 23 to July 15, weeks 1-12), and the remainder took place during the late season period (July 16 to September 10, weeks 13-20; Table 11). C/f was also higher during early season (0.42) than during late season (0.26). Trout dominated the early season harvest (94% of seasonal total) and bullhead dominated the late season harvest (70% of seasonal total).

Seasonal and Daily Use Patterns

Angler effort, as indicated by instantaneous angler-counts, was compared during mornings (8 a.m. - 2 p.m.) and afternoons (2-8 p.m.), weekdays and weekends, and early (April 23 - July 15) and late season (July 15 - September 10) periods at Lake Lawrence. Effort was significantly higher (Mann-Whitney U test) on weekends than on weekdays ($p < 0.0001$), during mornings periods than during afternoon periods ($p = 0.0003$), and in early season compared with late season ($p < 0.0001$). A three-way ANOVA indicated that there were no significant interactions among time of day, time of the week, and season.

Age and Size of the Harvest

Lengths and weights were obtained from 117 fish from Lake Lawrence in 1989. Pumpkinseed, at 136 mm in mean length, were the smallest species in the harvest, and rainbow trout, at 320 mm in mean length, were the largest (Table 12). Yellow perch and brown bullhead were intermediate. All trout were age 1, perch were ages 1 and 2, and bullhead were not aged.

Discussion

Reduction of aquatic macrophytes levels from those that presently exist (approximately 38% cover) would likely have a mixed effect on the Lake Lawrence sport fishery. During summer and fall, access for anglers to nearshore areas would be improved by reductions in aquatic vegetation. Maximal production of the put-grow-and-take trout fishery would probably be obtained with 20-25% plant cover (Swanson and Bergerson 1988). Conversely, bass production is felt to be greatest at the existing level of 38% macrophyte surface cover (Wiley et al. 1984b), and bluegill and pumpkinseed production is thought to be maximal at 100% macrophyte cover (Wiley et al. 1984a) if water quality remains adequate (Frodge et al. 1991). Therefore, reductions in macrophyte cover may benefit the trout fishery, but may be detrimental to the spiny-ray fishery.

Recommendations for Future Studies

Angler use patterns observed in 1989 suggest that in future surveys, sampling effort should be concentrated early in the season, on weekends, and on mornings. Regardless, some sampling should be conducted at other times because use patterns may change due to control of nuisance macrophytes, or for other unforeseen reasons.

CHAPTER 4. AQUATIC MACROPHYTES IN LAWRENCE LAKE AND THE EFFICACY OF STOCKING STERILE TRIPLOID GRASS CARP

Introduction

Many methods are available for controlling aquatic plant populations which have reached nuisance densities. These are generally grouped into three categories: mechanical, chemical, and biological. Mechanical and chemical methods have been used previously for plant control in Washington state. The development of a sterile grass carp in the early 1980's provided the opportunity for biological control in Northwest waters. Other sections of this report examine how reduction of Lake Lawrence plant populations below their current levels may effect water quality and gamefish production. The emphasis of this chapter is to describe the Lake Lawrence plant community and evaluate the ability of grass carp to control the plant populations of this lake if plant control is desired. We had four objectives for this section of the study: (1) determining the amount of the various aquatic plant species of Lake Lawrence (2) assessing their palatability to grass carp, (3) calculating a grass carp stocking rate for Lake Lawrence and (4) investigating the potential positive and negative effects of grass carp on Lake Lawrence.

Methods

Plant Biomass and Cover Measurements

The abundance and seasonal fluctuation of each aquatic plant species were evaluated by measuring their biomass five times during their growing season (April-October). Sampling sites were chosen randomly from a grid superimposed over a map of the lake. Plants were collected from fifty sites by SCUBA using a 0.25 m^2 quadrat sampler (Purkerson and Davis 1975), transported back to the laboratory, and stored at 6°C until they could be sorted to species. They were then spun in a washing machine for 1 minute to remove excess water (Wiley and Gorden 1984) and weighed to the nearest gram. Plants were then pressed between wire screens, dried for roughly seven days on a rack equipped with fans, and weighed to the nearest tenth of a gram to assess dry weights.

Plant community surface area coverage was assessed by examination of oblique 35 mm color photographs in September 1988 and vertical 35 mm color photographs in September 1989, which were taken from fixed-wing aircraft. Photography was conducted during clear weather and as close to midday as possible to provide maximum light penetration of the water. Plant community cover was determined by digitizing using Sigma Scan software on an IBM PC.

Feeding Preference Experiments

Palatability of Lake Lawrence plant species to grass carp was determined by experiments conducted in six 4,270 l recirculating tanks. To evaluate the effect of fish size on plant preference, three tanks were each stocked with 11-16 fingerling grass carp ($\bar{x}$ = 269 ± 18 g; 264 ± 18 mm total length) and three other tanks were each stocked with 4 larger fish ($\bar{x}$ = 927 ± 148 g; 414 ± 22 mm total length) to determine if fish size had any effect on plant preference. Nine species of plants were used in the experiment: *Ceratophyllum demersum*, *Vallisneria americana*, thin-leaved *Potamogeton* spp., *Potamogeton praelongus*, *Elodea canadensis*, *Brasenia schreberi*, *Typha* spp., *Juncus* spp., *Nuphar* spp., and *Nymphaea* spp.

The experiment was conducted for three days, during which the plants were offered to the fish six times (two three-hour periods each day). At the start of the experiment, 150 g (spun weight) of each of the plant species was tied to weighted trays to closely resemble their natural growth form, and then randomly placed on the bottom of each tank. Any plants remaining after each three hour period were removed from the tanks, spun to remove excess water, and weighed to the nearest gram. At the end of each day, remaining plants were stored overnight in wading pools adjacent to the tanks. We did not replace plant species the grass carp had eaten under the assumption that the fish would remove the most palatable species first and switch to others when the most palatable were no longer available. This experiment was replicated twice to confirm preference results.

Stocking Rate Calculation

We used the "biomass" stocking rate model designed by Bonar (1990) to estimate stocking rates. This model requires inputs of air temperature data, management objectives, maximum seasonal plant biomass, and plant palatability to calculate a stocking rate.

Temperature units were calculated from 30-year monthly means obtained from nearby weather stations in Buckley and Olympia, Washington (Ruffner and Bair 1985). Calculation of temperature units available for grass carp grazing is described in Bonar (1990).

Lake Lawrence is a multi-use water body which provides habitat for many fish and wildlife species and is important for water skiing, swimming, fishing. Because total plant removal is usually not the goal for multi-use waters or those managed specifically for fisheries or wildlife, the plant management objective of Lake Lawrence was assumed to be the control of plants to a reduced level without eradication. Therefore, the control submodel of the biomass model was used for stocking rate predictions.

Plant palatability was determined through the feeding preference experiments and by comparing the dominant species of the lake to the results of other feeding experiments and field tests of grass carp preference in the Pacific Northwest (Bowers et al. 1987; Bonar 1990). The amount of palatable plants and maximum plant biomass was determined from the biomass surveys.

Four stocking rate estimates for Lake Lawrence were calculated for different management goals. Two estimates were based on the biomass of the entire plant community, which included species of low palatability, such as _B. schreberi_ and _Nymphaea_ spp. The other estimates were based only on the more palatable submergent plant community biomass.

Estimates of plant biomass are always associated with a degree of uncertainty, and were commonly ±15% in previous Washington and Oregon grass carp studies (Pauley et al. 1987, Thomas et al. 1990a). Therefore, for both the total plant community and the palatable submergent plant community, a stocking rate was calculated based on the actual maximum plant biomass. A more conservative estimate was based on the average lower 15% confidence interval of plant biomass (mean biomass - 15%). This procedure resulted in the following four stocking rate estimates: 1) entire plant community at maximum biomass, 2) entire plant community at average lower 15% C.I., 3) submergent plant community at maximum biomass, 4) submergent plant community at average lower 15% C.I.

Results

Plant Biomass

Biomass sampling revealed that the Lake Lawrence plant community was diverse (Figure 23). Dominant species in Lake Lawrence were Nymphaea spp., P. praelongus, V. americana, and E. canadensis. Other species found in the lake included Nuphar spp., C. demersum, P. crispus, B. schreberi, U. vulgaris, Chara spp., and other Potamogeton spp. Lake margins were inhabited by Typha spp. and Juncus spp.; however, these plants were not collected during the biomass sampling. Total plant biomass was low in comparison with other lakes in the Pacific Northwest that have been stocked with triploid grass carp (Figure 24).

Because of the extensive phytoplankton populations present in all aerial photographs, water transparency was not sufficient to make an exact estimate of submergent plant coverage. However, combining data from the air photos and SCUBA observations, coverage could be estimated at approximately 38% (Figure 25). This amount of plant coverage is in the range suggested as optimal by Wiley et al. (1984a) for largemouth bass production.

Feeding Experiments

Feeding experiments revealed a variation in preference of grass carp for the plant species found in Lake Lawrence (Figure 26). While _E_. _canadensis_ and the thin-leaved _Potamogeton_ spp. were preferred to _V_. _americana_, and _P_. _praelongus_, all species were eaten by grass carp during the experiment. _Brasenia_ _schreberi_ was only slightly grazed. _Typha_ spp., _Juncus_ spp. _Nuphar_ spp., and _Nymphaea_ spp. were not measurably grazed, and were left off the figure for clarity. The leaf tips of _Typha_ spp. and _Juncus_ spp., were grazed during the experiment, however the amount of grazing caused no measurable changes in plant biomass. _Nuphar_ spp. and _Nymphaea_ spp. were not grazed at all. Breaking down the results of preference experiments by the two sizes of grass carp revealed that 269 g fish may have preferred thin-leaved _Potamogeton_ spp. (TLP) to _E_. _canadensis_ while the reverse was true for the 927 g fish. Otherwise there were no discernible differences in preference by fish size (Figures 27 and 28).

Stocking Rate Calculations

A stocking rate of 9.326 fish per metric ton of vegetation was calculated to control Lake Lawrence plants within 2-5 years. Assuming the total plant community (including _B_. _schreberi_ and _Nymphaea_ sp.) had a maximum seasonal plant biomass of 1,010 g m^{-2} and the lake area was 137.38 ha, 12,940 fish (200-280 mm each) would be introduced. Basing the stocking rate on the average lower 15% C.I. of the total plant biomass (859 g m^{-2}) would require an introduction of 11,006 fish. While 15% is not the actual lower confidence interval of the Lake Lawrence maximal seasonal biomass estimate, we felt that basing the conservative estimate on the actual lower confidence interval ($\pm$ 43%) would be too low and not result in adequate plant control.

A stocking rate based on the maximum seasonal biomass of only the submergent plant community (831 gm^{-2}) would require 10,647 fish. The stocking rate based on the lower 15% C.I. of submergent plant biomass (706 g m^{-2}) would result in the planting of 9,045 fish.

Discussion

If plant control in Lake Lawrence is desired, grass carp could be used with, or as an alternative to other more conventional aquatic plant control techniques. However, like any other plant control method, grass carp are better suited for some waters than others. Therefore, the potential positive and negative aspects of using grass carp in Lake Lawrence need to be discussed.

There are several potential advantages of using grass carp for plant control in Lake Lawrence. Grass carp are inexpensive compared with other plant control methods. Each fish presently costs $3.50 with an additional \$0.63 each for shipping. Stocking 9,045 fish in Lake Lawrence would cost \$37,356 for approximately 10 years of plant control, or an annual cost of \$3,736. A comparison of grass carp with other methods of aquatic plant control for Devils Lake, Oregon (Table 13) demonstrates the low cost of using grass carp.

Fish can usually be stocked and then ignored, unlike other techniques such as harvesters and chemical applicators which need regular maintenance. Furthermore, the fish are sterile, and will eventually die off, allowing regrowth of plants if management objectives change.

The water temperature of Lake Lawrence is high enough to support vigorous feeding by the grass carp. Grass carp start feeding intensively at approximately 20°C. Since Lake Lawrence's surface temperatures were >20°C for much of the 1989 growing season (Chapter 1), low water temperatures would probably not provide a barrier to effective grazing.

Many of the nuisance plants of Lake Lawrence are quite palatable to the grass carp. *Elodea canadensis*, thin-leaved *Potamogeton* spp., *P. crispus* and *V. americana* are highly preferred. *P. praelongus*, although less preferred, was still eaten by the grass carp. Grass carp would probably remove *E. canadensis*, thin-leaved *Potamogeton* spp., and *P. crispus* first, followed by *V. americana*, *P. praelongus*, *C. demersum*, and *U. vulgaris*

(Table 14). While grass carp are removing the most palatable species, less palatable plants could temporarily colonize areas cleared of the more preferred species. Grass carp would probably not feed effectively on floating-leaved or emergent plants for several years, if at all. However, these plants are confined to shallow regions (usually < 3.5 m) and while they do comprise an important part of the aquatic plant biomass, they do not presently represent the major plant infestation in the lake by coverage.

There are also several negative factors associated with the use of grass carp. Because grass carp tend to move around water bodies extensively, they may not remove plants around docks, swimming areas, and boat launches where control is desired until palatable species in other areas of the lake are eaten first. Furthermore, since grass carp feeding behavior is affected by human activity (Swanson 1986), the fish may avoid heavily-used areas. Unfortunately, these areas are also where plant control is most often wanted. Grass carp can migrate out of water bodies, so outlet and inlets need to be screened to prevent their movement.

When stocked at moderate densities, grass carp usually take longer to control the aquatic plant community (from 2-5 years) than other plant control techniques. This can also be an advantage, since gradual reductions in aquatic plants are less likely to result in degradations of water quality caused by the plants' immediate mass mortality. A major problem in Lake Lawrence has been the development of excess algal populations, particularly blue-green (Chapter 1). Grass carp feces, along with a removal of some species of plants which may compete with phytoplankton for nutrients and light could accelerate this problem. In a survey designed to evaluate the effects of grass carp stocking in areas around the world (Bonar 1990), a highly significant number ($p < 0.01$) of respondents reported increases in phytoplankton populations following the stocking of grass carp. Grass carp may not be the best plant control method in lakes where algae currently is a problem.

Obtaining a specific degree of plant control can be very difficult using grass carp, more than many other available plant control methods. In fact, lake owners using the grass carp should be prepared to accept the risk of possible plant eradication. While 20-40% cover is usually suggested as optimal for gamefish populations (Wiley et al. 1984a; Swanson 1986), few managers have been able to achieve this using grass carp (Bonar 1990). This probably results from the large number of factors which can influence effective grass carp stocking rate and cannot be accounted for when stocking individual sites. Figure 29 shows a plot of stocking rate (number of fish per metric ton of vegetation) with temperature for sites around the world where eradication of all plants, control, and no control occurred. No statistically significant differences were found in the stocking rates used for control of different plant species, so data for individual plant species were pooled. There was a good curvilinear correlation (R^2=0.88) between air temperature and stocking rate in sites where plants were controlled (not eradicated). However, the overlap of stocking rates of sites where all plants were eradicated, controlled, and not controlled suggests that many variables can affect stocking rates besides temperature and major plant species. These variables include factors which can reduce grass carp populations, such as mortality or escapement (Swanson 1986), or those which can affect the feeding behavior of grass carp, such as water quality (Bonar et al. 1990), fish size (Prowse 1972, Bonar 1990), and human disturbance (Swanson 1986). The large variability in effective stocking rates should be considered when evaluating grass carp use for lakes containing plant communities important for fish and wildlife populations.

Because grass carp are very difficult to remove once they are stocked, it is usually preferable to stock low numbers of fish, adding more in subsequent years if control is not achieved. Therefore, we recommend the lowest, most conservative rate of 9,045 fish if grass carp are to be stocked. If the desired results are not obtained within four years, supplemental plant control may be provided as needed and/or the stocking rate can be gradually increased.

In summary, grass carp are an inexpensive, effective control of many types of aquatic vegetation, and could reduce the biomass of several problem plants in Lake Lawrence. However, there are potential negative aspects that are associated with the use of these fish which must be considered in a comprehensive management plan. For Lake Lawrence, these would include the possibility of increased algal problems; the unpredictability of control with a specific stocking rate, which could result in the potential removal of all submergent plants; and control of plants in areas where plant removal is not desired. A method of selective removal, such as harvesting or bottom barriers, may be better suited for control of plants in specific locations such as around docks, boat launches or swimming areas. The potential positive and negative consequences of an introduction of grass carp into Lake Lawrence should be carefully considered by lake managers and residents.

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Table 1. Lake Lawrence temperature, dissolved oxygen, and conductivity from the surface and at bottom (approximately 4.0 m) for 1974, 1975, 1981, 1986-89.

	mean	standard deviation	minimum	maximum	n
		1974[a] (surface)			
temperature (°C)	15.63	7.43	6.80	22.50	4
DO (mg l^{-1})	11.00	1.20	9.90	12.40	4
conductivity (usiemans cm^{-1})	62.75	7.80	53.00	70.00	4
pH			8.2	9.4	8
		(bottom)			
temperature (°C)	11.53	4.45	6.80	17.00	4
DO (mg l^{-1})	4.47	5.61	.20	12.10	4
conductivity (usiemans cm^{-1})	68.75	13.23	53.00	82.00	4
pH			6.2	8.2	4
		1975[a] (surface)			
temperature (°C)	12.93	6.77	5.80	19.80	4
DO (mg l^{-1})	11.23	1.47	9.10	12.30	4
conductivity (usiemans cm^{-1})	50.03	30.02	6.10	72.00	4
pH			7.2	8.7	4
		(bottom)			
temperature (°C)	11.05	4.45	5.90	19.50	4
DO (mg l^{-1})	6.50	5.47	0.00	12.00	4
conductivity (usiemans cm^{-1})	69.75	15.99	56.00	91.00	4
pH			6.8	7.6	4
		1981[b] (surface)			
temperature (°C)	18.30	.	.	.	1
DO (mg l^{-1})	10.00	.	.	.	1
conductivity (usiemans cm^{-1})	66.00	.	.	.	1
pH			8.1		1
		(bottom)			
temperature (°C)	13.20	.	.	.	1
DO (mg l^{-1})	0.20	.	.	.	1
conductivity (usiemans cm^{-1})	75.00	.	.	.	1
pH			7.3		1

Table 1. (continued)

	mean	standard deviation	minimum	maximum	n
		1987^b (surface)			
temperature (°C)	11.73	6.23	5.00	19.35	4
DO (mg l^{-1})	10.93	.67	10.18	11.60	4
conductivity (usiemans cm^{-1})	106.72	54.02	48.67	155.50	3
pH			5.5	7.1	8
		(bottom)			
temperature (°C)	9.62	5.52	5.75	17.80	4
DO (mg l^{-1})	7.01	4.82	.20	10.50	4
conductivity (usiemans cm^{-1})	105.06	43.72	58.67	145.50	3
pH			7.3		1
		1988^b (surface)			
temperature (°C)	15.47	8.31	5.88	25.50	7
DO (mg l^{-1})	11.27	1.26	9.43	12.85	7
conductivity (usiemans cm^{-1})	58.42	10.57	43.00	71.33	6
pH			6.1	8.6	10
		(bottom)			
temperature (°C)	12.67	6.03	5.35	20.00	7
DO (mg l^{-1})	5.47	3.96	.70	10.60	5
conductivity (usiemans cm^{-1})	85.59	40.81	54.05	162.00	6
pH			6.2	8.7	7
		1989^c (surface)			
temperature (°C)	20.14	4.74	6.50	23.04	11
DO (mg l^{-1})	9.81	1.00	8.72	12.20	11
conductivity (usiemans cm^{-1})	92.19	29.64	43.00	134.37	11
pH			6.1	9.8	71
		(bottom)			
temperature (°C)	19.06	9.34	5.35	42.00	10
DO (mg l^{-1})	4.68	3.42	.30	9.30	9
conductivity (usiemans cm^{-1})	115.42	27.31	67.50	145.50	10
pH			6.1	9.8	71

a - data from Water Supply Bulletin 1975-1976. Data on Selected Lakes in Washington.
b - data from Thurston County Health Department
c - data from this study

Table 2. Mean temperature, dissolved oxygen, and conductivity for sampling dates in Lawrence Lake in 1989. Ranges are given for pH

	East Basin						West Basin					
	surface			bottom			surface			bottom		
date	mean	CI	n	mean	CI	n	mean	CI	n	mean	CI	n
						Temperature (^oC)						
02/28	7.0		1	5.5		1	6.0		1	5.2		
05/09	20.0	0.00	12	12.0	0.00	12	19.0	0.00	12	12.0	0.00	1
05/21	23.0	0.80	19	19.0	4.26	19	19.9	3.78	13	12.0	0.45	1
06/12	19.9	2.77	19	16.4	0.59	19	19.9	0.48	16	14.9	2.57	1
07/21	22.8	0.99	19	21.9	0.90	19	22.2	0.29	18	21.1	1.82	1
09/21	23.0	0.85	11	19.8	0.66	11	19.8	1.21	11	19.0	1.01	1
10/24	20.3	2.16	21	18.4	1.64	21	21.1	0.41	6	19.4	0.98	
						dissolved oxygen (mg l^{-1})						
02/28	12.2		1									
05/09	8.4	0.45	12	9.6	0.08	12	9.4	0.11	12	9.0	0.45	1
05/21	9.3	1.04	19	6.2	4.77	19	9.5	0.47	13	7.0	1.77	1
06/12	11.7	1.27	19	3.1	3.98	19	9.2	1.02	16	1.2	0.12	1
07/21	8.3	1.12	19	5.8	0.43	19	9.5	0.51	18	5.8	4.36	1
09/21	10.5	0.23	11	7.3	4.26	11	10.2	1.21	11	4.0	3.22	1
10/24	8.5	0.82	21	7.0	2.61	21	9.6	0.58	6	11.5	2.84	
						conductivity (usiemens)						
02/28	44		1				42		1	60		
05/09	65	5.03	12	80	3.00	12	65	0.95	12	87	0.07	1
05/21	108	9.43	19	132	23.52	19	79	4.59	13	87	3.41	1
06/12	107	11.31	19	120	2.12	19	111	2.82	16	153	25.46	1
07/21	117	4.08	19	122	2.21	19	119	1.19	18	125	7.06	1
09/21	75	19.58	11	80	23.00	11	70	1.88	11	125	11.07	1
10/24	135	2.40	21	138	4.34	21	132	2.59	6	135	3.43	
						pH						
	max	min	n	max	min	n	max	min	n	max	min	
02/28	6.2		1	6.2		1	6.1		1	6.5		
05/09	8.8	6.2	12	8.7	6.4	12	7.4	7.4	12	6.5	6.2	1
05/21	8.6	8.1	19	7.6	6.8	19	8.6	6.8	13	6.2	6.1	1
06/12	8.4	7.4	19	7.3	7.3	19	8.3	6.7	16	7.9	6.4	1
07/21	8.8	6.8	19	9.0	6.5	19	8.1	6.7	18	8.0	6.8	1
09/21	9.0	8.1	11	8.3	7.1	11	9.4	7.4	11	7.7	6.7	1
10/24	9.8	7.0	1	9.2	6.6	21	9.1	8.7	6	9.8	8.2	

Table 3. Lawrence Lake total phosphorus (TP), soluble reactive phosphorus (SRP), and chlorophyll *a*, at the surface and bottom (approximately 4 m) and secchi depth for 1974, 1975, 1981, 1986-89.

	mean	standard deviation	minimum	maximum	n
		1974 (surface)			
TP ($ug\ l^{-1}$)	35.25	13.38	27.00	55.00	4
SRP ($ug\ l^{-1}$)	2.50	.58	2.00	3.00	4
chlorophyll *a* ($ug\ l^{-1}$)	10.30	4.25	4.20	14.00	4
secchi (m)	6.13	1.13			4
		(bottom)			
TP ($ug\ l^{-1}$)	117.75	117.43	41.00	290.00	4
SRP ($ug\ l^{-1}$)	26.75	43.71	2.00	92.00	4
		1975 (surface)			
TP ($ug\ l^{-1}$)	33.00	17.63	18.00	52.00	4
SRP ($ug\ l^{-1}$)	4.25	1.26	3.00	6.00	4
chlorophyll *a* ($ug\ l^{-1}$)	26.78	25.36	4.20	53.00	4
secchi (m)	5.38	2.87			4
		(bottom)			
TP ($ug\ l^{-1}$)	35.50	5.92	27.00	40.00	4
SRP ($ug\ l^{-1}$)	4.25	2.87	2.00	8.00	4
		1981 (surface)			
TP ($ug\ l^{-1}$)	20.00	.	20.00	20.00	1
SRP ($ug\ l^{-1}$)	20.00	.	20.00	20.00	1
secchi (m)	5.00	.			1
		(bottom)			
TP ($ug\ l^{-1}$)	50.00	.	50.00	50.00	1
SRP ($ug\ l^{-1}$)	30.00	.	30.00	30.00	1
		1987 (surface)			
TP ($ug\ l^{-1}$)	21.25	6.14	14.00	29.00	4
SRP ($ug\ l^{-1}$)	8.08	4.38	3.75	12.50	3
chlorophyll *a* ($ug\ l^{-1}$)	10.52	6.83	3.93	19.40	4
secchi (m)	1.90	0.49			4
		(bottom)			
TP ($ug\ l^{-1}$)	36.50	5.02	31.00	41.00	4
SRP ($ug\ l^{-1}$)	9.00	2.83	7.00	11.00	2

Table 3. (continued)

	mean	standard deviation	minimum	maximum	n
		1988 (surface)			
TP (ug l^{-1})	26.00	10.94	16.00	46.50	6
SRP (ug l^{-1})	1.67	.75	1.00	3.00	6
chlorophyll *a* (ug l^{-1})	10.45	7.54	3.22	18.88	6
secchi (m)	2.21	1.04			6
		(bottom)			
TP (ug l^{-1})	41.75	13.48	23.50	57.50	6
SRP (ug l^{-1})	5.08	4.64	1.50	13.00	6
		1989 (surface)			
TP (ug l^{-1})	24.03	7.25	19.00	38.20	6
SRP (ug l^{-1})	4.80	1.42	3.73	7.49	6
chlorophyll *a* (ug l^{-1})	13.71	11.71	3.00	47.00	21
secchi (m)	3.33	0.11			6
		(bottom)			
TP (ug l^{-1})	56.96	21.57	30.21	87.00	6
SRP (ug l^{-1})	9.50	3.33	5.92	13.83	6

a - data from Water Supply Bulletin 1975-1976. Data on Selected Lakes in Washington.
b - data from Thurston County Health Department
c - data from this study

Table 4. Total phosphorus (TP), soluble reactive phosphorus (SRP), and chlorophyll a in Lawrence Lake in 1989.

	East Basin						West Basin					
	surface			bottom			surface			bottom		
date	mean	CI	n	mean	CI	n	mean	CI	n	mean	CI	n
					Total Phosphorus (ug l^{-1})							
02/28												
05/09	17	4.32	4	79		1	24		1	95	22.35	
05/21	25	9.95	6	52	18.53	6	21	7.02	6	57	22.35	
06/12	21	13.31	6	61	13.71	6	15		1	136		
07/21	48	9.73	6	71	35.93	6	36	9.43	4	56	8.41	
09/21	19	9.98	4	30	15.28	4	21	5.99	3	35	13.54	
10/24	16	5.51	4				29	31.00	2			
					soluble reactive phosphorus (ug l^{-1})							
02/28												
05/09	3	0.85	4	10	3.63	3	5	1.38	3	11	4.38	
05/22	5		1	6		1	5		1	8		
06/12	4	2.61	6	12	2.69	6	3	0.58	3	27	3.37	
07/26	9	1.44	4	14	7.05	4	7	1.85	4	11	1.65	
09/18	4	1.96	4	6	3.00	4	4	0.97	3	7	2.66	
10/24	3	1.17	4				6	6.68	2			
					chlorophyll a (ug l^{-1})							
02/28	10		1				17		1			
05/09	13	4.43	4				24		1			
05/22	6		1				4		1			
06/12	7	4.00	2				3		1			
07/26	36		1				6	1.91	4			
08/15	20		1									
09/18	14	7.53	4				26		1			
10/24	47		1									

Table 5. Densities (#/ha.), computed from mark and recapture population estimates, of largemouth bass in Northwest lakes.

Lake	Ha.	Length (mm)	#	#/Ha.
Keevies Lake 1986	12.5	>200	2392	184.0
Keevies Lake 1988	12.5	>200	1035	79.6
Keevies Lake 1989	12.5	>200	123	9.5
East Pipeline Lake 1986	1.0	>200	354	354.0
East Pipeline Lake 1989	1.0	>200	467	467.0
Lake Washington[1]	8959.0	N/A	2600	0.3
Long Lake[2]	138.0	>200	10977	79.5
Devils Lake[3]	275.0	>180	4640	16.9
Big Chambers[4]	29.3	>200	293	10.0
Little Chambers[4]	19.9	>200	149	7.5
Lawrence[5]	137.3	>200	223	1.6

1. Stein (1970), length not available
2. Gonyea (1979)
3. Thomas et al. (1990a)
4. Thomas et al. (1990b)
5. Thomas et al. (1990c)

Table 6. Backcalculated length at age for largemouth bass from northwest lakes.

	Backcalculated Length at Annulus Formation									
	I	II	III	IV	V	VI	VII	VIII	IX	X
Keevies Lake 1986[1]	84	137	168	189	221	271	334	425	448	466
Keevies Lake 1988[1]	82	148	190	217	234	262	311	380		
Keevies Lake 1989[1]	66	138	192	217	245	263	290			
E. Pipeline 1986[1]	99	205	265	289						
E. Pipeline 1989[1]	93	186	257	309	353					
Lake Lawrence[1]	68	196	316	390	421	445	461			
Little Chambers	63	116	146	182	230	310	351	392	418	451
Big Chambers	66	118	145	168	202	267	316	349	417	
Devils Lake[4]	61	176	281	353	396	430	451	466	482	469
Oregon[5]	86	177	249	304	344	388	446	471	498	523
Oregon[6]	71	163	242	295	336	371	407	437	463	485
South Tenmile	70	163	228	269	300	323	351			
Lake Washington[7]	107	213	290	344	377	401	428	449	484	
Long Lake[8]	69	142	201	253	293	336	374	401	423	468
Lake Sammamish[9]	88	186	269	320	349	370	387			

1. Present Study, total length.
2. Thomas et al. (1990c), total length.
3. Thomas et al. (1990b), total length.
4. Thomas et al. (1990a), fork length.
5. Carlander (1977), unweighted mean of Oregon lakes, total length.
6. Unpublished data from Oregon Dept. of Fish and Wildlife, fork length.
7. Stein (1970), Lake Washington, Washington, total length.
8. Gonyea (1979), Long Lake, Washington, total length.
9. Pflug (1981), Lake Sammamish, Washington, total length.

Table 7. The percentage prey composition of different size classes of largemouth bass during July 1989 in Lake Lawrence.

Size	N	Insects	Other Invert.	Brown Bullhead	Yellow Perch	Unidentified Fish
100-200 mm	10	12%	1%	32%	8%	47%
200-300 mm	0	---	---	---	---	---
300-400 mm	1	2%	0%	15%	0%	83%
400-500 mm	1	0%	0%	0%	0%	100%

Table 8. Mean length at age of pumpkinseed in Lake Lawrence, Keevies Lake, and East Pipeline Lake captured during spring or summer 1989.

	Mean Length (mm) at Age						
	I	II	III	IV	V	VI	VII
Lake Lawrence[1]	91	118	112				
Keevies Lake[2]	69	114	146	144	151		
East Pipeline[2]	57	121	149	156	164	172	
Carlander[3]	70	103	124	137	160	179	

1. Present study, 1989 samples (total length).
2. Thiesfeld et al. (Unpublished data)
3. Carlander 1977 (total length).

Table 9. Sampling schedule for the 1989 Lawrence Lake creel survey. The fishing season ended September 10. □ = morning (8 a.m.-2 p.m.), ○ = afternoon (2-8 p.m.).

Month	Week	Su	Mo	Tu	We	Th	Fr	Sa
		Day of the week and month						
April	1	$\boxed{23}$	24	25	26	27	28	29
	2	$\boxed{30}$						
May	2		1	2	3	4	5	6
	3	$\boxed{7}$	8	9	10	11	12	13
	4	14	15	16	17	18	19	20
	5	$\boxed{21}$	22	23	24	25	26	27
	6	28	29	30	31			
June	6					1	2	3
	7	4	5	6	7	8	$\boxed{9}$	10
	8	11	12	13	14	15	16	17
	9	18	19	20	21	22	23	24
	10	25	26	27	28	29	30	
July	10							1
	11	2	3	4	5	6	7	8
	12	9	10	11	12	13	14	15
	13	16	17	18	19	20	21	22
	14	23	24	25	26	27	28	29
	15	30	31					
Aug	15			1	2	3	4	$\boxed{5}$
	16	6	7	8	9	10	11	12

Table 9. Continued.

Month	Week	Su	Mo	Tu	We	Th	Fr	Sa
		Day of the week and month						
	17	13	14	15	16	17	$\boxed{18}$	19
	18	20	21	22	23	24	25	26
	19	27	28	29	30	31		
Sept	19						1	2
	20	3	4	5	6	7	8	9
	21	$\boxed{10}$	11	12	13	14	15	16
	22	17	18	19	20	21	22	23
	23	24	25	26	27	28	29	30
Oct	24	1	2	3	4	5	6	7
	25	8	9	10	11	12	13	14
	26	15	16	17	18	19	20	21
	27	22	23	24	25	26	27	28
	28	29	30	31				

Table 10. Annual harvest, effort and C/f estimates for the 1989 Lake Lawrence sport fishery.

	Harvest		Effort (angler-hours)		
Species	Estimate	Confidence interval	Estimate	Confidence interval	C/f
bullhead	1245	935- 1554	24195	20921-27469	.051
y. perch	194	142- 246	"	"	.008
trout	8026	6774- 9277	"	"	.332
pumpkinseed	14	9- 19	"	"	.001
total	9479	8076-10882	"	"	.392

Table 11. Seasonal harvest, effort, and C/f estimates for the 1989 Lake Lawrence sport fishery.

Season[1]	Species	Harvest	Effort (angler hrs.)	C/f
early	bullhead	460	19802	.023
	y. perch	93	"	.005
	trout	7804	"	.394
	pumpkinseed	0	"	.000
	total	8358	"	.422
late	bullhead	784	4393	.178
	y. perch	101	"	.023
	trout	222	"	.051
	pumpkinseed	14	"	.003
	total	1121	"	.255

[1] Early season, April 23 to July 15; late season July 16 to September 10.

Table 12. Mean length and weight of fish in the 1989 Lake Lawrence sport harvest.

Species	Length (mm)		Weight (g)		Sample size
	mean	SD	mean	SD	
bullhead	287	21.1	308	62.0	78
y. perch	209	42.3	148	146.8	8
trout	320	37.4	403	154.9	30
pumpkinseed	136	--	60	--	1

Table 13. Estimated annual costs of various treatments for Devils Lake macrophyte control (assumes 300 veg. acres).

Method	Annual Cost
Grass Carp	$10,200[1]
Harvesting	$117,500 - $200,000[2,3]
Dredging (one time cost)	$1,100,000[2]
Herbicides	$54,000 - $65,000[2,3]

[1]Bonar 1990
[2]Liao and Grant 1983
[3]Terry McNabb, Aquatics Unlimited, Pers. Comm.

Table 14. Ranking of Lake Lawrence macrophyte palatability based on triploid grass carp feeding preference. Preferences were developed from Lake Lawrence feeding experiments and the results of Bowers et al. 1987. Preference within groups is not ordered.

Highly Preferred Macrophytes

Elodea canadensis
Thin-leaved *Potomogeton* spp.
P. crispus
Vallisneria americana

Moderately Preferred Macrophytes

P. praelongus
Ceratophyllum demersum
Utricularia spp.
Other Broad-leaved *Potamogeton* spp.

Non-preferred Macrophytes

Brasenia schreberi
Nymphaea spp.
Typha spp.
Juncus spp.
Nuphar spp.

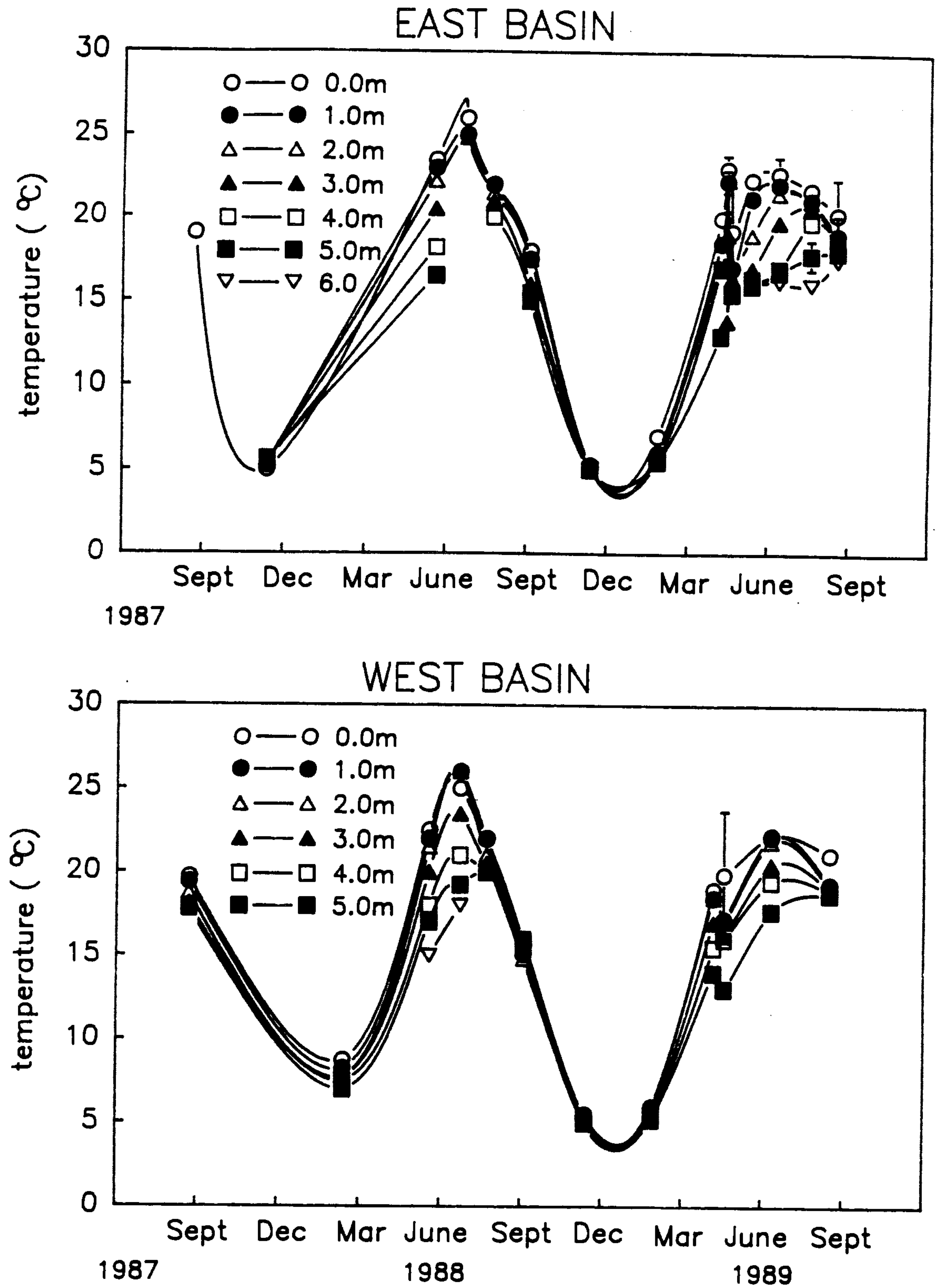


Figure 1. Mean temperature at 1.0 m depth intervals in the east and west basins of Lake Lawrence from 1987 to 1989.

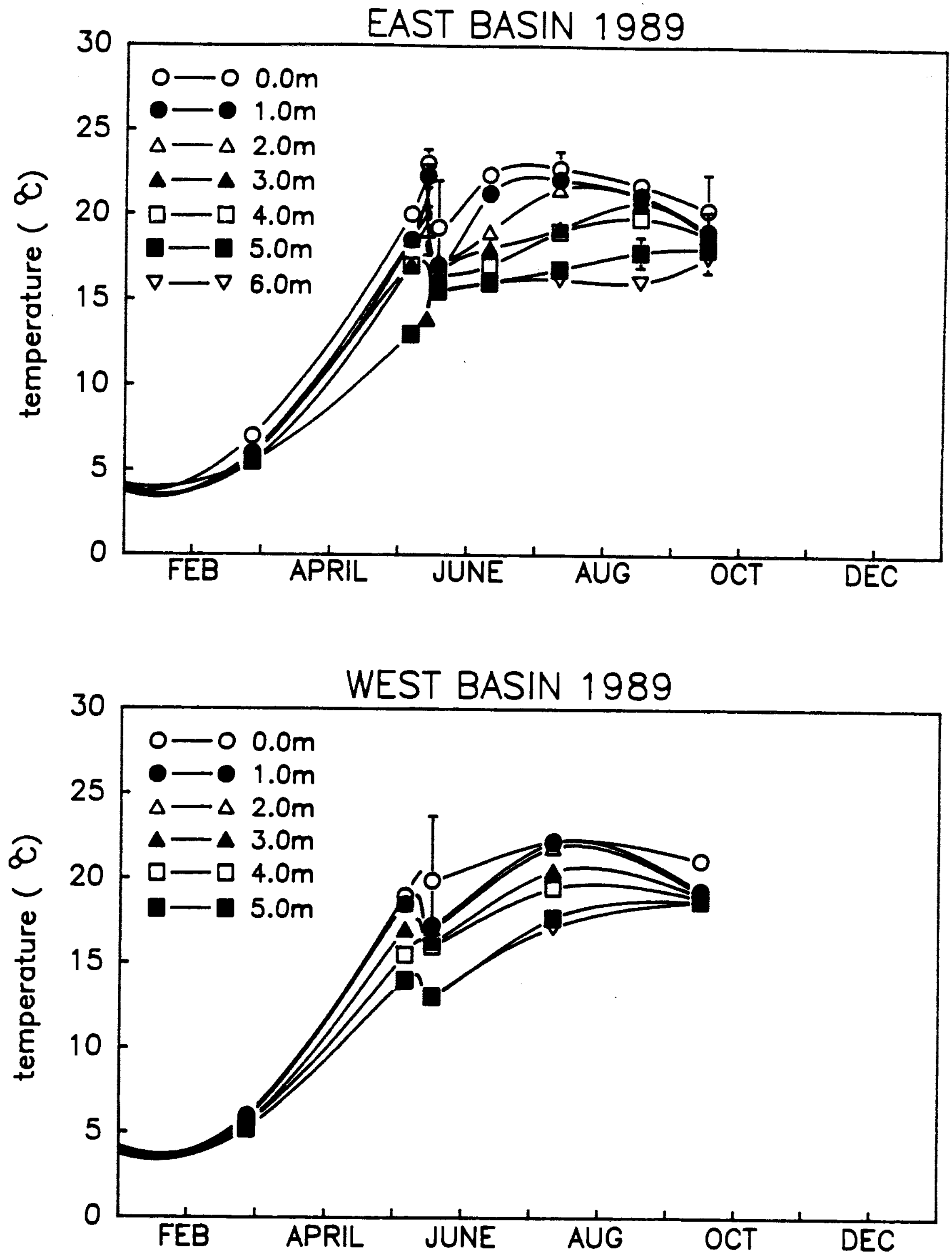


Figure 2. Mean temperature at 1.0 m depth intervals in the east and west basins of Lake Lawrence in 1989.

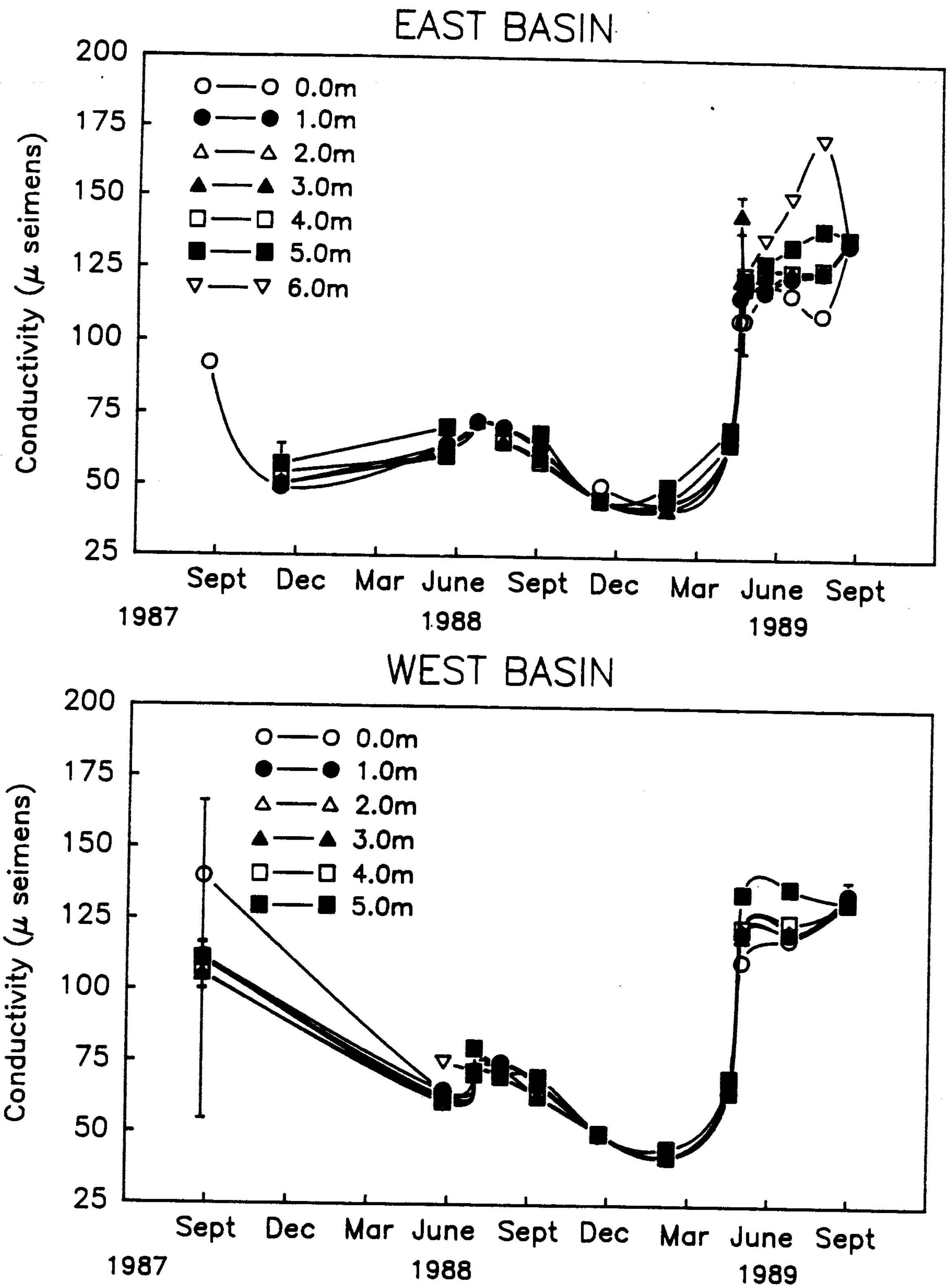


Figure 3. Mean conductivity at 1.0 m depth intervals in the east and west basins of Lake Lawrence from 1987 to 1989.

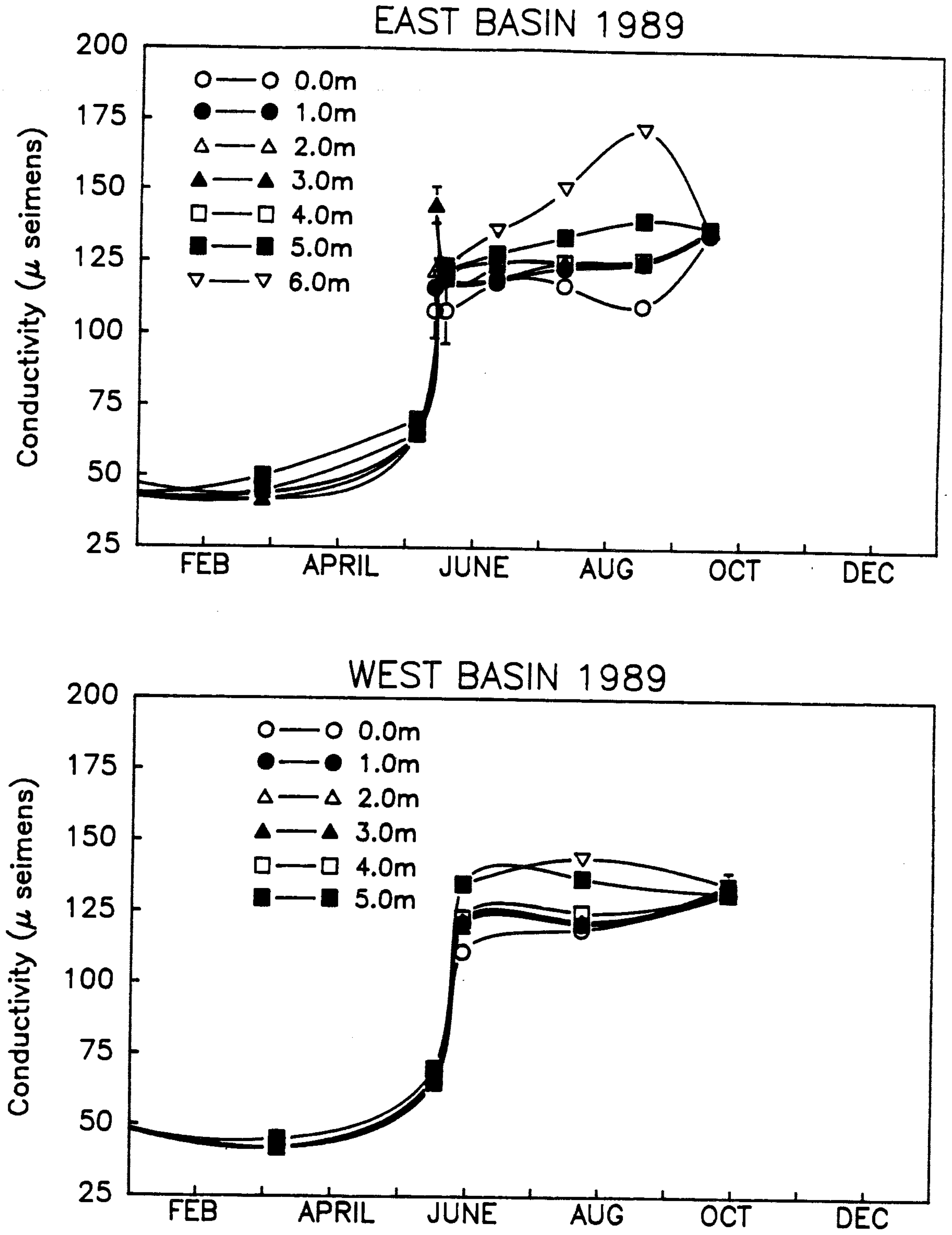
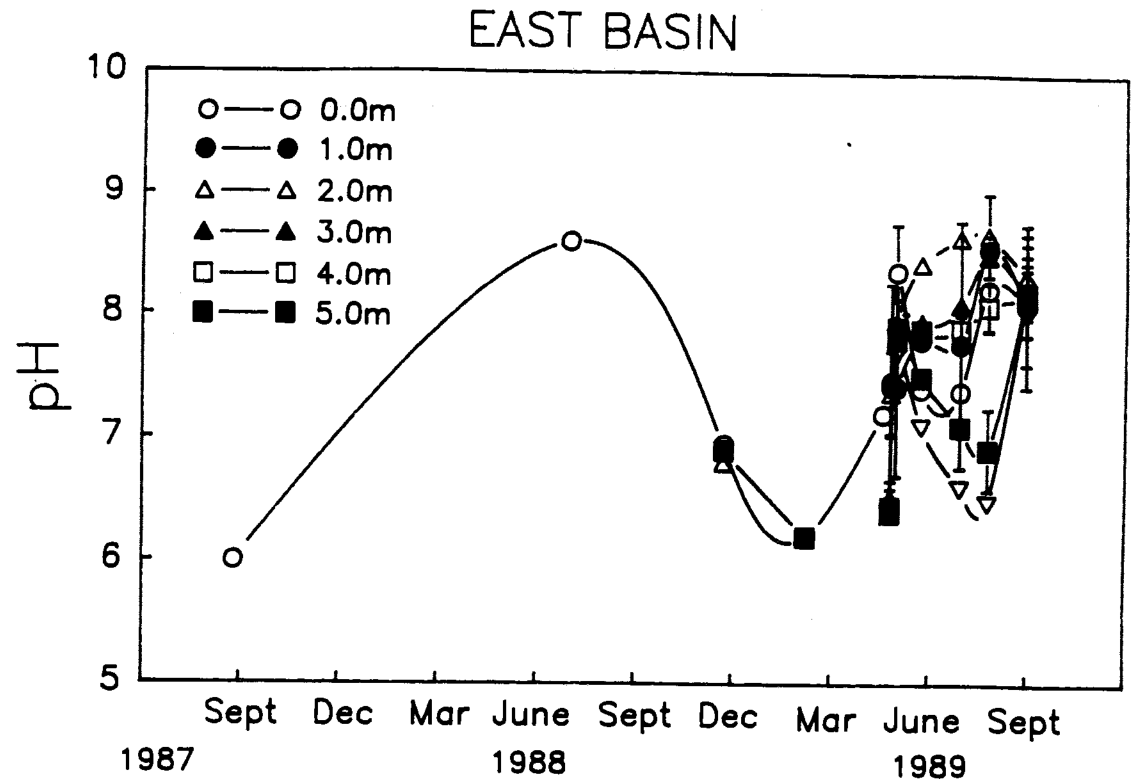


Figure 4. Mean conductivity at 1.0 m depth intervals in the east and west basins of Lake Lawrence in 1989.



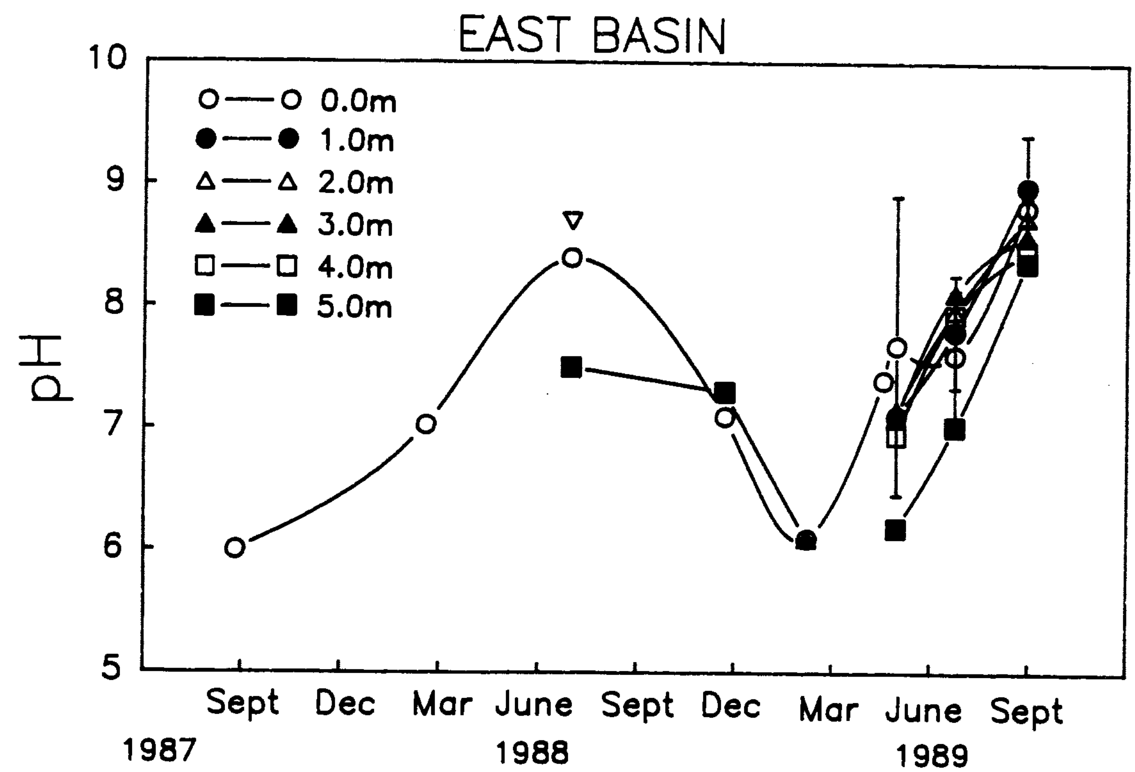


Figure 5. Lake Lawrence pH at 1.0 m depth intervals in the east and west basins from 1987 to 1989.

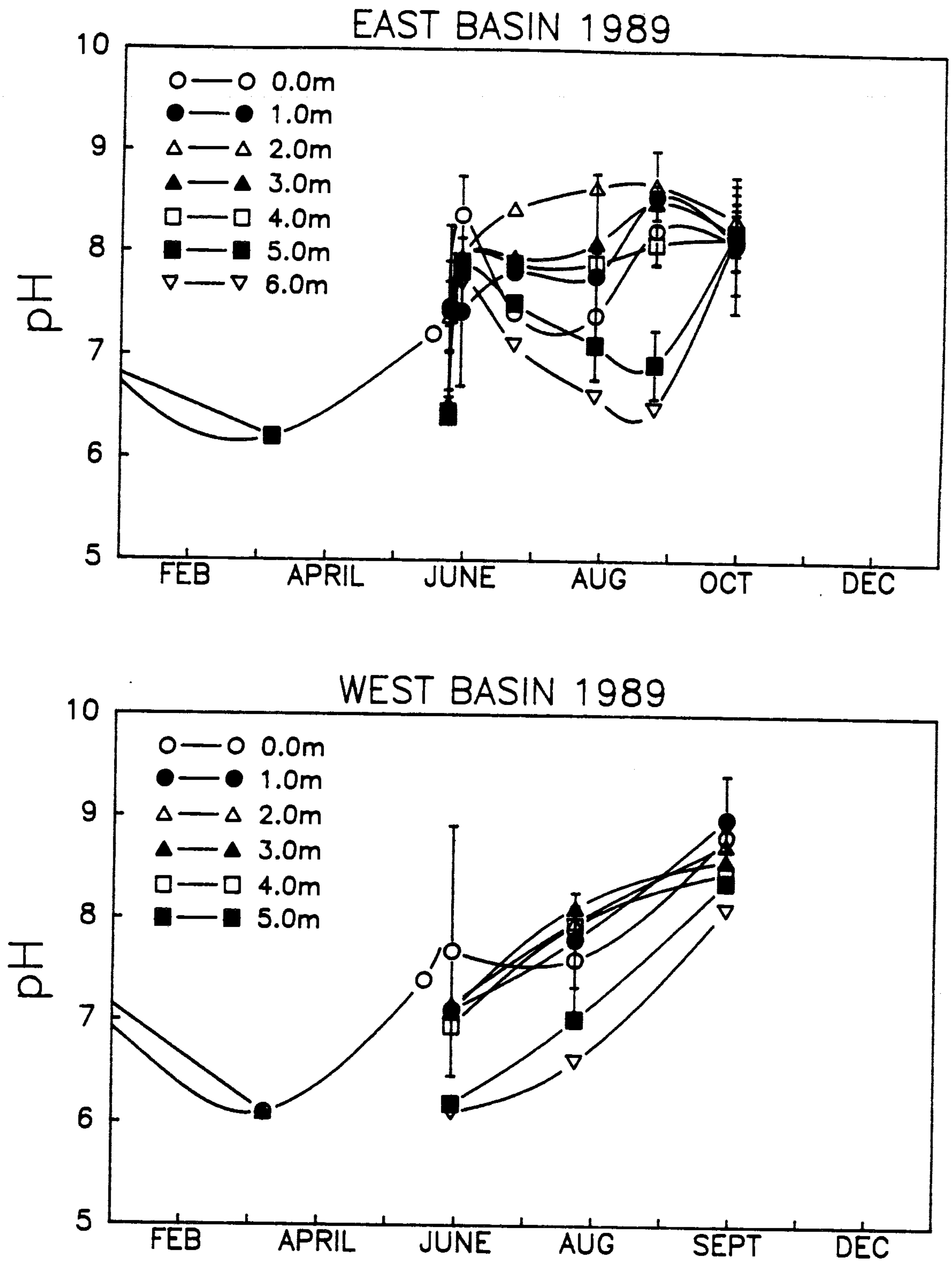
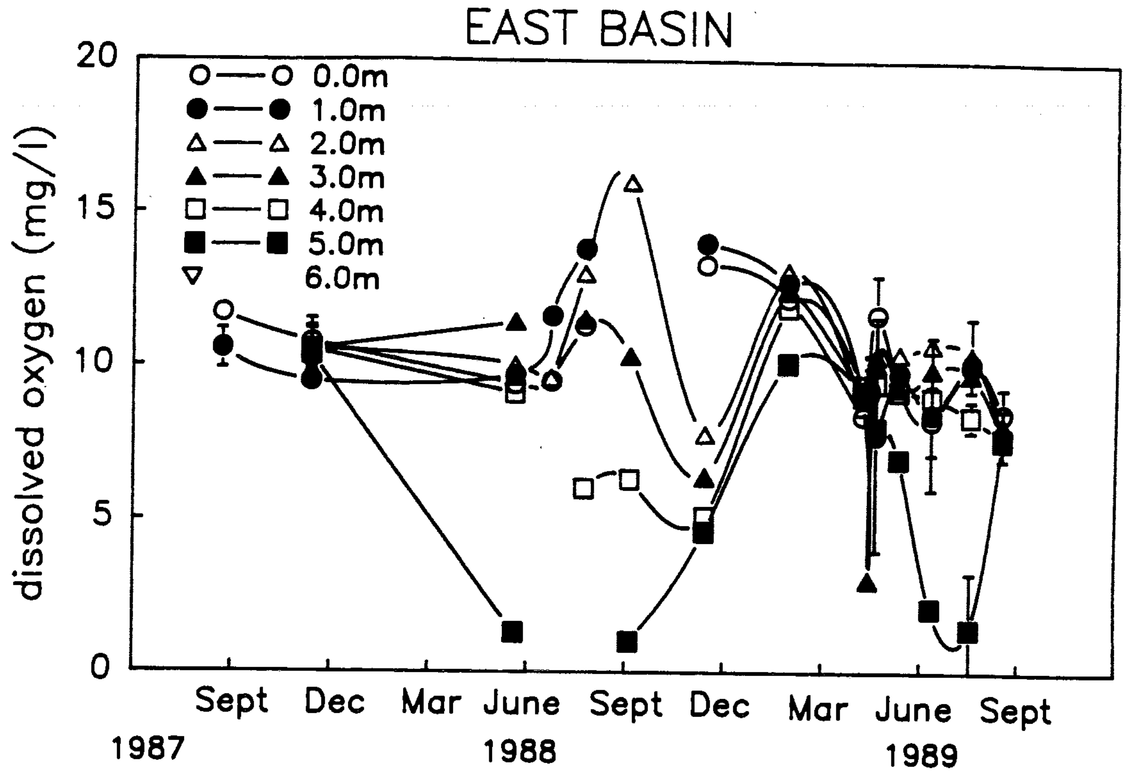


Figure 6. Lake Lawrence pH at 1.0 m depth intervals in the east and west basins in 1989.



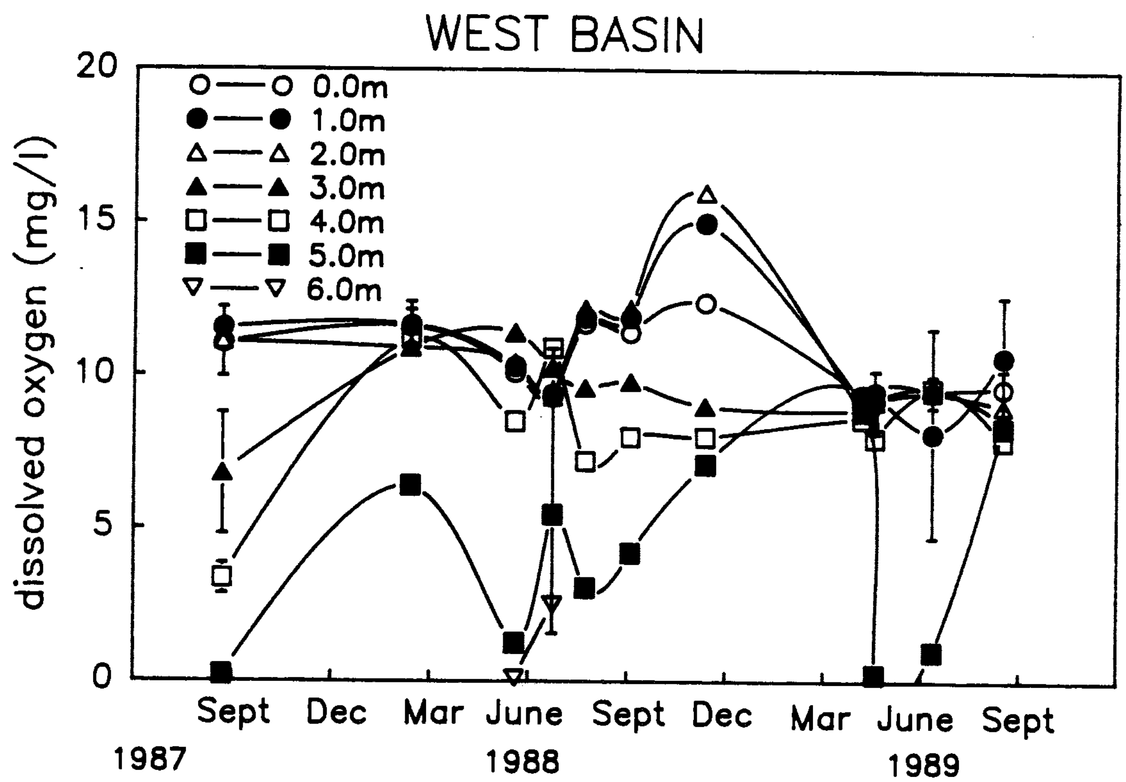


Figure 7. Mean dissolved oxygen concentrations at 1.0 m depth intervals in the east and west basins of Lake Lawrence from 1987 to 1989.

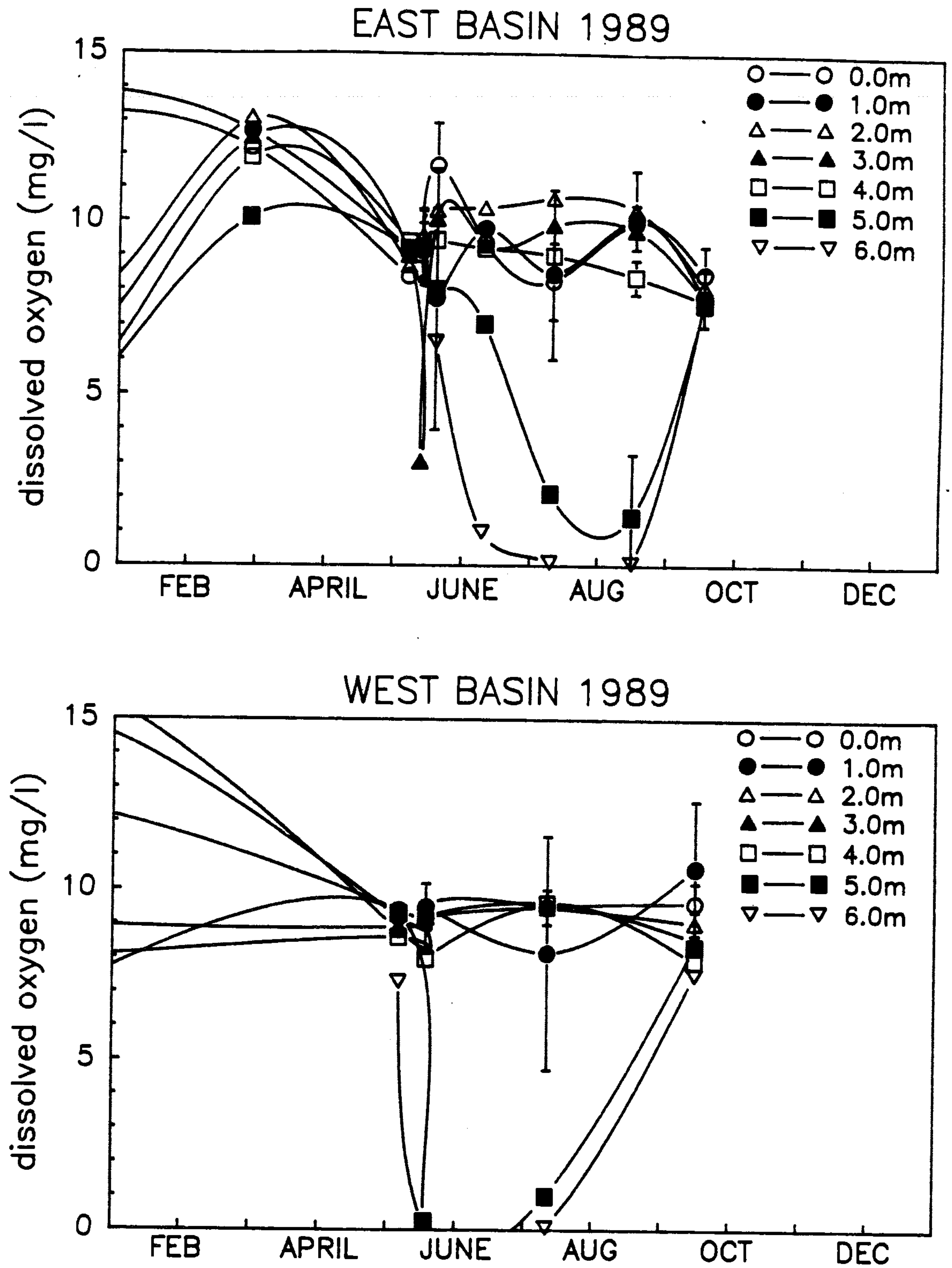


Figure 8. Mean dissolved oxygen concentrations at 1.0 m depth intervals in the east and west basins of Lake Lawrence in 1989.

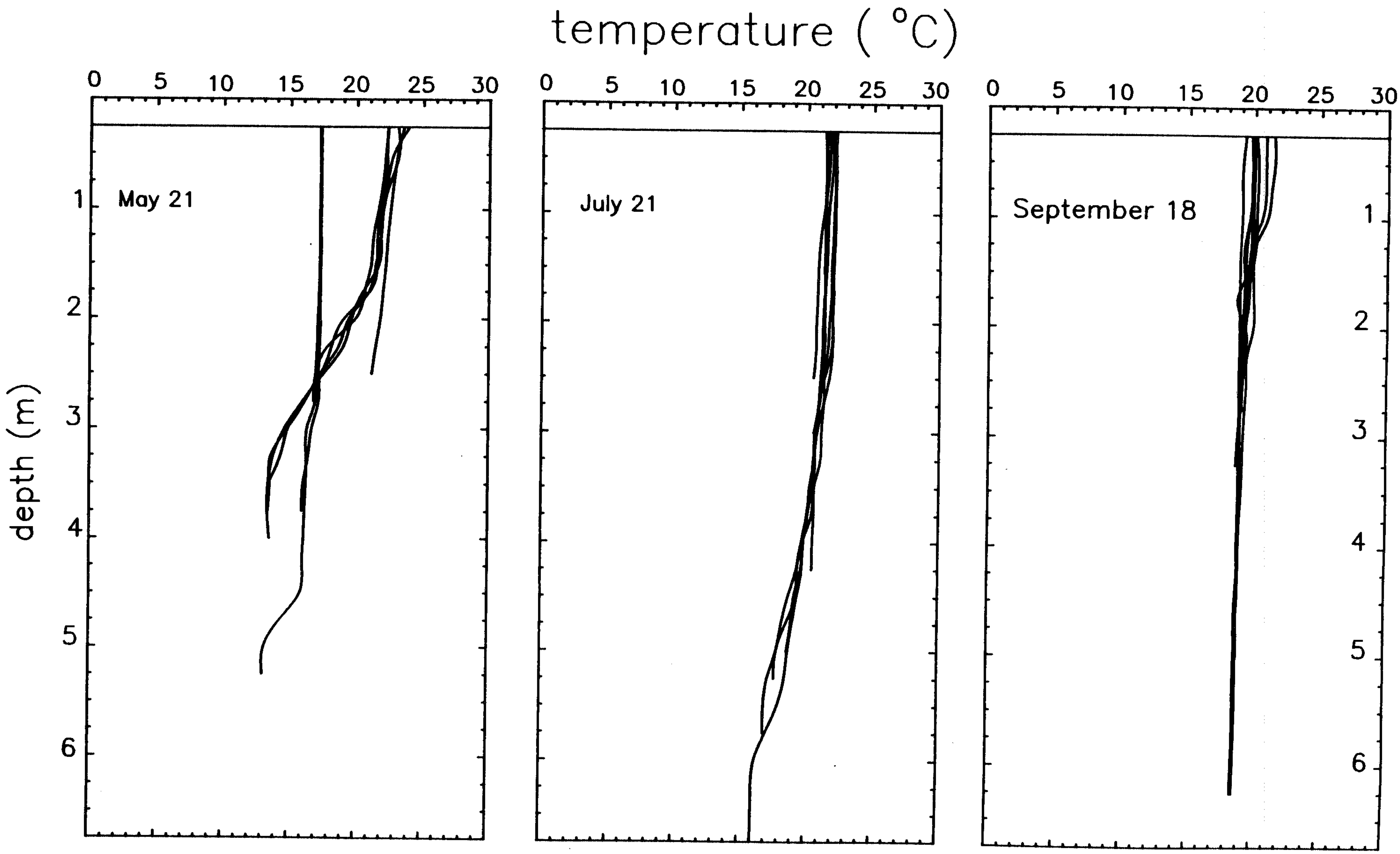


Figure 9. Temperature (^{o}C) by depth at individual random sampling sites deeper than 2.0 m on May 21, July 21 and September 18, 1989.

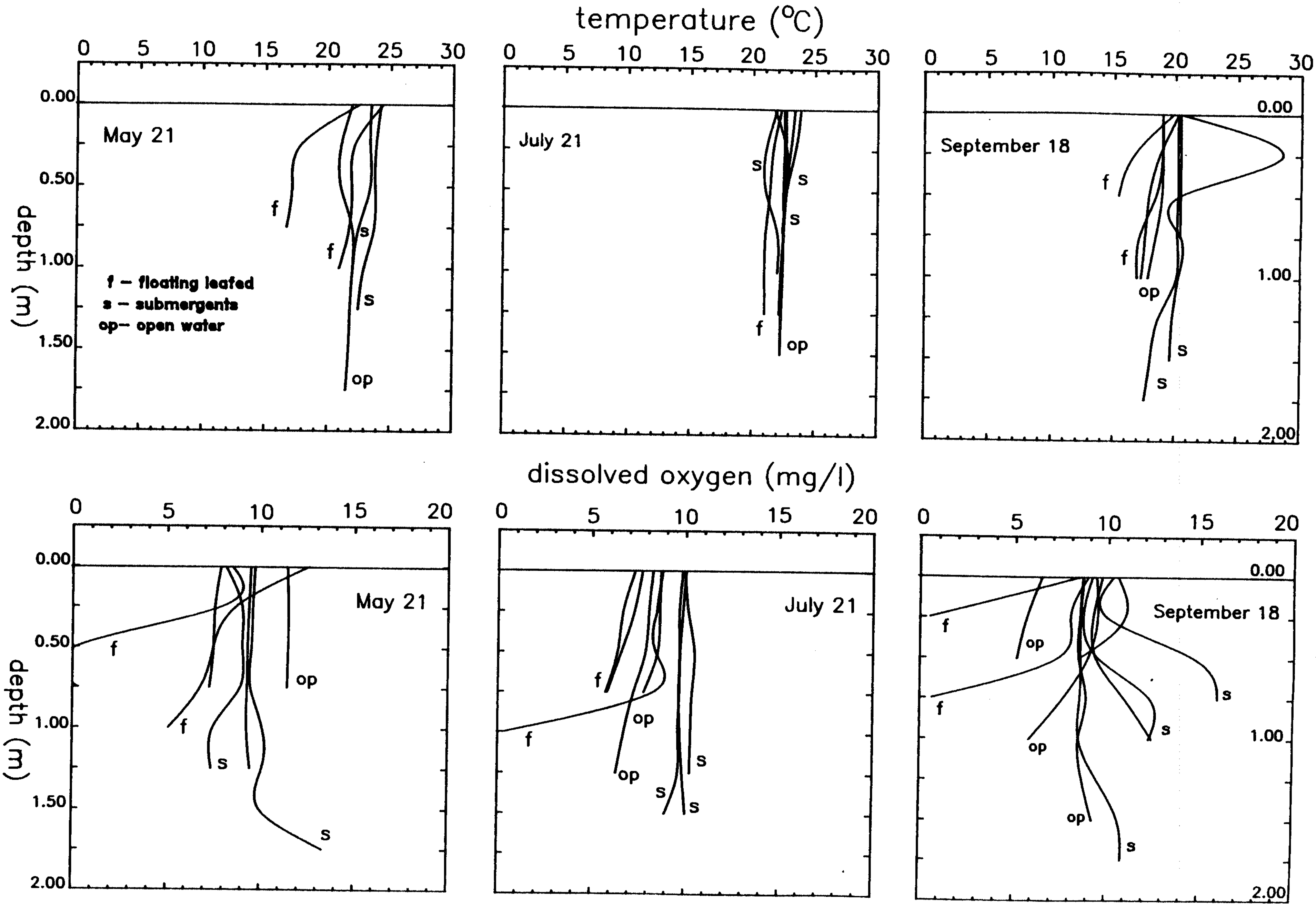


Figure 10. Temperature (^{o}C) and dissolved oxygen ($mg\ l^{-1}$) by depth at individual random sampling sites <2.0 m on May 21, July 21 and September 18, 1989.

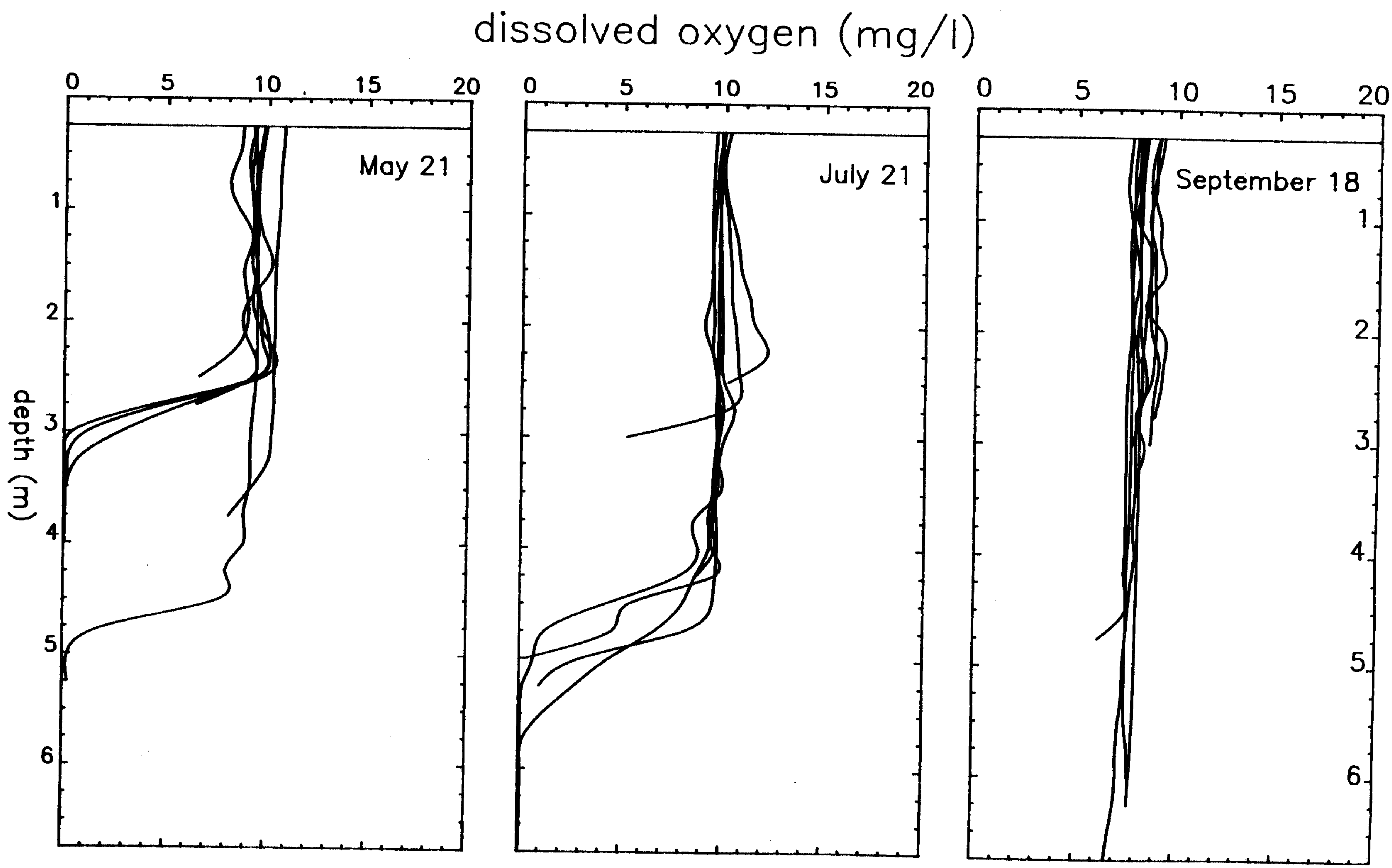


Figure 11. Dissolved oxygen (mg l^{-1}) by depth at individual random sampling sites deeper than 2.0 m on May 21, July 21 and September 18, 1989.

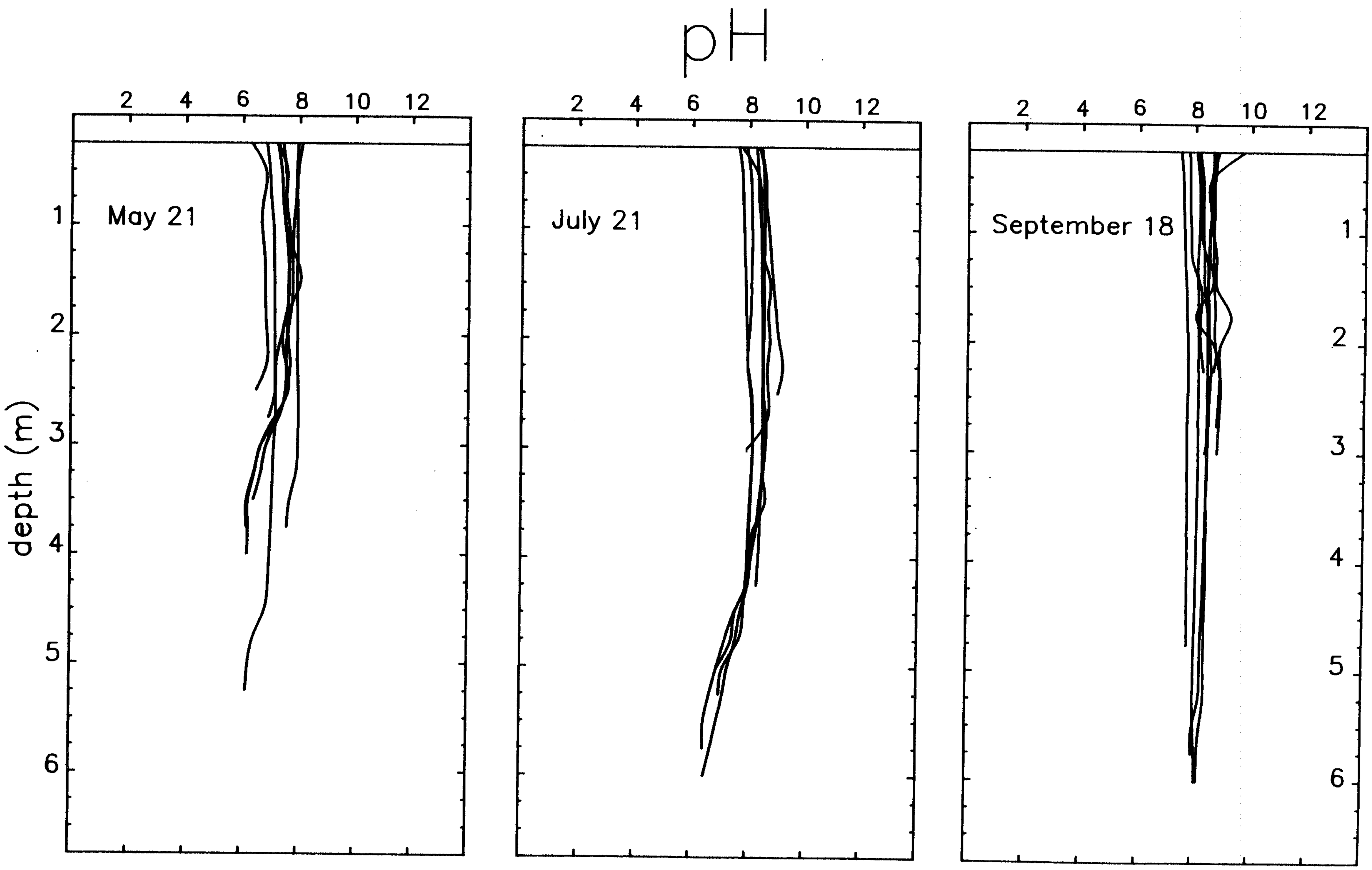


Figure 12. Lake Lawrence pH by depth at individual random sampling sites deeper than 2.0 m on May 21, July 21 and September 18, 1989.

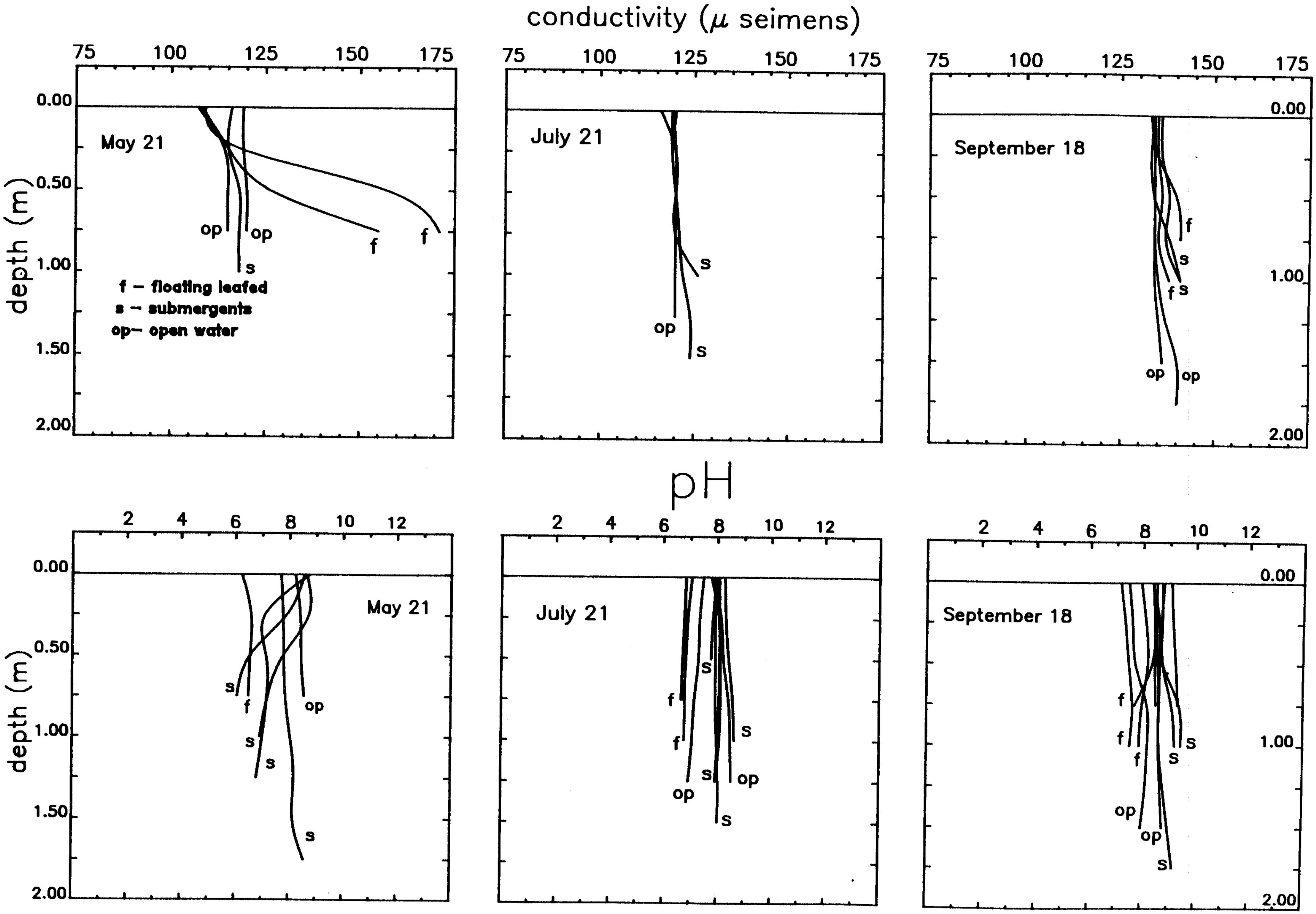


Figure 13. Lake Lawrence conductivity and pH by depth at individual random sampling sites <2.0 m on May 21, July 21 and September 18, 1989.

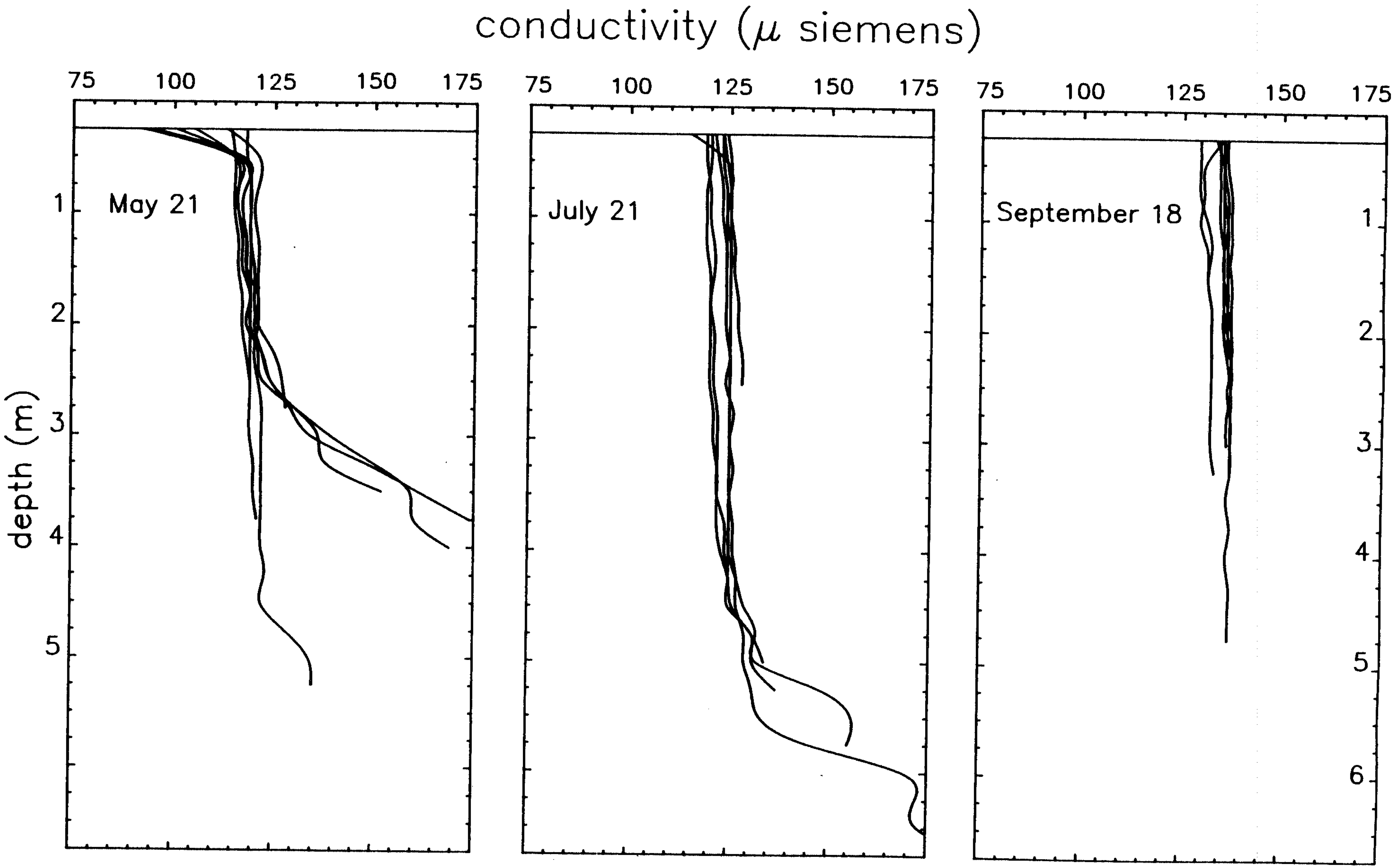


Figure 14. Conductivity by depth at individual random sampling sites deeper than 2.0 m on May 21, July 21 and September 18, 1989.

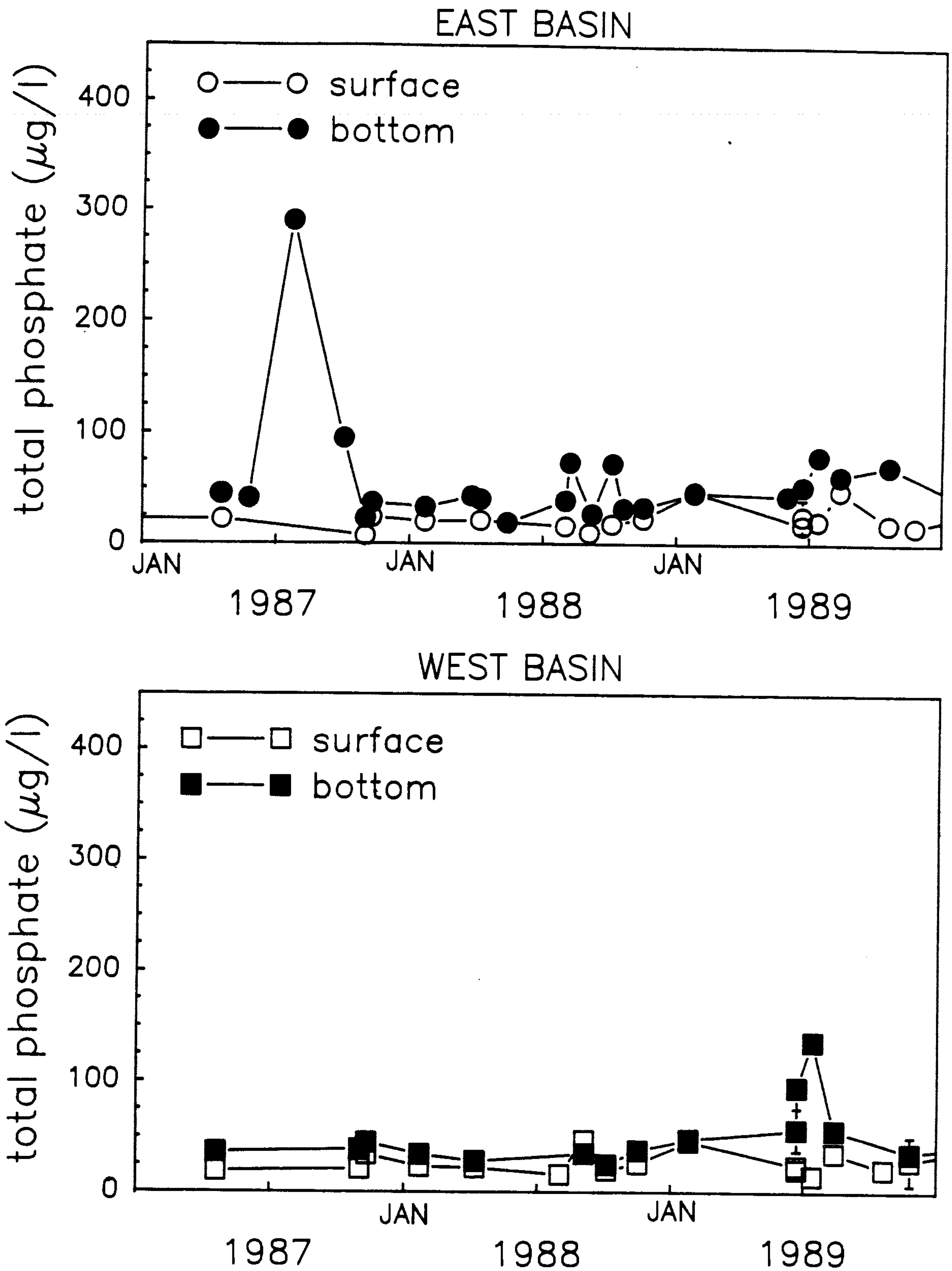


Figure 15. Mean total phosphorus (ug l^{-1}) in the east and west basins of Lake Lawrence from 1987 to 1989.

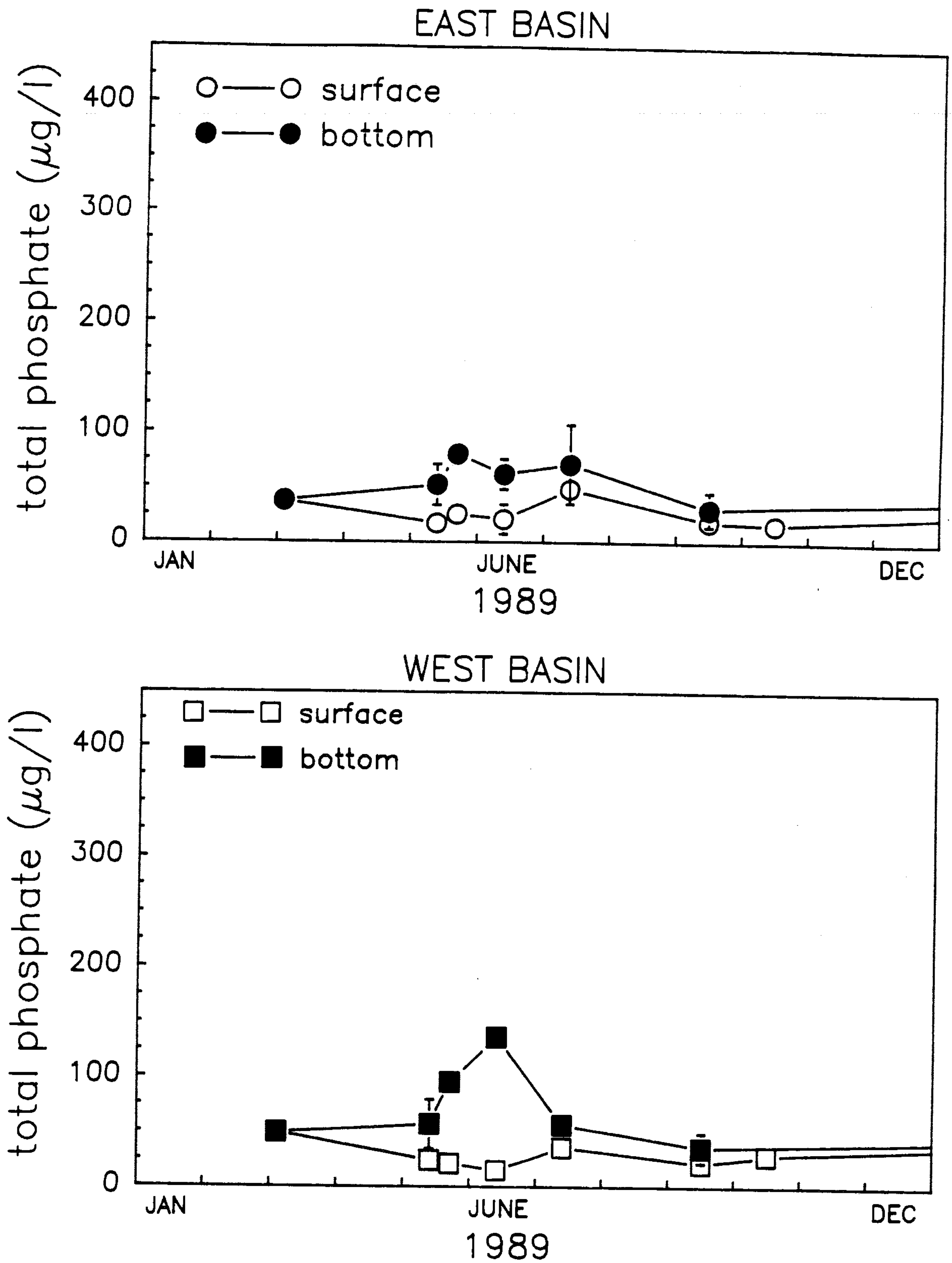


Figure 16. Mean soluble reactive phosphorus (ug l^{-1}) in the east and west basins of Lake Lawrence from 1987 to 1989.

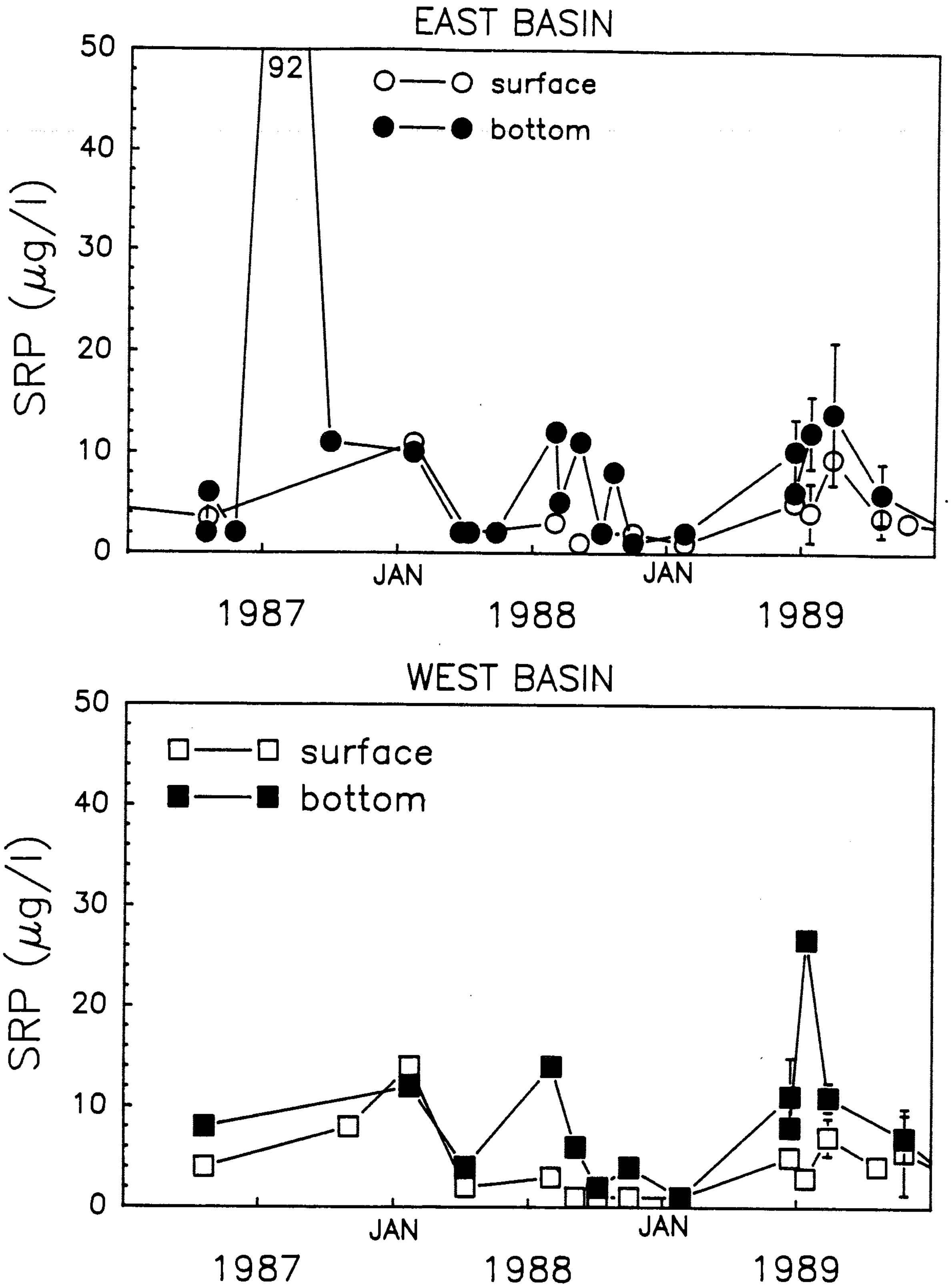


Figure 17. Mean total phosphorus (ug l^{-1}) in the east and west basins of Lake Lawrence in 1989.

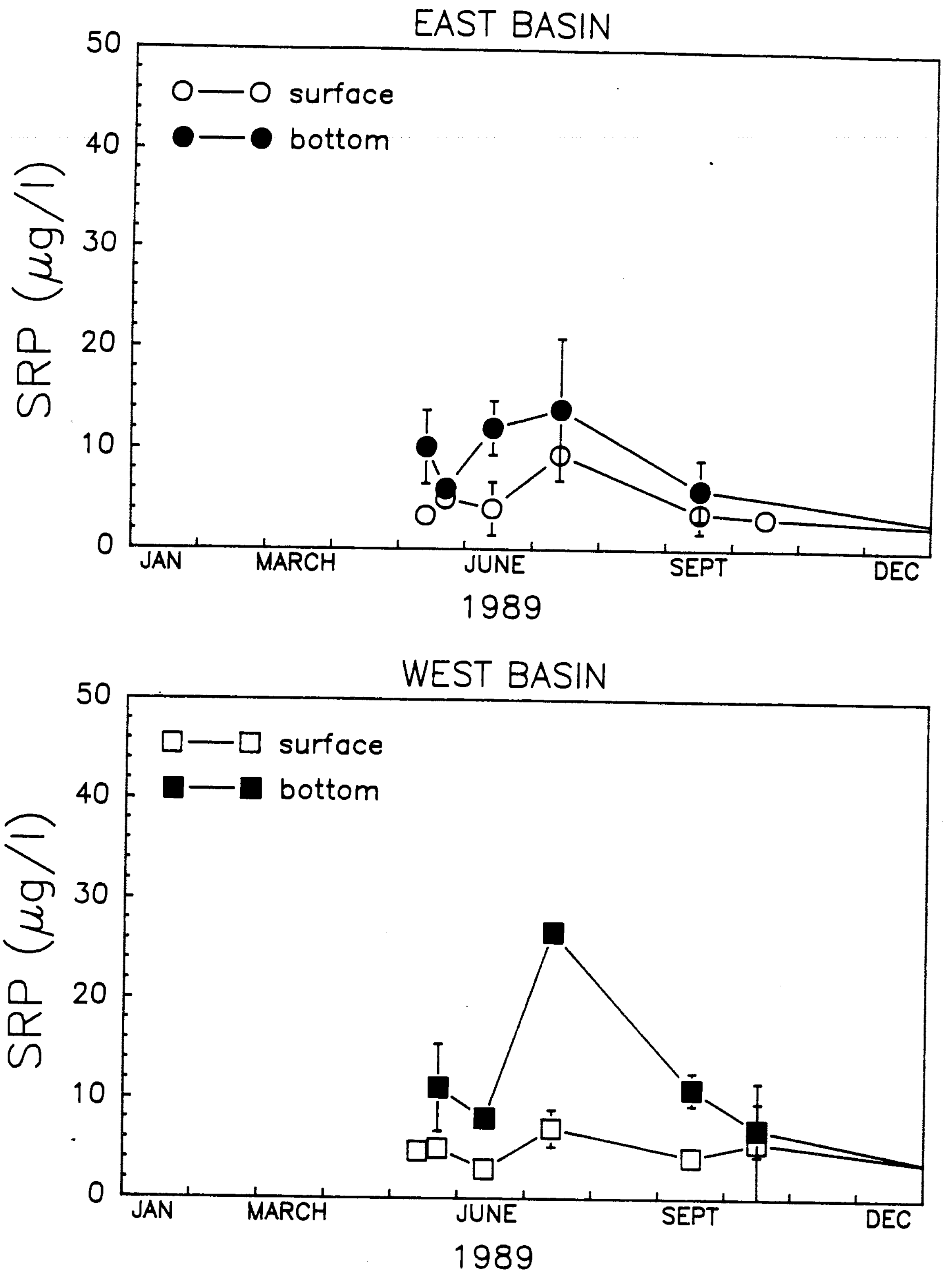
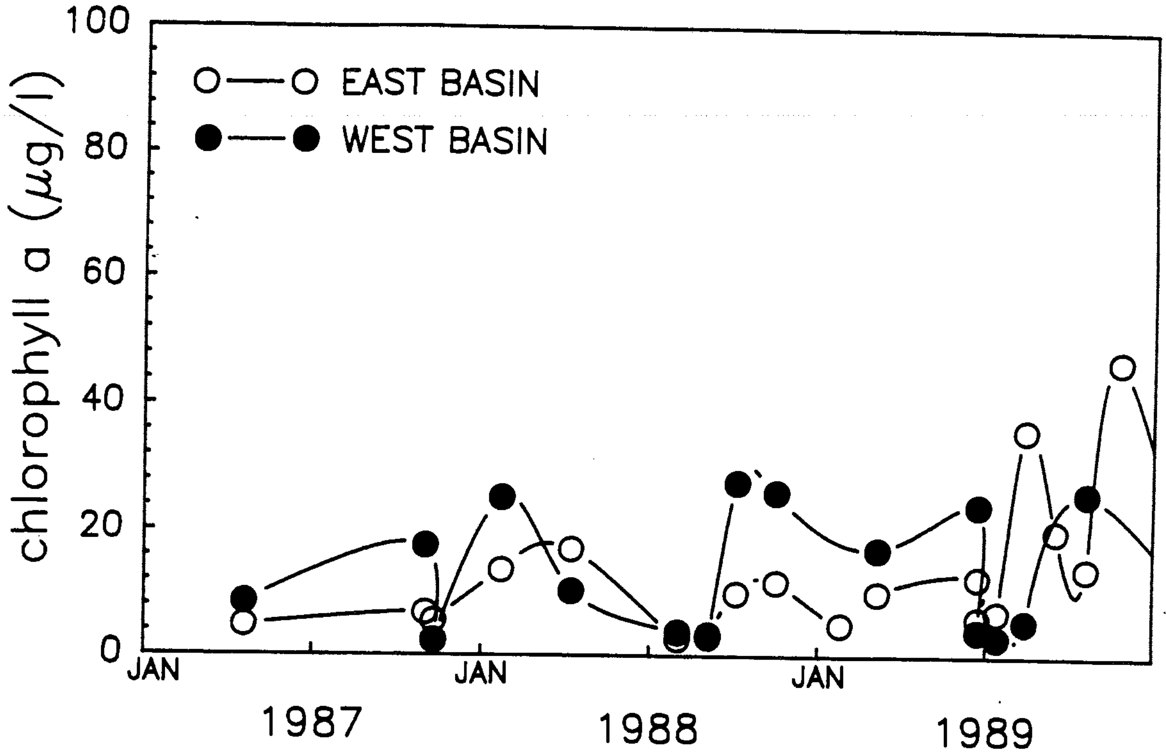


Figure 18. Mean soluble reactive phosphorus (ug l^{-1}) in the east and west basins of Lake Lawrence in 1989.



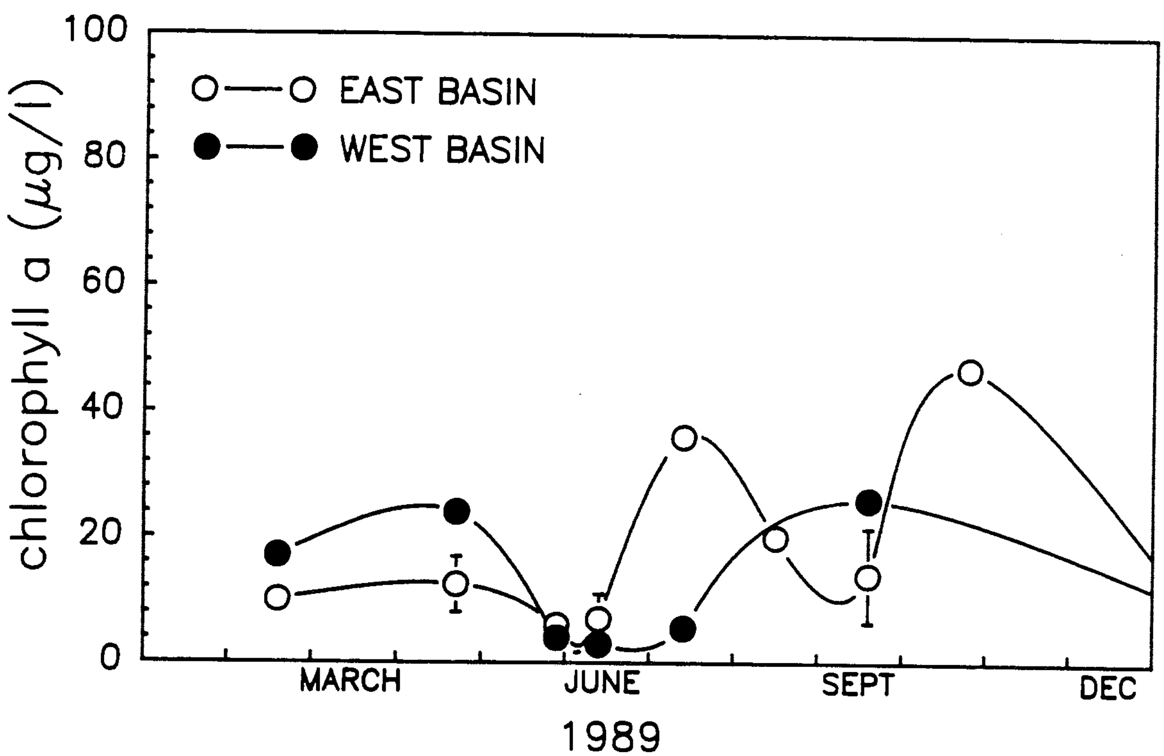


Figure 19. Chlorophyll a in the east and west basins of Lake Lawrence a) from 1987 to 1989 and b) in 1989.

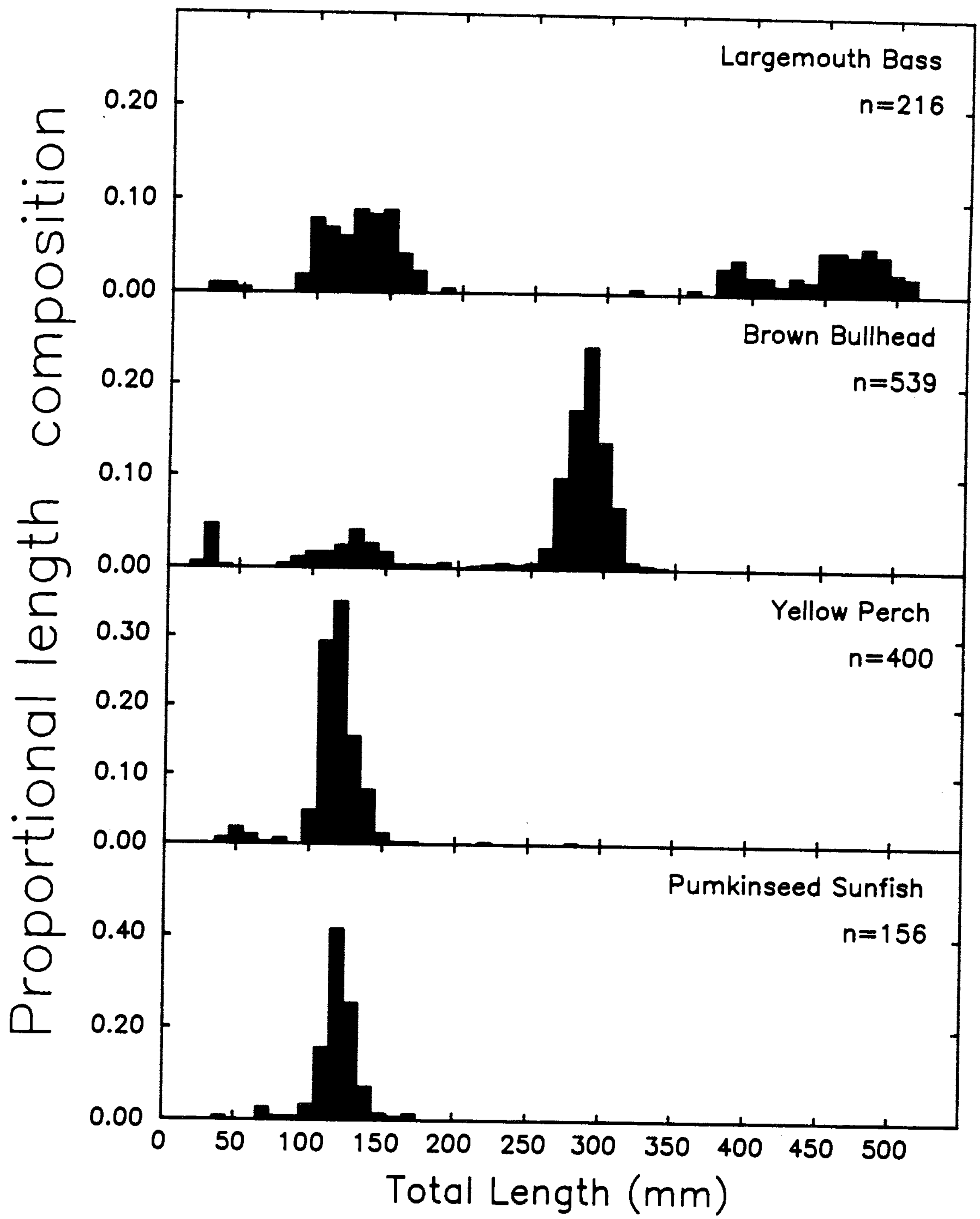


Figure 20. Length-frequency histograms for four fish species in Lawrence Lake in 1989.

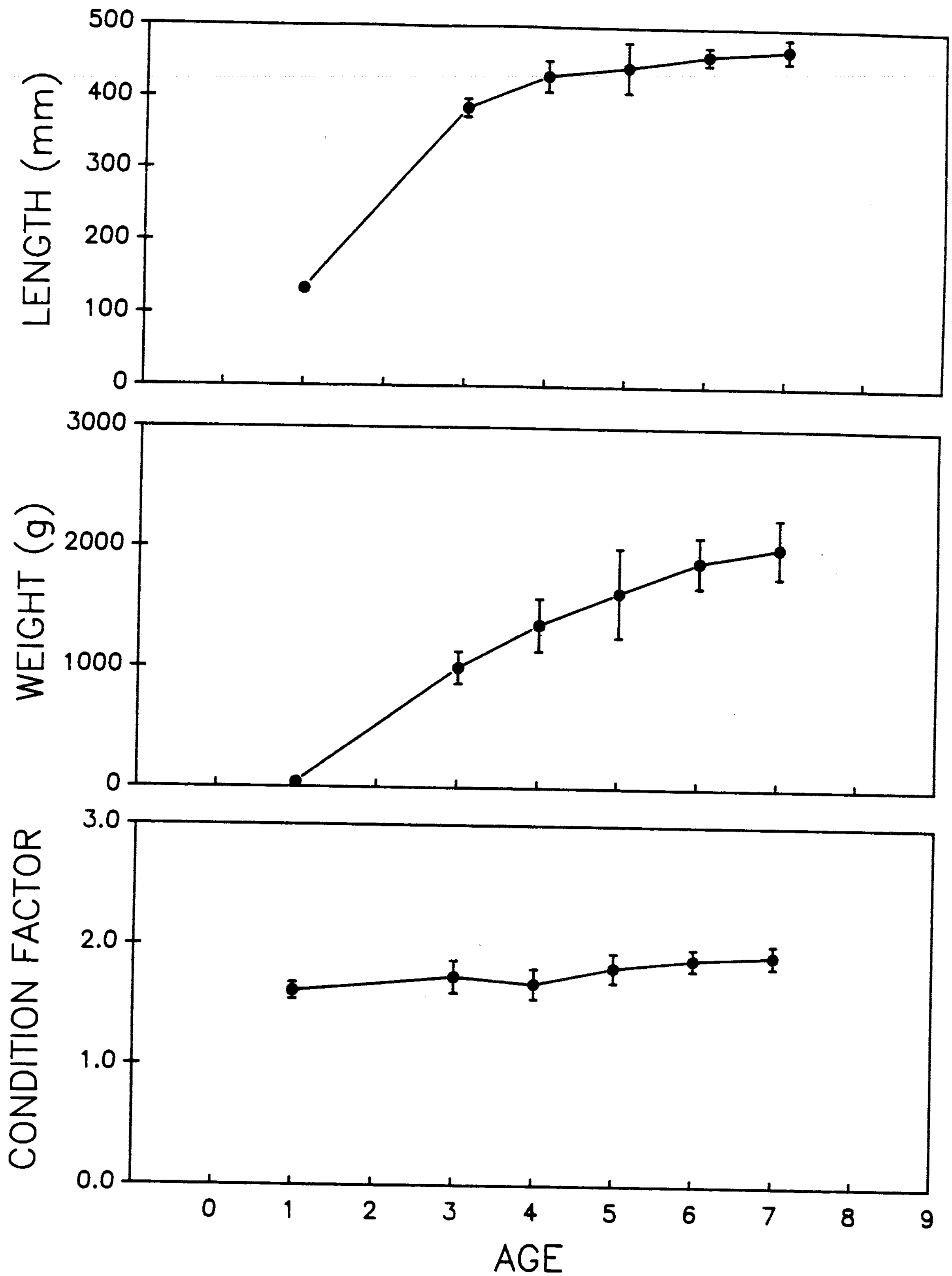


Figure 21. Condition factor, weight, and length versus age for largemouth bass in Lawrence Lake in 1989.

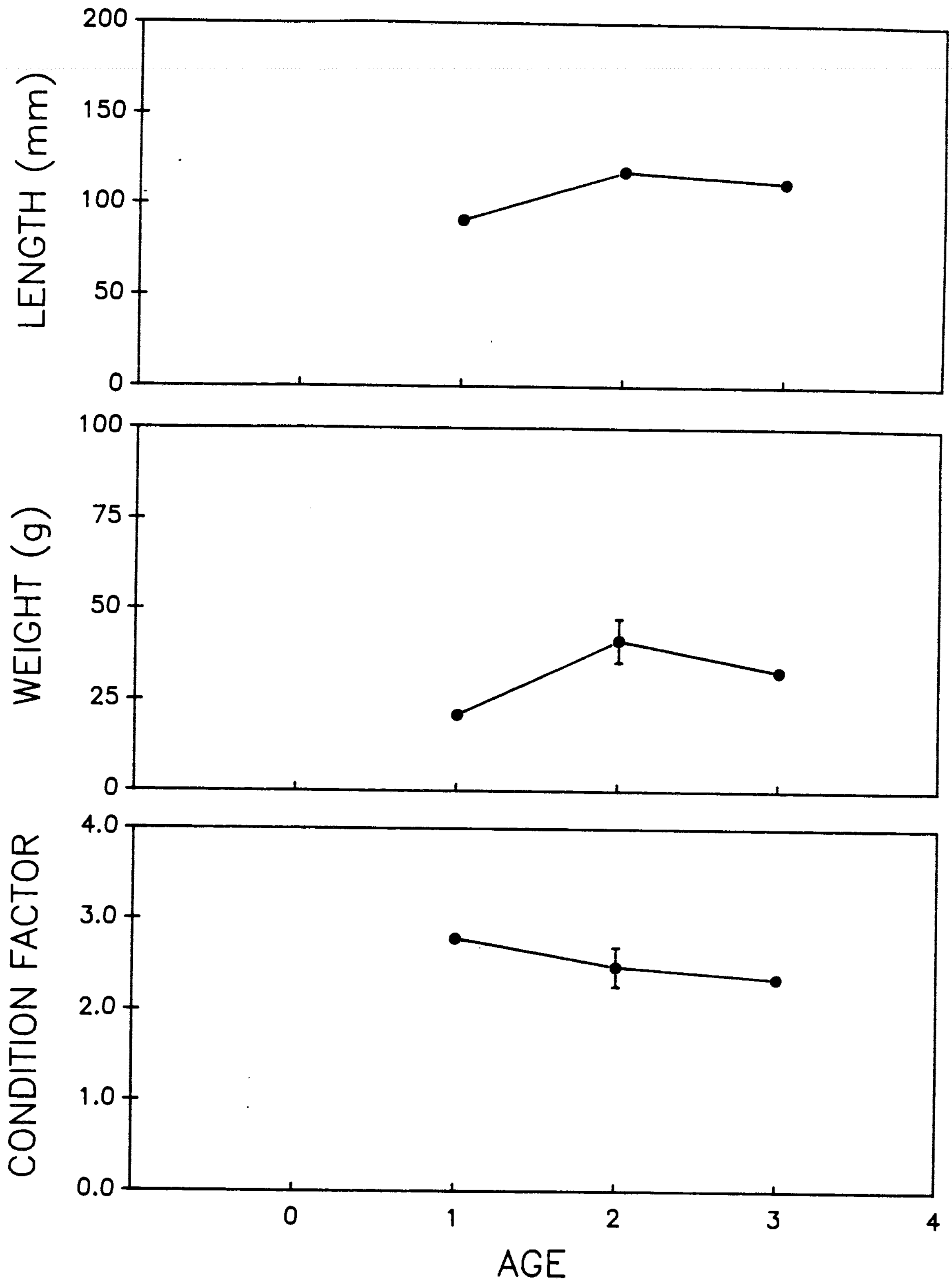


Figure 22. Condition factor, weight, and length versus age for pumpkinseed sunfish in Lawrence Lake in 1989.

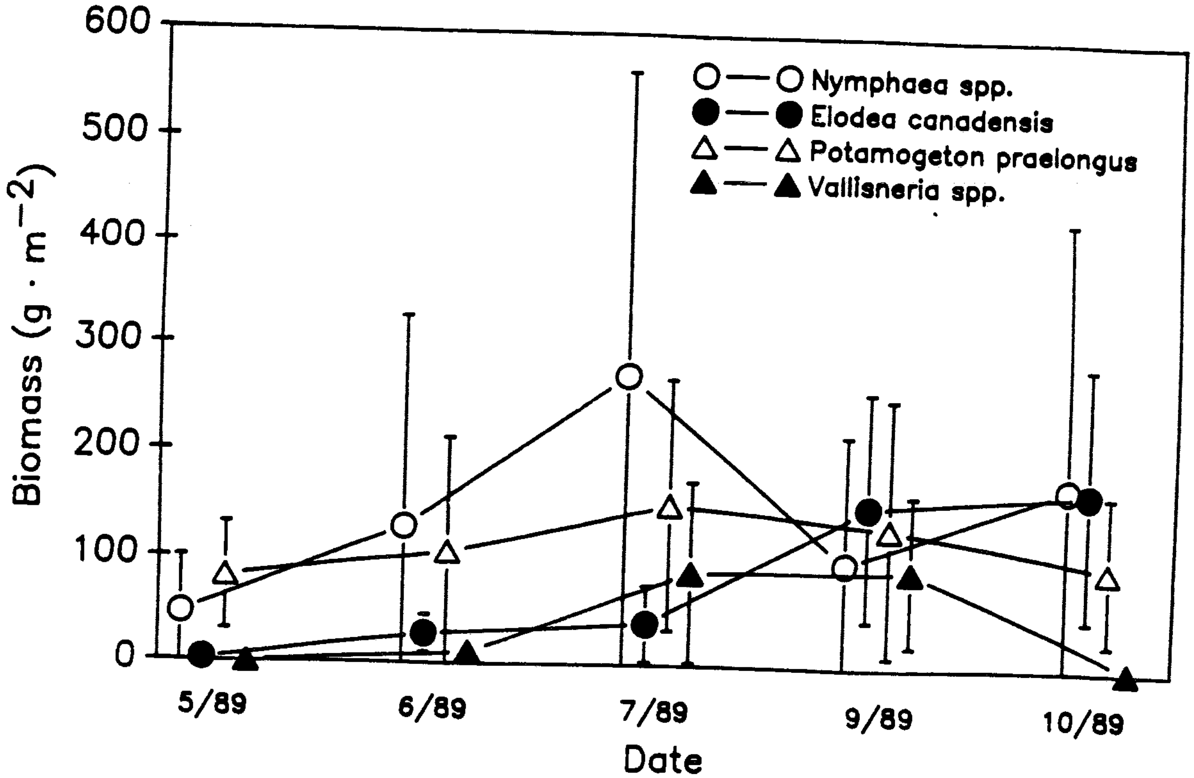


Figure 23. Biomass (g/m^2) vs. time of the major aquatic plant species in Lake Lawrence.

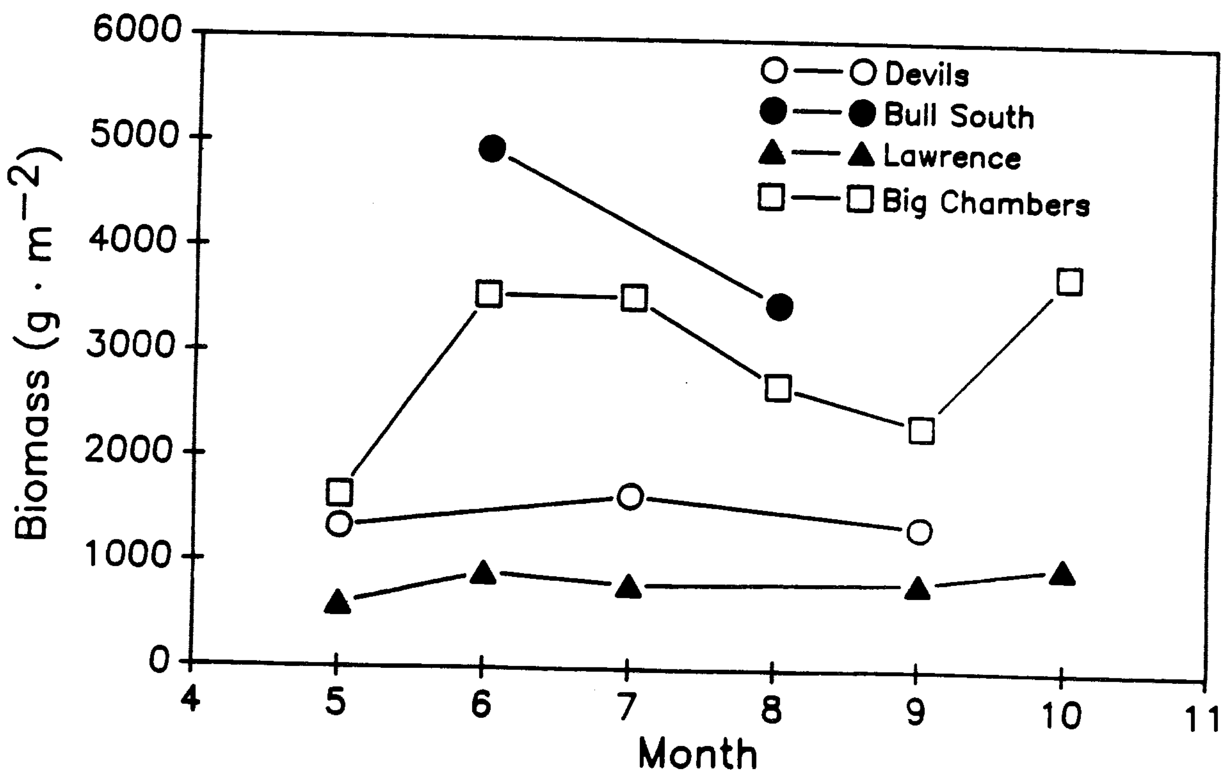


Figure 24. Total aquatic plant biomass (g/m^2) of Lake Lawrence compared to other Pacific Northwest lakes which have been stocked with grass carp.

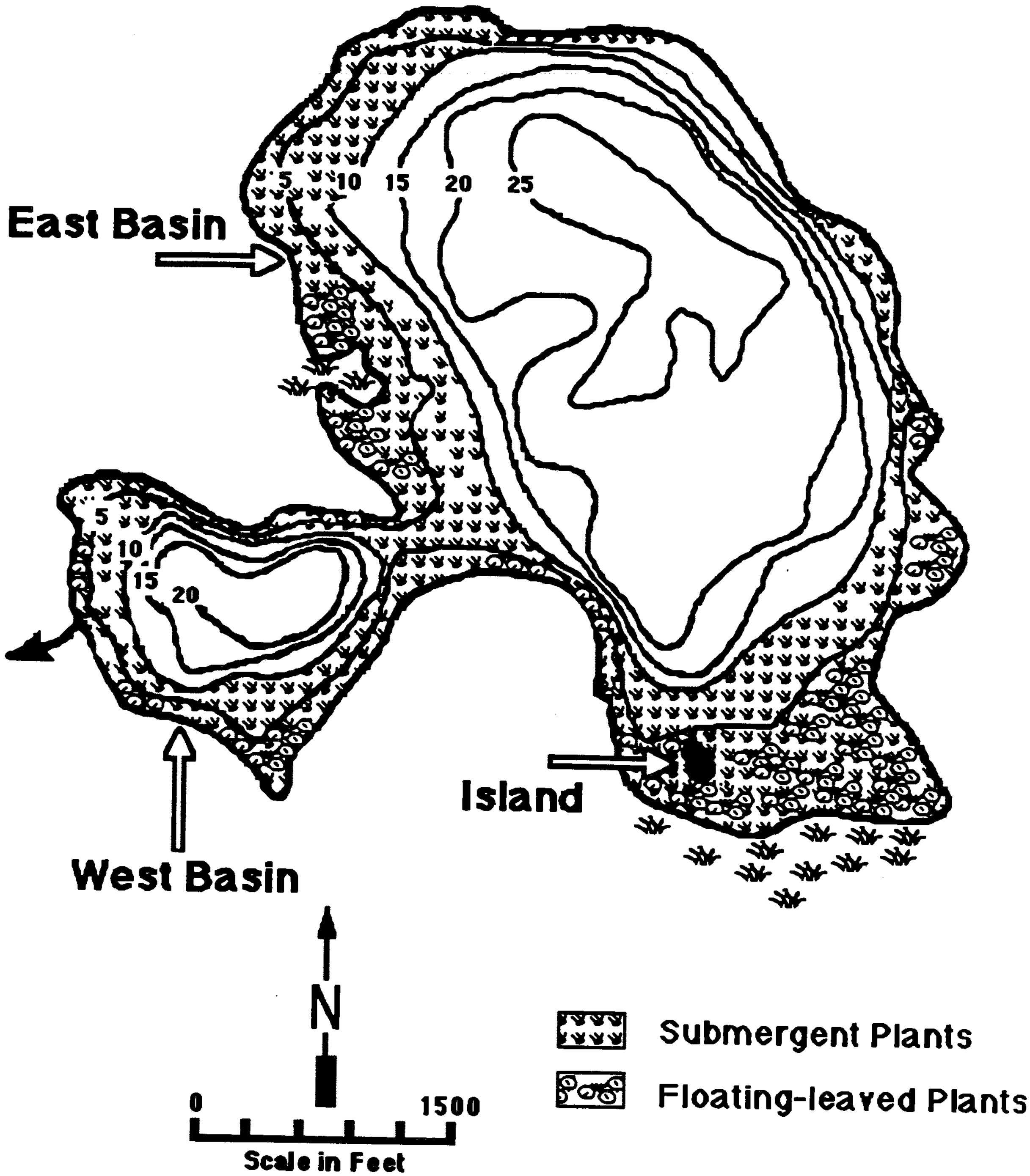


Figure 25. Approximate coverage of aquatic plants in Lake Lawrence.

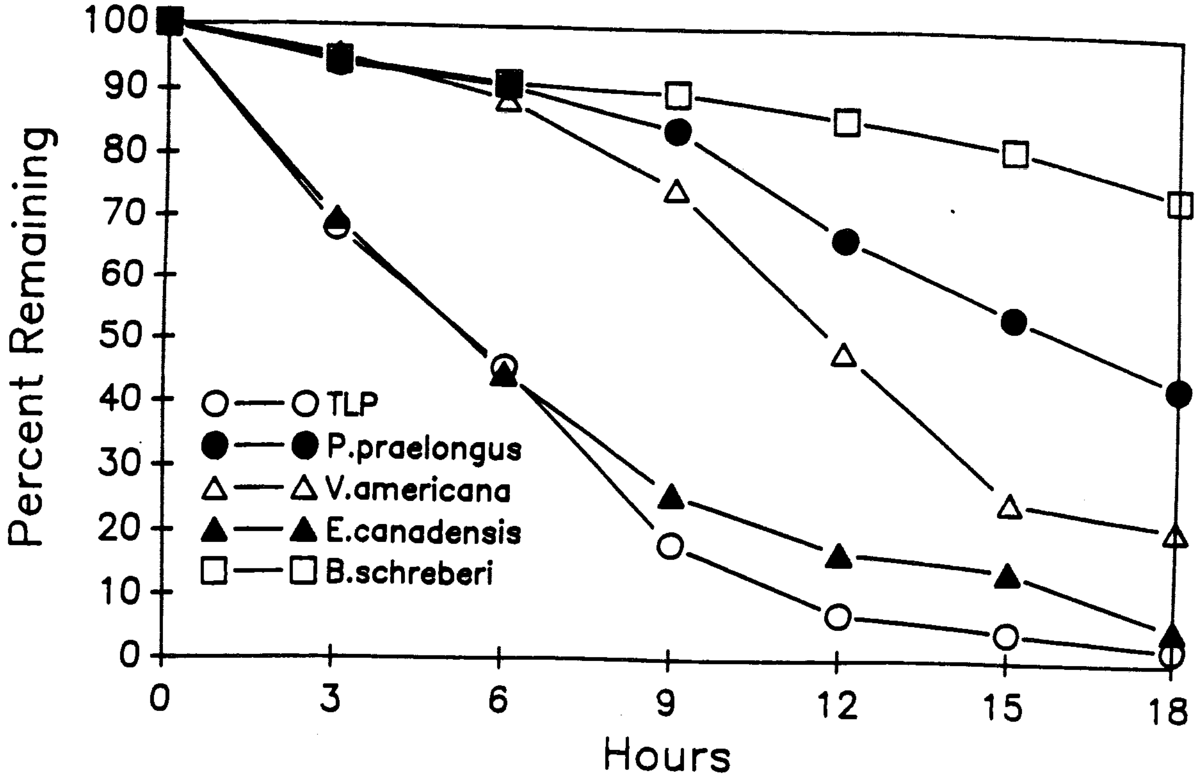


Figure 26. Percentage of aquatic plant biomass remaining over time in feeding preference experiments. All fish sizes combined.

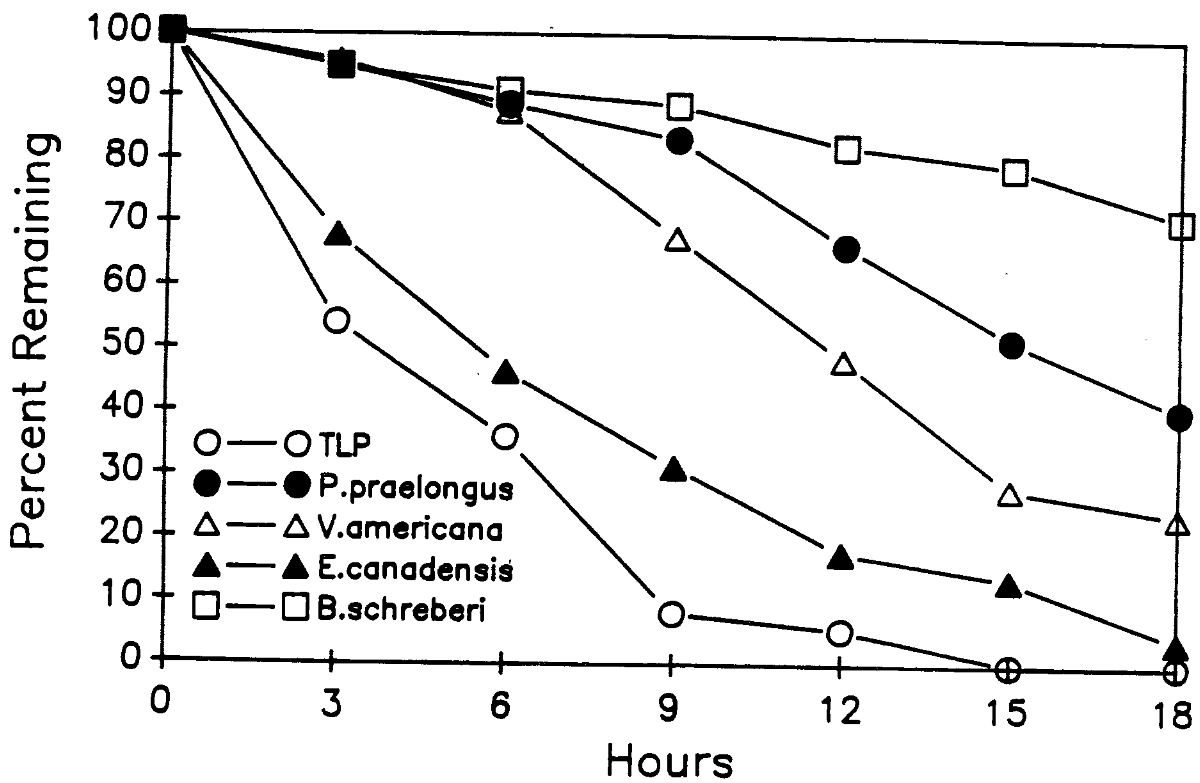


Figure 27. Percentage of plant biomass remaining over time in feeding preference experiments using small (x = 269 g) fish.

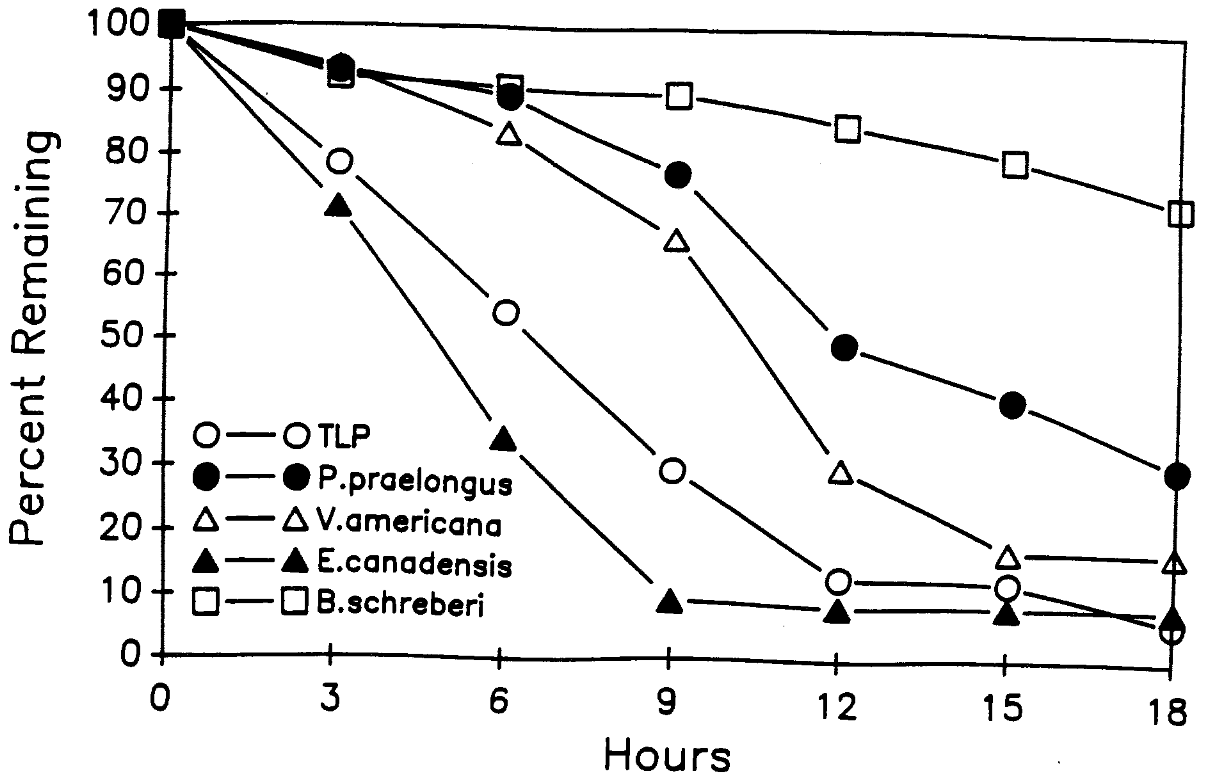


Figure 28. Percentage of plant biomass remaining over time in feeding preference experiments using large (x = 927 g) fish.

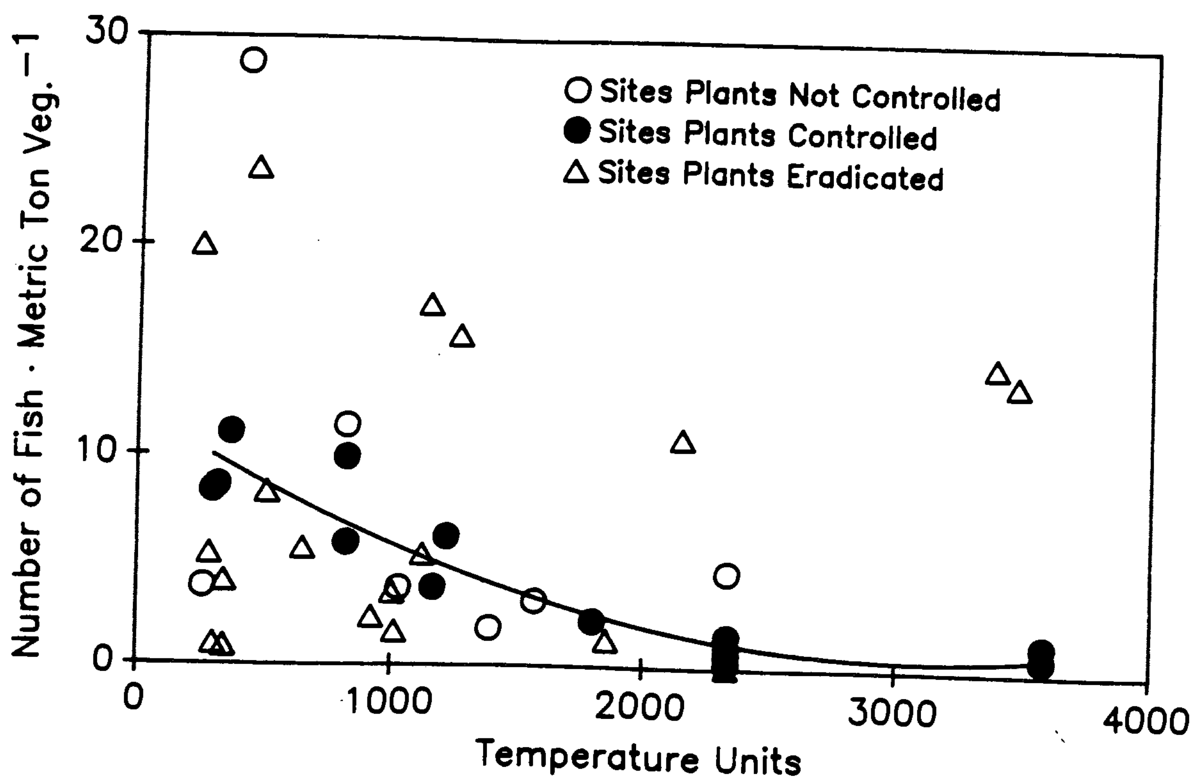


Figure 29. Stocking rate (# fish/metric ton vegetation) vs. temperature units for control, no-control, and eradication of aquatic plants.

APPENDIX. Biomass (g m^{-2}) of the aquatic plants of Lake Lawrence.

Date	Spun ± C.I.		Dry ± C.I.	
	Potamogeton praelongus			
5/2/89	82	51	14.2	9.8
6/13/89	106	107	11.4	12.9
7/14/89	151	118	16.1	13.5
9/18/89	132	121	14.2	17.1
10/26/89	95	70	25.0	21.6
	Ceratophyllum demersum			
5/2/89	1	1	0.1	0.1
6/13/89	2	2	0.1	0.1
7/14/89	3	4	0.2	0.3
9/18/89	3	4	0.2	0.2
10/26/89	1	2	0.1	0.1
	Elodea canadensis			
5/2/89	3	2	0.3	0.3
6/13/89	28	18	1.3	0.9
7/14/89	39	36	3.0	3.0
9/18/89	152	107	17.0	14.9
10/26/89	166	119	58.7	51.0

Date	Spun ± C.I.		Dry ± C.I.	
	Vallisneria americana			
5/2/89	0	0	0.0	0.0
6/13/89	11	8	0.5	0.5
7/14/89	88	85	6.2	7.2
9/18/89	92	71	5.3	4.3
10/26/89	1	2	0.1	0.1
	Potamogeton crispus			
5/2/89	0	0	0.0	0.0
6/13/89	0	0	0.0	0.0
7/14/89	0	0	0.0	0.0
9/18/89	0	0	0.0	0.0
10/26/89	1	1	0.1	0.1
	Brasenia schreberi			
5/2/89	0	0	0.0	0.0
6/13/89	0	0	0.0	0.0
7/14/89	7	14	0.5	1.0
9/18/89	24	49	3.6	7.1
10/26/89	8	17	1.8	3.5

Date	Spun ± C.I.		Dry ± C.I.	
		Utricularia spp.		
5/2/89	1	1	0.1	0.1
6/13/89	0	0	0.0	0.0
7/14/89	0	0	0.0	0.0
9/18/89	4	8	0.1	0.1
10/26/89	2	3	0.2	0.3
		Chara spp.		
5/2/89	1	2	0.1	0.1
6/13/89	36	30	1.3	1.4
7/14/89	2	3	0.1	0.1
9/18/89	38	35	8.2	13.8
10/26/89	32	31	9.6	14.8
		Thin-leaved *Potamogeton* sp.		
5/2/89	2	2	0.2	0.3
6/13/89	26	22	1.4	1.3
7/14/89	30	24	2.2	1.7
9/18/89	4	6	0.3	0.6
10/26/89	1	1	0.1	0.1

Date	Spun ± C.I.		Dry ± C.I.	
	Potomogeton amplifolius			
5/2/89	0	0	0.0	0.0
6/13/89	0	0	0.0	0.0
7/14/89	0	0	0.0	0.0
9/18/89	0	0	0.0	0.0
10/26/89	1	1	0.1	0.1
	Nymphaea odorata			
5/2/89	47	54	10.4	13.9
6/13/89	129	198	24.7	42.3
7/14/89	272	292	31.5	32.0
9/18/89	99	119	14.9	22.1
10/26/89	171	254	83.8	142.1
	Isoetes spp.			
5/2/89	0	0	0.0	0.0
6/13/89	0	0	0.0	0.0
7/14/89	0	0	0.0	0.0
9/18/89	0	0	0.0	0.0
10/26/89	1	1	0.1	0.1

Date	Spun ± C.I.		Dry ± C.I.	
	Najas spp.			
5/2/89	0	0	0.0	0.0
6/13/89	0	0	0.0	0.0
7/14/89	43	43	2.6	2.6
9/18/89	0	0	0.0	0.0
10/26/89	1	1	0.1	0.1
	Miscellaneous algae and leaf litter			
5/2/89	468	192	94.3	40.8
6/13/89	562	288	95.0	53.2
7/14/89	182	77	25.0	11.6
9/18/89	277	135	38.2	18.7
10/26/89	533	291	120.7	57.1
	Others			
5/2/89	0	0	0.0	0.0
6/13/89	0	0	0.0	0.0
7/14/89	0	0	0.0	0.0
9/18/89	9	14	0.6	1.1
10/26/89	0	0	0.0	0.0

Date	Spun ± C.I.		Dry ± C.I.	
		Totals		
5/2/89	603	247	118.5	52.3
6/13/89	908	469	127.7	91.3
7/14/89	799	374	86.5	41.4
9/18/89	833	332	102.4	52.4
10/26/89	1010	436	300.0	177.9

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