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Alternative Stable States in Fox Lake, Dodge Co. WI

Results of 1995 Plankton and Water Quality Monitoring

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Summary

This report documents Fox Lake monitoring activities performed in 1995 by the Wisconsin Department of Natural Resources (WDNR) Bureau of Research, now Bureau of Integrated Science Services. Intensive water quality and plankton sampling, as well as macrophyte surveys and sedimentation studies were done in support of a Lake Planning Grant funded jointly by WDNR and the Fox Lake Inland Lake Protection and Rehabilitation District.

Major findings:

- 1995 represented an unusual year for Fox Lake, characterized by improved water clarity, reduced chlorophyll concentrations, and more extensive macrophyte growth compared to 1994 and the previous decade:
 - water clarity averaged 1.7 m
 - chlorophyll a averaged $14.1 \mu\text{g l}^{-1}$
 - macrophytes were present out to 7.5 ft water depth
- Total phosphorus (P) was not reduced in 1995 ($193 \mu\text{g L}^{-1}$), but dissolved P was very high, suggesting that algae were not utilizing readily available nutrients.
- The algal community was dominated by green and cryptophyte species through much of the summer, in contrast to previous years which were dominated by blue-green algae. Blue-green algae were present, but in low numbers until mid-August when they became dominant.
- The zooplankton community was dominated by large-bodied species and was very abundant through August.
- sedimentation and resuspension rates were very high compared to other lakes, although the more abundant plant growth in shallow Government Bay appeared to trap sediment particles and reduce resuspension.

These findings suggest that the clear water exhibited in 1995 was primarily due to the increased zooplankton abundance, which kept algal growth in check through high grazing rates. Macrophytes responded to the increased clarity by becoming more abundant and extending to greater depths. The increased macrophytes may also have contributed to increased clarity by holding sediments in place. It is not clear why the zooplankton were able to thrive so much in 1995, although weather conditions and the fish community likely played major roles. Future management efforts in Fox Lake should focus on these biotic relationships and attempt to improve water quality by enhancing macrophyte growth and zooplankton abundance (see Recommendations).

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I. Introduction

Fox Lake, Dodge Co., WI, is a 2625 acre lake located in the upper Beaver Dam River watershed. More than 70% of the watershed is in agricultural land use (primarily dairy and corn cropping). Many wetlands in the watershed have been drained, although several still exist near the inlet streams and along the southern and eastern shoreline of Fox Lake. The eastern half of the lake is a flooded wetland, created by the installation of a dam at the outlet in 1845. As a result, the lake is divided into two main basins, a shallow eastern basin (maximum depth < 3 m) and a deeper western basin (max. depth = 5.5 m) which rarely stratifies. The lake provides important habitat for a variety of wildlife, including a productive fishery. However, the lake has experienced a decline in water quality in recent decades, characterized by very high algal biomass, low water clarity, frequent sediment resuspension, and high nutrient levels (WRM 1984; Sesing et al. 1991; Garrison and Hurley 1996; Winkelman and Garrison 1996).

Shallow lakes are hypothesized to exist in one of two stable states, depending upon phosphorus (P) concentrations (Scheffer 1990; Blindow et al. 1993). At low P concentrations, aquatic macrophytes are the predominant plant life, water is relatively clear, and gamefish dominate. At high P levels, shallow lakes tend to be turbid, dominated by algae and rough fish. Feedback mechanisms related to sediment resuspension and biotic interactions tend to maintain lakes in one state or the other. At intermediate levels of P, however, lakes may alternate between the two stable states. Historical accounts and evidence from sediment cores suggest that Fox Lake has had extended periods of clear water dominated by macrophytes (Sesing et al. 1991; Garrison and Hurley 1996). It appears that Fox Lake may have shifted over time to the turbid/algal state as P loading increased. Current management goals aim to rehabilitate the lake by causing it to shift back to the clear water/macrophyte state using a variety of management techniques including removal of benthic fish, reestablishment of macrophytes, sediment stabilization, lower summer water levels, and stocking of piscivorous fish.

In 1995, the Bureau of Research undertook intensive monitoring of water chemistry and plankton to investigate the interactions between water quality and food web dynamics. We hoped to understand more fully the implications of food web relationships in order to evaluate the feasibility of various biomanipulation techniques. We also investigated sediment resuspension in four parts of the lake and performed a limited macrophyte survey. This project was completed as part of a planning grant partnership entered into by the Fox Lake Protection and Rehabilitation District and the Wisconsin Department of Natural Resources.

This report summarizes the detailed sampling from 1995 of water chemistry, plankton, and sediment resuspension. The lake had unusually clear water and associated changes in biota for much of the summer. Thus, detailed comparisons of water quality between 1994 and 1995 are made to illustrate the alternative stable state concept. Finally, trends in water quality and the plankton community are summarized and compared for 1986-1995.

II. Methods

A. Water chemistry

Water samples were collected from two sites in the lake from the beginning of May until the end of September. Samples were collected at least biweekly, with some parameters collected weekly from May to mid-August. The East Basin site was located in Government Bay, at approximately 1.5 m depth (Fig. 1). Most of this part of the lake is shallow and wind-swept. The Deep Hole site is located in the main western basin of the lake, with a maximum depth of about 5.5 m (water level fluctuations change the actual depth on a given date).

Temperature and dissolved oxygen were measured at each meter depth interval at the Deep Hole and at 0.5 m intervals at the East Basin site. Water clarity was measured with a 20 cm black and white Secchi disk. Water samples from the top 1 m were collected weekly for chlorophyll a (chl a), biweekly for pH, total phosphorus (TP) and dissolved reactive phosphorus (DRP), and monthly for total Kjeldahl nitrogen (TKN), and nitrate+nitrite ($\text{NO}_3+\text{NO}_2\text{-N}$). When the lake was stratified, samples from 4.5 m at the Deep Hole were analyzed for TP. Similar samples were collected by the Long Term Trend Monitoring program (LTTM) once a month in June, July, and August from the Deep Hole. This data was combined with our data in the analyses. Chemical analyses were performed at the WI State Laboratory of Hygiene (WSLH 1993), with the exception of chl a , which was determined using the spectrophotometric method at the DNR Research Center (APHA 1992).

B. Plankton sampling

Phytoplankton samples were collected weekly at 0.5 m from both sites. Water was placed in dark 250 ml bottles and preserved with Lugol's solution. Samples were scanned using an inverted microscope and relative abundances of each species determined on a scale from (P)resent, to (R)are to (S)omewhat common, to (C)ommon, to (D)ominant.

Vertical zooplankton tows were collected weekly from May through August, and once every two weeks thereafter. Tows were conducted from the bottom of the lake to the surface at both sites using a 12 cm diameter, 76 μm mesh, conical plankton net. At the East Basin, two tows were often combined into the same sample bottle to ensure that enough zooplankton were captured to give a representative sample. Each sample was preserved by adding enough 6% buffered formalin to double the volume.

Species of zooplankton were identified and counted, and demographic characteristics were estimated using a dissecting microscope. For copepods, we determined population sex composition, number of eggs, number of copepodites, number of nauplii and average length of each instar. For *Daphnia* species, we determined the number of eggs, minimum reproductive size, the number of eggs per female and the average length of each species. The lengths of approximately 25% of the individuals from each species encountered were measured for later

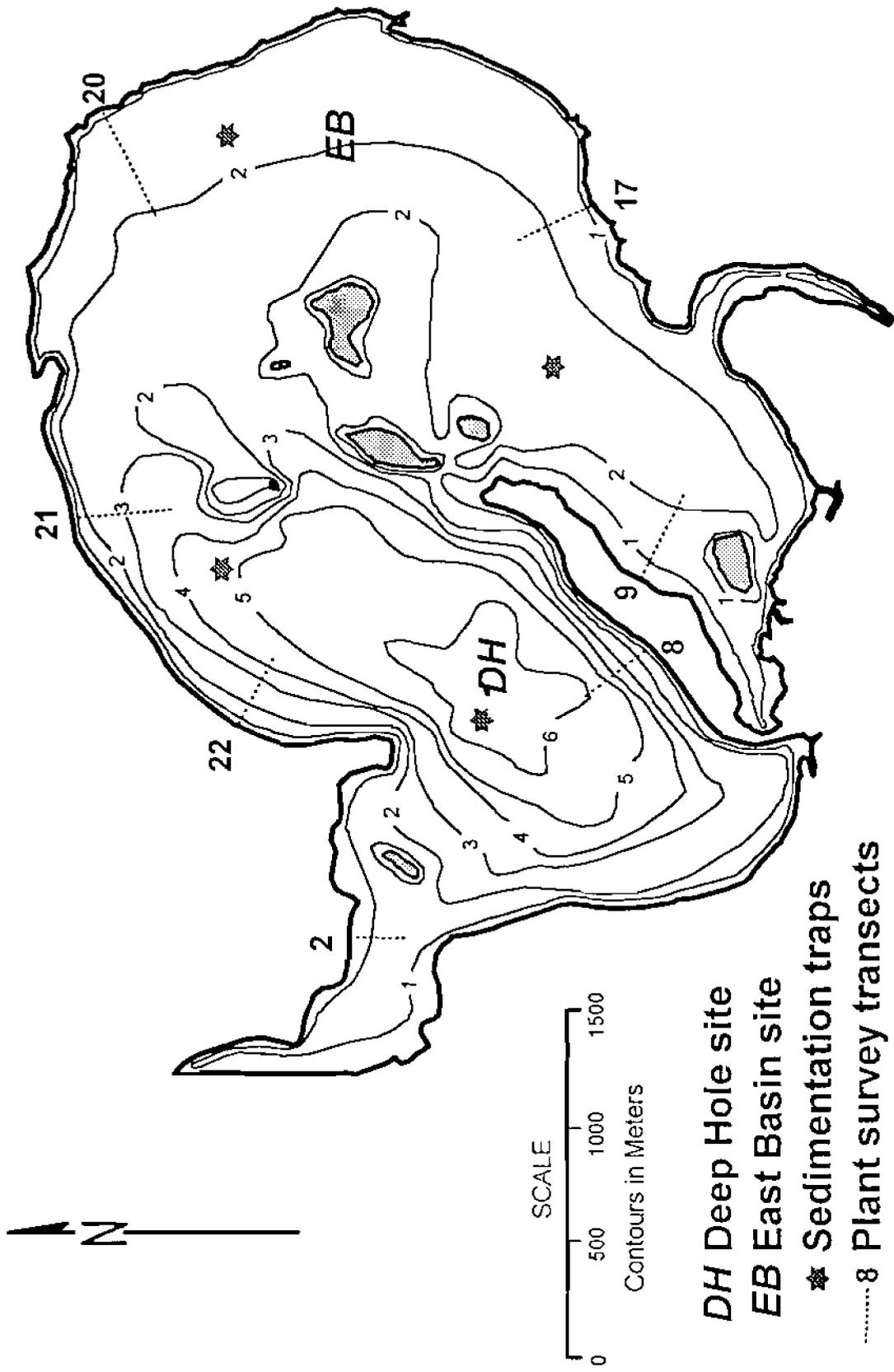


Figure 1. Map of Fox Lake showing sampling sites for water chemistry and plankton (DH and EB), location of sediment traps, and transects surveyed for macrophytes. Transect numbers correspond to previous macrophyte surveys (Winkelman 1995).

biomass calculation. Individual body lengths were measured with an ocular micrometer calibrated with a stage micrometer.

Biomass was calculated from the average length of each species using the formulae obtained from the literature and previous work (Table 1). Reproductive potential was estimated for *Daphnia* species by calculating the average number of eggs carried by each female in the population. Free eggs, those that were not contained within the brood chambers of female *Daphnia*, were counted and then divided between the encountered species in the same ratio as the brood eggs that had been found for each species.

Table 1. Equations used for calculating biomass of the major zooplankton species found in Fox Lake in 1994 and 1995. B = average biomass per individual in μg ; L = average length in mm.

Species	Equation	Reference
<u>Cladocerans</u>		
<i>Chydorus sphaericus</i>	$B = 14.0793 * L^{1.9796}$	Culver et al. 1985
<i>Daphnia galeata mendotae</i>	$B = 7.4997 * L^{1.5644}$	P. Garrison, unpub. data
<i>D. retrocurva</i>	$B = 3.7847 * L^{2.6807}$	P. Garrison, unpub. data
<i>D. schodleri</i>	$B = 9.631 * L^{1.719}$	P. Montz, unpub. data
<i>Diaphanosoma birgei</i>	$B = 5.07 * L^{1.0456}$	Culver et al. 1985
<u>Copepods</u>		
<i>Acanthocyclops vernalis</i>	$B = 10.968 * L^{1.634}$	P. Montz, unpub. data
<i>Diacyclops thomasi</i>	$B = 14.571 * L^{2.557}$	P. Montz, unpub. data
<i>Eucyclops speratus</i>	$B = 10.968 * L^{1.634}$	P. Montz, unpub. data
<i>Leptodiaptomus siciloides</i>	$B = 10.308 * L^{1.761}$	P. Montz, unpub. data
<i>Mesocyclops edax</i>	$B = 11.728 * L^{1.625}$	P. Montz, unpub. data

C. Fish stomach analysis

In order to assess predation pressure of panfish species on zooplankton, we collected bluegill (*Lepomis macrochirus*), yellow perch (*Perca flavescens*), pumpkinseed (*Lepomis gibbosus*), white crappie (*Pomoxis annularis*) and black crappie (*Pomoxis nigromaculatus*) on 21 June, 18

July, and 25 August, 1995, using a pulse DC boomshocker in shallow areas along the shoreline of Fox Lake. Sampling was conducted during the first few hours after sunrise when the fish would most likely be feeding. Fish were flash-frozen within 15 minutes of capture and kept frozen until analysis.

Thawed fish were identified to species, measured and divided into approximate age classes. The portion of the digestive tract from the esophagus to the beginning of the small intestine were removed from each fish with forceps, wrapped in plastic and frozen. The actual stomach and esophagus were peeled from the frozen contents, and then the remaining matter was thawed and diluted in a counting dish with gridlines. Prey items were identified and counted under a dissecting microscope.

Identified prey were grouped into four categories: cladocerans, copepods, insects, and "other," which included amphipods, isopods, decapods, clams, snails, mites and fish. The composition of the prey items chosen by each age class of each species of fish were estimated by dividing the total number of individuals from each group of prey by the number of stomachs analyzed. The average number of prey items from each prey category were then divided by the average number of prey items from all groups totaled to get a relative percentage of the total diet for each type of prey.

D. Macrophyte survey

A comprehensive macrophyte survey was performed in 1994 (Winkelman 1995a). In 1995, we resurveyed 7 of the 25 transects on 10 August using the rake method described in the aforementioned report (Fig. 1). Species presence and absence, relative abundance, and depth distribution were determined and compared with data from the same 7 transects of 1994.

E. Sediment characteristics and resuspension

Sedimentation and resuspension was investigated in four areas of the lake (Fig. 1) using a system of sedimentation traps deployed at two week intervals from mid-July to mid-October. The East and South Basin traps were in relatively shallow water (less than 2 m) while the Deep Hole and North Basin were in water 4 - 5 m deep. At each site, 3 acrylic tubes (4.4 cm diameter by 20.0 cm height) and 3 acrylic dishes (9.4 cm by 10.2 cm) were suspended just off the lake bottom on a plastic tray held up by Styrofoam floats (Winkelman 1995b). Sediment material that accumulated in the two kinds of traps was combined and quantified using techniques for total suspended solids (APHA 1992). We assumed that the tube traps measured gross sedimentation, or the total amount of sedimented material reaching the lake bottom. The dish traps presumably measure net sedimentation, or the actual amount of sediment accumulating on the lake bottom. The difference between the traps is an estimate of resuspension.

Surficial sediments were collected from each of these four sites on 19 July and analyzed for percent moisture, percent organic matter (Wetzel and Likens 1991), and physical composition (ASA 1965). Sediments from the East site and South site were also analyzed for TP, iron,

calcium, pH, ammonia-nitrogen, and TKN (WSLH 1993). In addition, we determined the P fractions for these sediments and evaluated their potential for algal stimulation using techniques outlined in Asplund (1996).

III. Results and Discussion

A. Water Chemistry

1995 turned out to be an unusual year for Fox Lake, and thus the detailed information here needs to be considered in that context. The data from 1995 are not representative of the conditions that Fox Lake has been experiencing over the past 10+ years. However, 1995 did provide a glimpse of what the lake could be like if management efforts are successful in moving the lake to a macrophyte-dominated and clear-water state. This point will be made by contrasting lake conditions in 1995 with those in 1994, a more representative year in the recent history of Fox Lake.

In general, 1995 was characterized by relatively good water clarity and low algal biomass in contrast to the preceding 9 years for which we have data (Fig. 2). From 1986-1994, Secchi disk readings rarely exceeded 0.5 m. In 1995, they averaged 1.7 m, with maximum values greater than 4.0 m. Average chl *a* concentrations have been above 50 $\mu\text{g L}^{-1}$ since 1986, reaching a maximum of close to 125 $\mu\text{g L}^{-1}$ in 1993. In contrast, the average concentration in 1995 was about 25 $\mu\text{g L}^{-1}$. During the summer months, the average was closer to 15 $\mu\text{g L}^{-1}$. These changes in water clarity and chl *a* occurred even though TP concentrations in 1995 were not much different from previous years. TP increased from just over 100 $\mu\text{g L}^{-1}$ in 1986 to a peak of 250 $\mu\text{g L}^{-1}$ in 1993. Levels dropped off in 1994 and 1995, but remained higher than the period from 1986-1989.

Detailed comparisons of water quality between 1994 and 1995 further illustrate the abnormal conditions experienced in 1995. Table 2 lists the mean and median values for chl *a*, Secchi, and nutrients from May through September 1994 and 1995 at the Deep Hole. As mentioned earlier, mean Secchi disk readings were higher and chl *a* concentrations were lower in 1995. While TP concentrations were comparable between 1994 and 1995, DRP values were more than ten times greater in 1995. It is very unusual for productive lakes such as Fox Lake to have DRP values on the order of 110 $\mu\text{g L}^{-1}$ during the summer (Lillie and Mason 1983) as phytoplankton usually take up DRP as soon as it is made available. Algal growth likely was not limited by nitrogen availability either as total nitrogen (TN) and $\text{NO}_3 + \text{NO}_2\text{-N}$ levels were higher in 1995 than in 1994. These observations indicate that nutrients were available but not being utilized by phytoplankton.

Seasonal dynamics of water clarity, chl *a* and nutrients are plotted in Fig. 3. In 1994, water clarity was very low throughout the summer (Fig. 3 a). Chl *a* concentrations steadily increased in May and June, with a large peak at the end of June (Fig. 3 b). Levels remained high through July and August with another peak in mid-August after which it declined somewhat. In contrast, 1995 was characterized by drastic fluctuations in water clarity from May through July, only reaching a fairly constant turbid state in August (Fig. 3 a). Peaks in chl *a* again occurred at the end of June and the

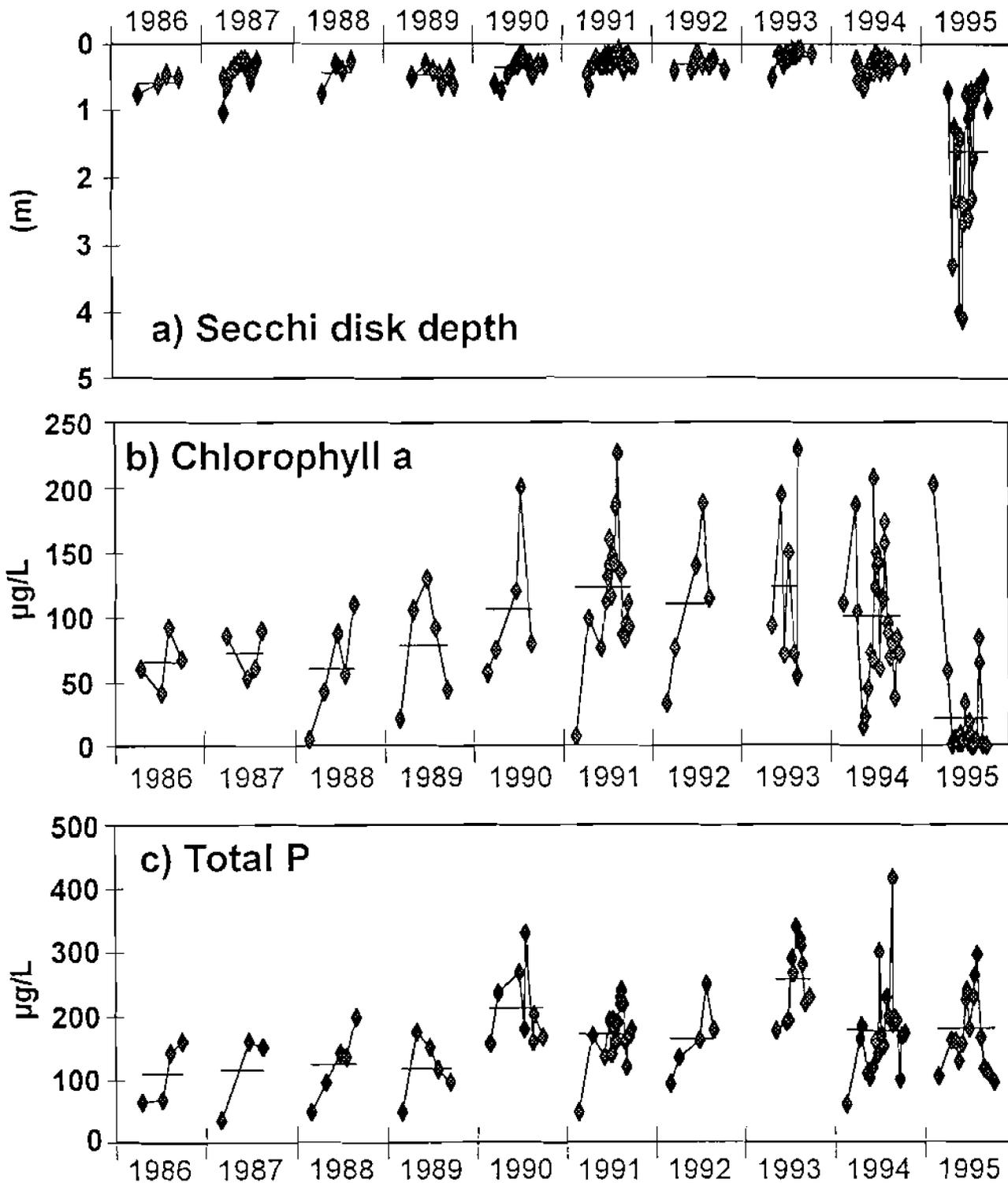


Figure 2. Ten year trends of a) Secchi disk water clarity; b) chlorophyll a; and c) total phosphorus (P) in the top 1 m at the Deep Hole of Fox Lake. Annual means are labeled and plotted as a horizontal line for each year. Data are primarily from the Long Term Trends Monitoring program, except for additional samples in 1991 (USGS), and 1993-1995 (DNR Research)

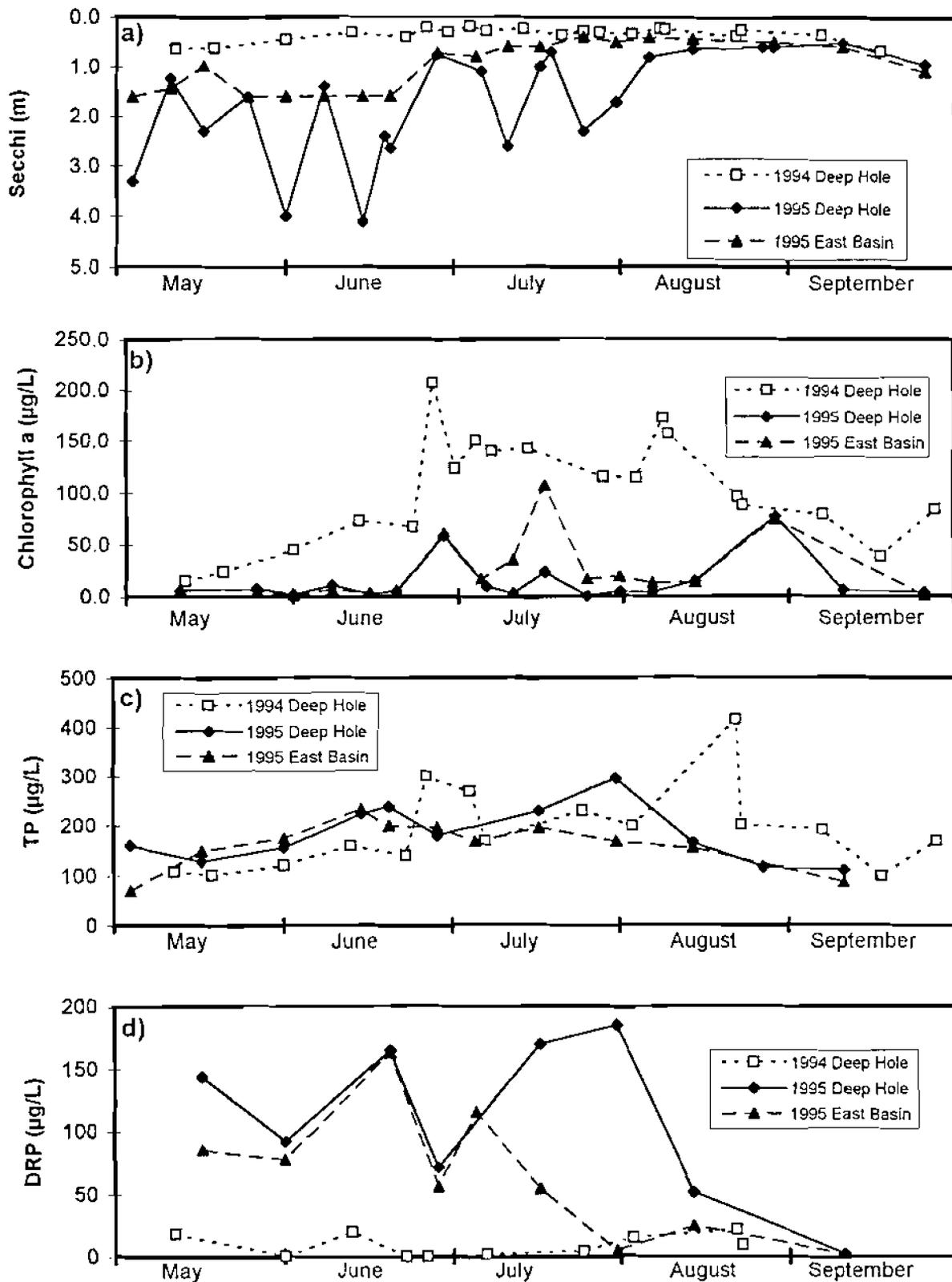


Figure 3. Seasonal trends in a) Secchi disk water clarity; and b) chlorophyll a; c) total phosphorus (TP); and d) dissolved reactive phosphorus (DRP) in the top 1 m at the Deep Hole in 1994 and 1995 and the East Basin in 1995.

Table 2. Mean and median surface water quality parameters from May - September for the Deep Hole in 1994 and 1995 and the East Basin in 1995. Samples collected from top 1 m of water column.

Site	Secchi	Chl a	TP	DRP	TN	NO ₃ + NO ₂ -N	TKN	N:P
	m	µg/L	µg/L	µg/L	mg/L	mg/L	mg/L	
Deep Hole - 1994								
mean	0.35	101.6	192	8.8	2.02	0.081	1.95	11.1
median	0.31	96.0	170	6.5	2.03	0.010	1.90	11.0
Deep Hole - 1995								
mean	1.69	14.1	193	110	2.36	0.108	2.26	12.7
median	1.33	6.0	180	118	2.52	0.058	2.30	11.9
East Basin - 1995								
mean	0.99*	24.2	163	65	2.18	0.186	2.05	15.8
median	0.80	14.0	167	56	2.03	0.164	2.00	13.2

* This number includes 6 occasions where the Secchi disk was observed on the lake bottom (1.6 m).

end of August, but these were short-lived and did not reach near the concentrations as in 1994 (Fig. 3 b). Much of the fluctuation in water clarity in May and June was likely due to wind-induced turbidity rather than algal blooms. We observed lower water clarity and more turbid conditions during windy days while chl α concentrations remained relatively low throughout this period.

TP followed fairly similar patterns in 1994 and 1995, though spikes in TP were more prevalent in 1994 (Fig. 3 c). In late June 1994, the TP spike was concurrent with a windy period and a peak in chl α , suggesting that nutrients were being stirred from the bottom and fueling algal growth. In 1995, there did not appear to be an association between chl α and TP. However, DRP values were very high in 1995, indicating that the algal standing crop was not limited by P (Fig. 3 d). The large drop in DRP at the end of June in 1995 was associated with a chl α peak. Interestingly, the lake was stratified for much of June (Fig. 4) and characterized by very warm, calm weather. TP built up in the anoxic bottom waters during this time. When the lake mixed again in early July, however, chl α concentrations decreased, apparently not taking up the P mixed back into the water column as indicated by the increase in DRP (Fig. 3 d). In mid-August of 1995, conditions returned to 1994 levels, with lower DRP and water clarity, and higher algal biomass.

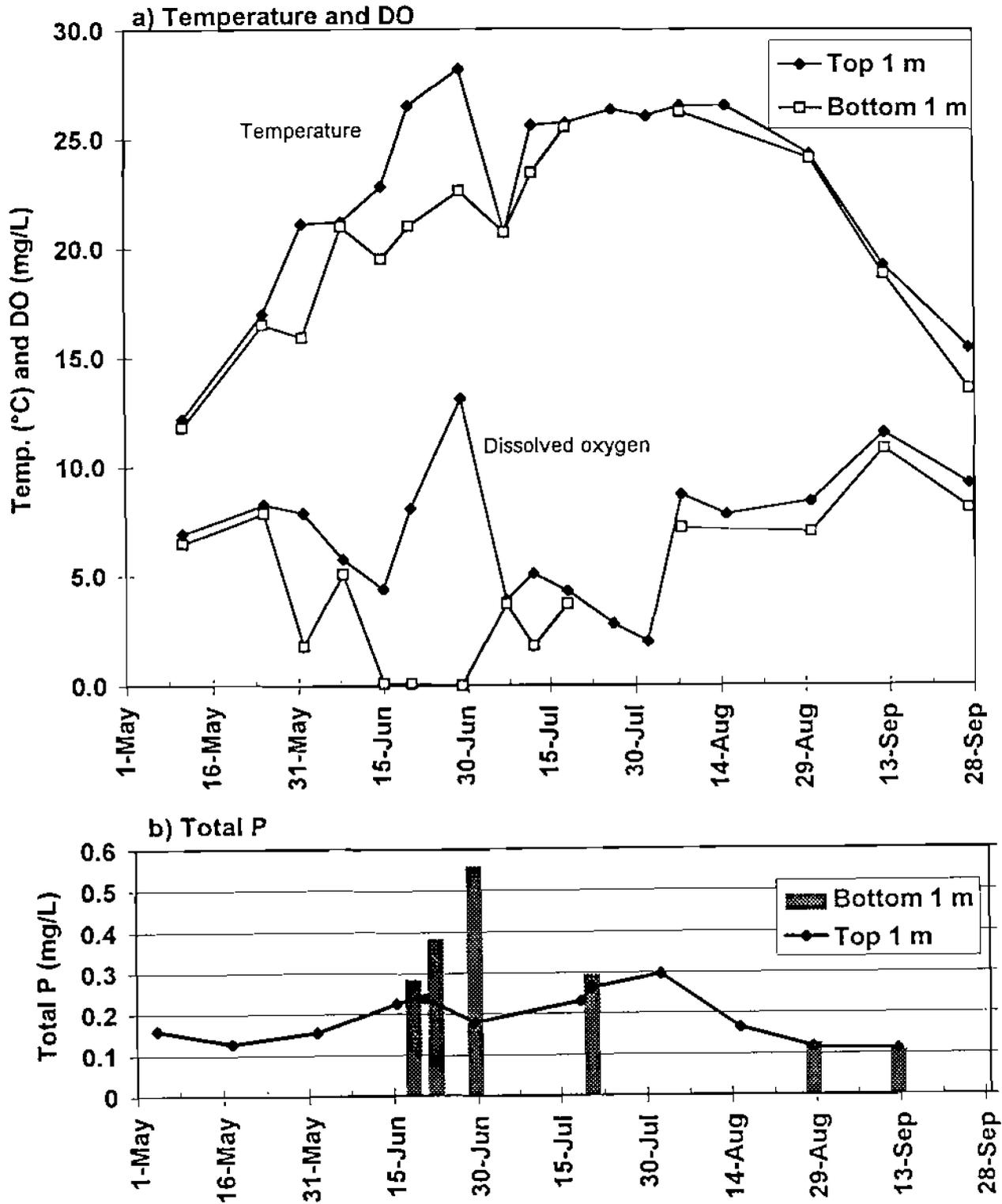


Figure 4. a) Seasonal trends in temperature and dissolved oxygen (DO) in 1995 at the Deep Hole. Data from the top 1 m are indicated by solid diamonds, at 1 m off the bottom by open squares. Periods of stratification are indicated by gaps between the two lines. b) Total P concentrations at the surface (solid line) and 1 m off the bottom (bars) at the Deep Hole in 1995.

Nitrogen concentrations showed some interesting patterns between 1994 and 1995 as well (Fig. 5). TKN fluctuated throughout the summer in both years, with no apparent relationship to chl a or water clarity. $\text{NO}_3+\text{NO}_2\text{-N}$ concentrations declined in 1994 from early May to the end of June, reaching non-detectable levels throughout the rest of the summer. In 1995, levels dropped to near the detection limit in late June with the peak in chl a , but then increased again during July and August although values remained low. The N:P ratio was below 10 for much of 1994. In 1995, the N:P ratio stayed above 10, due to the higher TKN and $\text{NO}_3+\text{NO}_2\text{-N}$. These N:P ratios further suggest that nitrogen was not limiting in 1995.

The East Basin site had higher average chl a and worse water clarity than the Deep Hole, though levels were still quite good compared to 1994 (Table 2). Water clarity, chl a , and DRP were actually quite similar in June and August between the two sites (Fig. 3). The main difference was seen in July at the East Basin, where chl a levels remained high and DRP and water clarity remained low after an initial algal bloom at the end of June. It is possible that algal growth was sustained in the shallower East Basin site through wind resuspension of sediments or nutrients. DRP levels declined in the East Basin throughout July, in contrast to the Deep Hole (Fig. 3).

B. Phytoplankton

In 1995, the Deep Hole phytoplankton community followed a seasonal succession of greens and cryptophytes early in the summer, followed by dominance of diatoms in July and blue-greens in August (Table 3). *Asterococcus* sp. and *Sphaerocystis schroeteri* were the dominant greens, while *Aulacoseira granulata* and *Stephanodiscus* sp. were the dominant diatoms. *Microcystis flos-aquae* a colonial globular species, was the dominant blue-green. The species composition of the East Basin site was very similar except for the July 18 sample which contained a bloom of the green alga *Actinastrum hantzschii* (Table 4). Most of these species are indicative of highly eutrophic systems (WRM 1984), but are also edible to zooplankton. *Microcystis* can form surface blooms, but can also grow on the sediment surface during periods of anoxia (Reynolds and Walsby 1975). *Aulacoseira* thrives in shallow systems because it relies on wind mixing to keep the cells in the photic zone (Harris 1986).

Microcystis flos-aquae was the dominant species all summer long in the summer of 1994, though greens and diatoms occurred in early June and were present at low levels later in the summer (Table 5). *Cryptomonas* species were virtually absent in 1994, in sharp contrast to 1995. The lower N:P ratios in the summer of 1994 may have favored the development and persistence of the blue-green dominance.

Microcystis aeruginosa and *Aulacoseira granulata* were dominant and very common respectively in samples from summer 1986 and 1987, both years with mean chl a values greater than $60 \mu\text{g L}^{-1}$. Samples scanned from the summer of 1993 also revealed dominance of *Microcystis* sp., while diatoms were most common in 1982, when chl a averaged $18 \mu\text{g L}^{-1}$ (WRM 1984). From this limited information, it appears that *Microcystis* sp. dominates when there are blooms of algae and high chl a , while *Aulacoseira* dominates when chl a values are low. However, both species

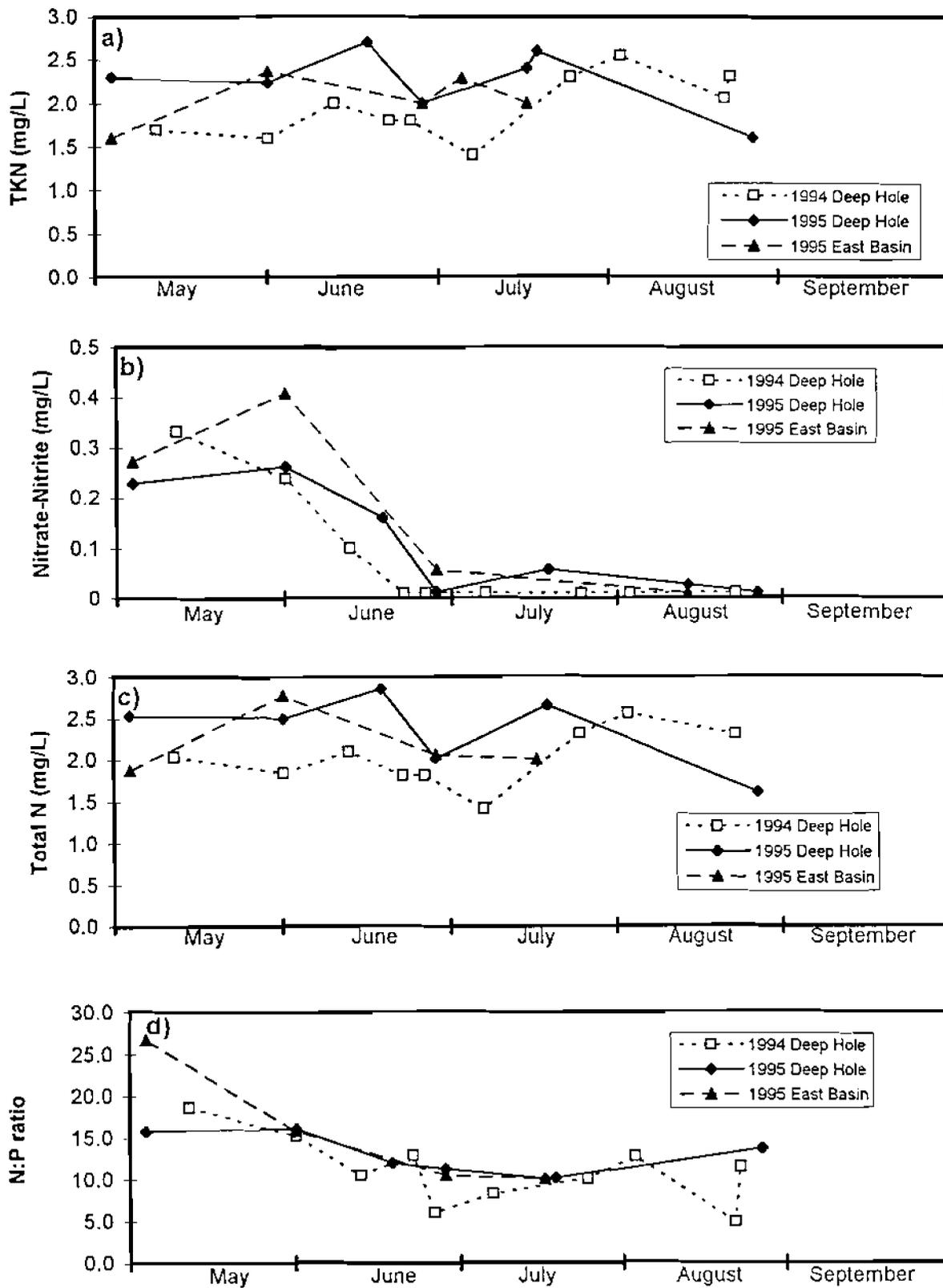


Figure 5. Seasonal trends in a) total Kjeldahl nitrogen (TKN); b) $\text{NO}_3 + \text{NO}_2\text{-N}$; c) total nitrogen (N); and d) the N:P ratio in the top 1 m at the Deep Hole in 1994 and 1995 and the East Basin in 1995.

Table 3. Phytoplankton species composition at the Deep Hole site (0.5 m) from May - Sept. 1995. D = Dominant, C = Common, S = Somewhat common, R = Rare, P = Present. Shaded areas indicate a "D" or "C" occurrence by a particular species. Species labeled "other" were grouped if they occurred only as "P".

	11-May-95	25-May-95	1-Jun-95	8-Jun-95	20-Jun-95	29-Jun-95	7-Jul-95	18-Jul-95	1-Aug-95	15-Aug-95	30-Aug-95	12-Sep-95	27-Sep-95
Blue-greens													
<i>Anabaena spiroides</i>	-	-	-	-	C	P	P	-	-	S	S	S	-
<i>Microcystis flos-aquae</i>	C	S	-	-	P	P	S	S	P	D	C	C	C
<i>Microcystis incerta</i>	-	-	-	-	-	-	-	-	-	D	-	-	-
<i>Oscillatoria agardhii?</i>	-	-	-	-	-	-	-	-	-	-	-	C	S
Other blue-greens	-	-	-	-	-	-	-	-	-	P	P	-	-
Cryptophytes													
<i>Chroomonas acuta</i>	P	-	-	-	C	S	-	C	-	-	-	-	-
<i>Cryptomonas brevis</i>	-	-	-	-	-	C	-	-	-	-	-	-	-
<i>Cryptomonas erosa</i>	-	-	C	S	D	S	-	S	-	-	-	-	-
<i>Cryptomonas erosa var. reflexa</i>	-	P	-	D	-	-	-	-	-	-	-	-	-
<i>Cryptomonas ovata</i>	-	-	P	-	-	C	C	C	P	S	S	-	C
<i>Cryptomonas rostriformis</i>	-	-	P	-	-	-	-	-	-	-	-	-	-
Diatoms													
<i>Aulacoseira granulata</i>	-	-	-	-	C	D	D	D	D	C	D	D	D
<i>Aulacoseira italica</i>	-	-	-	-	-	-	-	C	D	C	-	D	D
<i>Cyclotella</i> sp.	-	-	-	P	-	-	-	C	S	-	-	-	-
<i>Stephanodiscus</i> sp.	-	P	-	-	-	-	C	C	-	-	-	-	-
Other diatoms	-	-	-	P	-	-	-	P	-	-	-	P	P
Dinoflagellates													
<i>Ceratium hirudinella</i>	-	-	-	-	-	-	-	-	-	R	D	C	C
<i>Gymnodinium</i> sp.	-	-	-	-	-	-	-	-	-	-	P	S	-
Greens													
<i>Actinasirum hantzschii</i>	-	-	-	-	-	-	-	-	-	R	-	-	-
<i>Ankistrodesmus braunii</i>	-	-	-	R	-	-	-	-	-	-	-	-	-
<i>Asterococcus limneticus</i>	-	C	S	-	P	-	S	-	-	-	-	-	-
<i>Asterococcus superbus</i>	D	-	-	-	-	-	-	-	-	-	-	-	-
<i>Pediastrum boryanum</i>	-	-	-	C	R	P	P	P	P	P	-	P	P
<i>Sphaerocystis Schroeteri</i>	C	D	D	-	S	P	S	S	S	S	-	-	-
Other greens	P	-	-	P	P	P	P	P	P	P	P	P	P

Other blue-greens include: *Oscillatoria minima*, *Spirulina* sp.; other diatoms include: *Achnanthes* sp., *Aulacoseira* sp. (larger), *Cymbella* sp., *Fragellaria* sp., *Nitzschia* sp., *Synedra* sp.; other greens include: *Cerasterias irregularis*, *Cosmarium* sp., *Oocystis* sp., *Rhizoclonium hieroglyphum*, *Scenedesmus quadricauda*, *Spirogyra* sp., *Staurastrum* sp.

Table 4. Phytoplankton species composition at the East Basin site (0.5 m) from May - Sept 1995. D = Dominant, C = Common, S = Somewhat common, R = Rare, P = Present. Shaded areas indicate a "D" or "C" occurrence by a particular species. Species labeled "other" were grouped if they occurred only as "P".

	11-May-95	25-May-95	8-Jun-95	20-Jun-95	29-Jun-95	6-Jul-95	18-Jul-95	1-Aug-95	15-Aug-95	30-Aug-95	12-Sep-95	27-Sep-95
Blue-greens												
<i>Anabaena spiroides</i>	-	-	-	D	S	-	-	-	R	S	S	S
<i>Aphanizomenon flos-aquae</i>	-	-	-	-	-	-	-	-	-	C	C	S
<i>Chroococcus</i> sp.?	-	-	P	-	-	-	-	-	-	-	-	-
<i>Dactylococcopsis</i> sp.	-	-	-	-	-	-	-	-	-	-	-	-
<i>Geminella interrupta</i> ?	-	-	-	-	-	-	-	-	-	-	-	D
<i>Microcystis flos-aquae</i>	D	-	-	S	S	S	S	D	C	C	C	S
<i>Microcystis tancera</i>	-	-	-	-	-	-	-	C	-	-	-	-
<i>Oscillatoria agardhii</i>	-	-	-	-	P	-	-	-	-	P	D*	C
Chrysophytes	-	-	-	-	-	-	-	-	-	-	-	-
<i>Ochromonas</i> sp.?	-	-	-	-	-	-	-	-	-	-	-	-
Cryptophytes												
<i>Chroomonas axuta</i>	-	-	-	C	S	S	S	S	-	-	-	-
<i>Cryptomonas brevis</i>	-	-	-	-	D	-	D	-	S	-	-	-
<i>Cryptomonas erosa</i>	-	-	-	D	C	C	-	S	S	-	P	C
<i>Cryptomonas erosa</i> var. <i>reflexa</i>	-	-	-	-	-	-	-	-	-	-	-	-
<i>Cryptomonas marssonii</i>	-	-	S	-	P	-	-	-	-	-	-	-
<i>Cryptomonas ovalis</i>	-	-	-	-	-	D	C	D	S	C	-	-
Diatoms												
<i>Aulacoseira granulata</i>	-	-	-	P	-	S	D	C	C	C	D	D*
<i>Aulacoseira itadica</i>	-	-	-	-	-	-	-	S	C	C	D	D*
<i>Aulacoseira</i> sp. (large)	-	-	-	-	-	-	-	-	-	-	-	C
<i>Cyclotella</i> sp.	P	-	-	-	-	S	S	S	D*	S	-	S
<i>Fragilaria crotonensis</i>	-	-	-	-	-	-	-	-	-	-	-	-
<i>Nitzschia acicularis</i>	-	-	-	-	-	-	-	S	-	-	-	-
<i>Stephanodiscus niagarae</i>	S	P	-	-	-	-	-	-	-	-	-	-
<i>Synedra</i> sp.	-	-	-	-	-	-	-	-	-	-	S	-
Other diatoms	-	-	-	-	-	-	-	-	-	-	-	-
Dinoflagellates	-	-	-	-	-	-	-	-	-	-	-	-
<i>Ceratium hirundinella</i>	-	-	-	-	-	-	-	-	S	C	S	S
Greens												
<i>Actinastrum hantzschii</i>	-	-	-	-	-	-	-	-	C	P	S	-
<i>Ankyra judayi</i>	-	-	-	-	-	-	-	-	-	-	-	-
<i>Asterococcus limneticus</i>	S	C	-	-	-	-	-	-	-	-	-	-
<i>Pediastrum boryanum</i>	S	-	C	-	P	-	S	P	P	P	-	P
<i>Sphaerocystis schraeterei</i>	P	D	-	-	D	-	-	C	S	-	-	P
Other greens	-	-	-	-	-	-	-	-	-	P	P	P

Other diatoms include: *Amphora ovalis*, *Mastogloia braunii*, *Nitzschia sigmaioideae*; other greens include: *Cladocorm* sp., *Oocystis* sp., *Pseudonitzschia* sp., *Scenedesmus abundans*, *Scenedesmus quadricauda*, *Schroederia setigera*, *Siaurostrum* sp.

Table 5. Phytoplankton species composition at the Deep Hole site (0.5 m) from June - Sept. 1994. D = Dominant, C = Common, S = Somewhat common, R = Rare, P = Present. Shaded areas indicate a "D" or "C" occurrence by a particular species. Species labeled "other" were grouped if they occurred only as "P".

	1-Jun-94	23-Jun-94	8-Jul-94	10-Aug-94	8-Sep-94
Blue-greens					
<i>Aphanizomenon flos-aquae</i>	--	S	S	--	--
<i>Chroococcus</i> sp.	S	C	C	--	--
<i>Microcystis flos-aquae</i>	S	C	D	D	D
<i>Microcystis incerta</i>	D	D	C	--	--
<i>Oscillatoria agardhii</i>	S	P	--	P	P
Cryptophytes					
<i>Cryptomonas erosa</i>	--	--	P	--	--
Diatoms					
<i>Asterionella formosa</i>	C	--	--	--	--
<i>Aulacoseira granulata</i>	P	S	S	S	P
<i>Aulacoseira italica</i>	--	S	S	--	P
<i>Stephanodiscus niagare</i>	P	P	P	S	P
Dinoflagellates					
<i>Ceratium hirudinella</i>	--	--	P	P	--
Greens					
<i>Pediastrum boryanum</i>	C	P	P	--	--
<i>Scenedesmus quadricauda</i>	S	--	--	--	--
<i>Sphaerocystis Schroeteri</i>	C	--	--	--	--
Other greens ¹	P	P	--	P	--

¹Other greens include: *Staurastrum* sp. and *Oocystis* sp.

appear to be present at all times. Similar shifts have been observed on other shallow lakes, such as Cedar Lake, Polk Co. (Garrison, unpubl. data).

One possible explanation for this shift in dominance could be the availability of nitrogen. N:P ratios in the lake are near the transition zone between N limitation and P limitation. As P levels are rather high, the availability of inorganic N may have the most effect upon the N:P ratio. Years with low inorganic N may favor dominance of blue-greens, while years with higher inorganic N may favor *Aulacoseira*. It is possible that the high abundance and grazing pressure of the zooplankton community kept the algae from using all of the available inorganic N or even recycled the N, making conditions more favorable to greens and diatoms and allowing *Aulacoseira* to become the dominant phytoplankton species.

Another explanation could have to do with the timing and amount of anoxia at the sediment

surface. Blue-greens in general, and *Microcystis* in particular are favored by low oxygen levels (Reynolds and Walsby 1975; Trimbee and Prepas 1988). *Microcystis* overwinters at the sediment surface where it forms colonies. *Microcystis* may also be favored during periods of temporary stratification in the summer. More frequent or longer periods of stratification may allow greater build up of *Microcystis* populations. Unfortunately records of stratification and winter conditions are spotty, if known at all for Fox Lake.

C. Zooplankton

In 1995, the zooplankton community was dominated by the cladocerans *Daphnia schodleri* and *D. galeata mendotae*, and the copepods *Leptodiaptomus siciloides* and *Acanthocyclops vernalis*. The relative abundance of the species encountered were quite similar to the zooplankton community in 1994 with the notable exception that we observed a shift in cladoceran dominance to *D. schodleri* in 1995 from *D. galeata mendotae* in previous years (Table 6).

Table 6. Species composition and relative abundance of the Fox Lake zooplankton community, 1974 - 1995. 0 = absent, 1 = present, 2 = occasional, 3 = common, 4 = very common, 5 = abundant. Shaded areas indicate 4 and 5 ratings for a particular species.

	1974 ¹	1986 ²	1987 ²	1988 ²	1994	1995
<i>CLADOCERANS</i>						
<i>Daphnia schodleri</i>	0	0	0	0	3	5
<i>D. retrocurva</i>	3	3	2	5	2	3
<i>D. pulicaria</i>	0	2	0	0	0	2
<i>D. galeata mendotae</i>	2	3	0	2	5	4
<i>Diaphanosoma sp.</i>	3	4	3	4	0	2
<i>Ceriodaphnia sp.</i>	0	1	0	0	0	1
<i>Chydorus sphaericus</i>	4	3	5	4	0	4
<i>Eubosmina coregoni</i>	2	4	4	5	0	1
<i>Bosmina longirostris</i>	0	2	0	0	0	0
<i>Leptodora sp.</i>	1	2	0	1	0	1
<i>COPEPODS</i>						
<i>Leptodiaptomus siciloides</i>	3	3	2	1	5	5
<i>Skistodiaptomus oregonensis</i>	0	2	0	2	0	0
<i>Diacyclops thomasi</i>	1	1	0	1	1	1
<i>Acanthocyclops vernalis</i>	3	3	2	5	4	4
<i>Mesocyclops edax</i>	3	2	1	1	0	1
<i>Eucyclops speratus</i>	0	0	0	0	0	1
<i>Mucrocyclops albidus</i>	0	0	0	0	0	1

¹ Data from Torke 1979.

² Data from LTTM program (unpublished).

Although the species composition observed in 1995 was similar to previous years, we observed a marked increase in the overall biomass of the zooplankton population and that large-bodied forms were present for a more prolonged period. Zooplankton biomass was 2 to 3 times higher in 1995 than in 1994 for most of the summer, mostly due to the increased abundance of *D. schodleri* (Fig. 6). (Note: we have lumped together *D. schodleri* and *D. pulicaria* for this analysis.) Copepods were also more abundant in 1995.

The drastic increase in the abundance of large bodied *D. schodleri* in 1995 was the most notable difference from previous years. *D. schodleri* biomass was extremely high under the ice in 1995 and remained very high throughout the spring months. The *Daphnia* population crashed by late June, but then reemerged in July (Fig. 6). Large *Daphnia* are capable of exerting much more intense grazing pressure on the algal community than small bodied *Daphnia* (Luecke et al. 1992; Vanni et al. 1992). Thus the prolonged period of increased *D. schodleri* biomass seen in 1995 translated to much more intense grazing pressure exerted on the algae community and likely contributed to the observed increase in water clarity.

The population dynamics of *D. schodleri* suggest that food availability was the predominant limiting factor on population size. By comparing *Daphnia* reproductive potential (eggs per female) to population biomass, it is possible to determine if food availability or predation pressure reduced the population. Reproduction appeared to drop at the same times that biomass fell (Fig. 7), suggesting that food was scarce and the *Daphnia* allocated less energy to reproduction, consequently reducing the size of the population.

Predation did not appear to be the major factor in reducing the *Daphnia* population, despite a history of abundant planktivorous fish in Fox Lake. Predation may have been buffered by the abundant macrophyte growth seen in 1995 which could have provided refugia for zooplankton. Indeed, the reemergence of *D. schodleri* in July of 1995 coincided with a large growth of curly-leaf pondweed (*Potamogeton crispus*) in shallower areas. In addition, 1995 may have been a poor year for the recruitment of young white crappie, the dominant zooplanktivore in Fox Lake. White crappie populations are highly cyclical and exhibit regular increases and declines in their population (Congdon, pers. comm.). In 1995, the age structure appeared to be dominated by large adults, suggesting that there may have been relatively few juveniles to prey on zooplankton. This may have created a window of opportunity for the large zooplankton to dominate. Reduced predation may also have been related to unusual climatic factors, such as cool spring temperatures or high June temperatures, which may have delayed or interfered with the normal hatching of white crappie and other planktivores.

D. Fish Diet

Diet patterns were estimated for each major species captured in June, July, and August of 1995. With the data collected, we were able to look at diet shifts within an age class over one summer as well as differences among age classes. Sampling limitations reduced the capture of younger age classes, so assessment of the diet for young-of-the-year (YOY) and immatures was not as

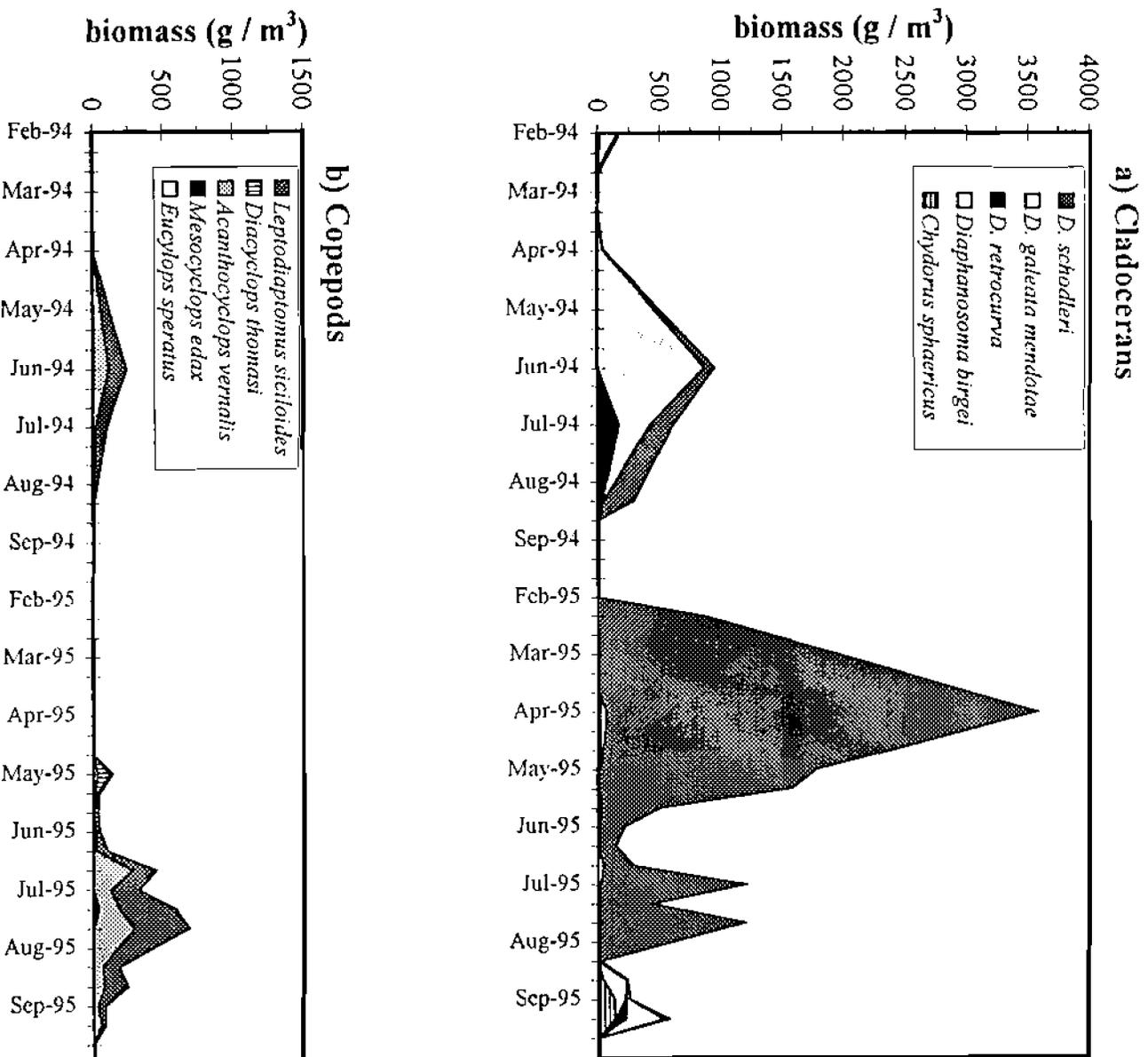


Figure 6. Cumulative biomass of zooplankton collected from tows at the Deep Hole in 1994 and 1995. a) Cladoceran species; and b) Copepod species. Total biomass for each group is indicated by the top of the area plot with the proportion of individual species indicated by different shades. Species are ordered by decreasing abundance.

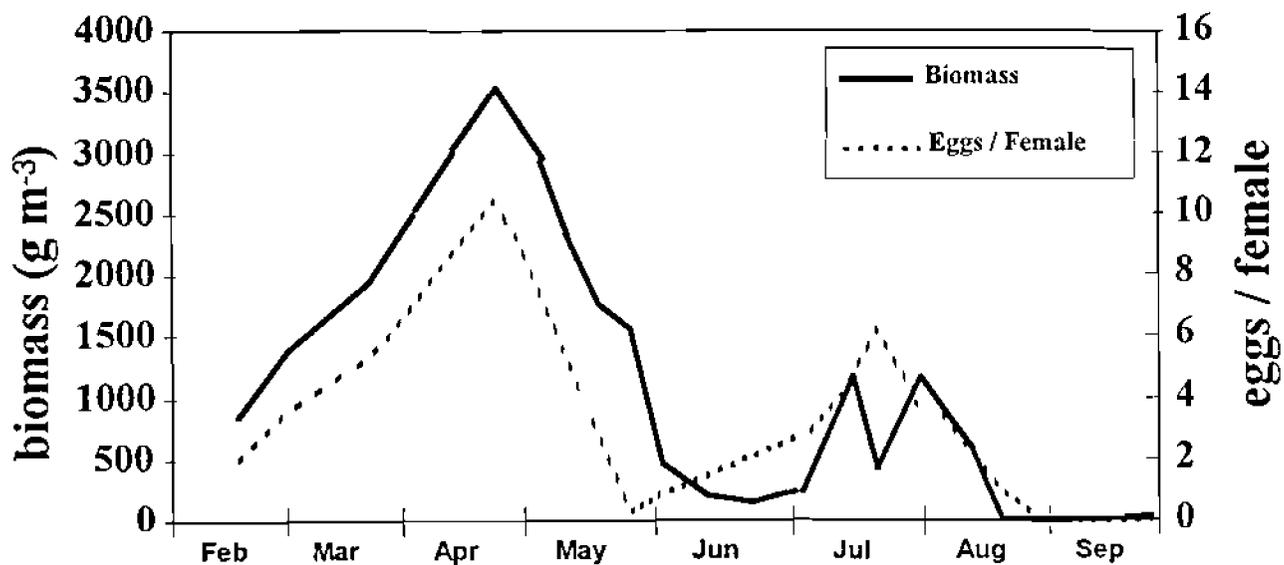


Figure 7. Biomass and reproductive potential (eggs/female) of *Daphnia schodleri* collected from the Deep Hole in 1995.

complete as for adults. It is important to note that several species have months where very few fish were captured from a given age class, so the patterns discussed here should only be treated as rough estimates.

Bluegill (*Lepomis macrochirus*) exhibited a seasonal diet shift from predominantly cladocerans in June to insects in August (Table 7). This may have been the result of natural fluctuations in the availability of these prey throughout the summer, or due to foraging shifts in response to increased competition with other fishes as the summer progressed (Becker 1983). YOY bluegill showed a preference for copepods throughout the summer and did not seem to show as much of a shift from cladocerans to insects as in the immatures and adults. In July and August, copepods made up over 80% of the prey items chosen by the YOY.

Yellow perch (*Perca flavescens*) adults showed a marked shift from insects in early summer to what we termed "other:" amphipods, isopods, decapods, clams, snails and small fish (Table 7). Cladocerans were also taken in June and July, but were never the dominant prey choice. As with the bluegill, these shifts in diet were likely the result of changes in prey availability or competition. Diet analysis for immature and YOY perch were not conducted due to low sampling yield of these age classes.

Pumpkinseed (*Lepomis gibbosus*) showed diet shifts very similar to those seen in the bluegill. In both immatures and adults, we observed a general shift from cladocerans in early summer to predominantly insects in mid and late summer (Table 7). Once again, diet analysis of YOY was not conducted due to low sampling yield.

White crappie (*Pomoxis annularis*) appeared to prey most heavily upon copepods as YOY, and then shift to cladocerans and insects as adults. Further analysis of diet patterns was hampered by low sampling yield across all age classes, although white crappie was the dominant panfish species in 1995.

Black crappie (*Pomoxis nigromaculatus*) adults showed a diet shift from predominantly insects in early summer to predominantly cladocerans in late summer. This pattern is the opposite of those seen in bluegill and pumpkinseed, and suggests that the black crappie may have competed with these fishes for their preferred diet of pelagic cladocerans.

Although the fish diet data is not complete, we can draw a few conclusions and support the trends in water quality and zooplankton biomass. Cladocerans (primarily *D. schodleri*) made up a significant proportion of the stomach contents for several fish species in June, implying that fish were preying heavily upon the abundant *Daphnia* population. By July, fish diets had shifted to other groups of organisms (insects and copepods), allowing a resurgence of the *Daphnia*. Black crappie were preying on cladocerans again in August, possibly contributing to the second decline of the *D. schodleri* (Fig. 6). With limited data, it is difficult to discern the cause and effect of the zooplankton biomass and fish forage habits, but it is probable that complex feedback loops were at work in the lake, as well as variable behavioral dynamics of the fish community. More detailed

Table 7. Relative percentages of prey items taken by different fishes of different age classes in June, July and August of 1995. Percentages are calculated as the average proportion of the total prey intake on average for an individual fish. (Calculated from the number of prey individuals consumed, not biomass or volume.)

Species	Age Class	21-Jun			18-Jul			25-Aug			
		N	item	%	N	item	%	N	item	%	
Bluegill	YOY < 7.5 cm	[shaded]	[shaded]	[shaded]	20	Cladocera	6.1%	20	Cladocera	17.3%	
			[shaded]	[shaded]							
			[shaded]	[shaded]							
	IMMATURE 7.5 - 12.5 cm	26	Cladocera	81.6%	16	Cladocera	3.1%	3	Cladocera	0.0%	
			Insects ¹	15.1%		Insects	62.0%		Insects	93.3%	
			Copepods	0.0%		Copepods	0.0%		Copepods	0.0%	
			Other ²	3.3%		Other	3.5%		Other	6.7%	
	ADULT > 12.5 cm	15	Cladocera	41.3%	1	Cladocera	72.5%	23	Cladocera	3.7%	
			Insects	56.6%		Insects	27.5%		Insects	77.6%	
Copepods			0.0%		Copepods	0.0%		Copepods	0.0%		
Other			2.1%		Other	0.0%		Other	18.7%		
Yellow Perch	ADULT 11 - 23 cm	21	Cladocera	13.7%	32	Cladocera	39.7%	24	Cladocera	0.0%	
			Insects	79.9%		Insects	57.9%		Insects	0.0%	
			Copepods	0.0%		Copepods	0.0%		Copepods	0.0%	
			Other	6.4%		Other	2.4%		Other	100.0%	
Pumpkinseed	IMMATURE < 7.5 cm	22	Cladocera	37.2%	20	Cladocera	1.0%	16	Cladocera	0.0%	
			Insects	57.0%		Insects	85.0%		Insects	96.6%	
			Copepods	0.0%		Copepods	0.0%		Copepods	0.0%	
			Other	5.9%		Other	14.0%		Other	3.4%	
	ADULT > 7.5 cm	6	Cladocera	71.6%	5	Cladocera	0.0%	1	Cladocera	0.0%	
			Insects	22.2%		Insects	100.0%		Insects	100.0%	
			Copepods	0.0%		Copepods	0.0%		Copepods	0.0%	
			Other	6.1%		Other	0.0%		Other	0.0%	
White Crappie	YOY < 5 cm	[shaded]	[shaded]		5	Cladocera	7.4%	[shaded]			
			[shaded]			Insects	0.2%	[shaded]			
			[shaded]			Copepods	92.2%	[shaded]			
	ADULT > 7.5 cm	36	Cladocera	59.1%	[shaded]		[shaded]				
			Insects	40.1%	[shaded]		[shaded]				
			Copepods	0.0%	[shaded]		[shaded]				
		Other	8.0%	[shaded]		[shaded]					
Black Crappie	ADULT 11 - 22 cm	17	Cladocera	3.1%	2	Cladocera	0.0%	9	Cladocera	52.8%	
			Insects	95.1%		Insects	60.0%		Insects	45.2%	
			Copepods	0.0%		Copepods	0.0%		Copepods	0.0%	
			Other	1.8%		Other	39.1%		Other	2.0%	

1 Insects include Trichoptera, Hemiptera, Ephemeroptera, Odonata, Coleoptera, Plecoptera, Chironomidae and other Diptera (mostly Chironomidae).

2 "Other" includes Amphipods, Isopods, Decapods, clams, snails, mites and fish

information on the temporal and spatial feeding behavior of the fish community in Fox Lake would be helpful.

E. Macrophytes

The dominant macrophyte species in 1995 was coontail (*Ceratophyllum demersum*), at about 59% relative frequency (Table 8). Eurasian water milfoil (*Myriophyllum spicatum*) and sago pondweed (*Potamogeton pectinatus*) were also common. These three species were also dominant in 1994, though at different proportions. More species were found in 1994 than in 1995, likely because of the greater number of transects surveyed in 1994. Coontail may be displacing sago pondweed in the lake as the dominant species; however, we do not have enough information to determine whether this is a long term trend or due to the clear water in 1995. Although it did not show up in our transects, large areas of curly-leaf pondweed (*P. crispus*) were established in the lake in early June of 1995, much of which had died off by the time we surveyed the lake in late July.

Table 8. Relative frequencies of macrophyte species in the aquatic plant community in Fox Lake, 1976 - 1995 (% of plants encountered).

Common name	Scientific name	1976 ¹	1989 ¹	1994 ¹	1995
Coontail	<i>Ceratophyllum demersum</i> L.	15.6	33.8	32.5 ²	58.7 ²
Elodea	<i>Elodea canadensis</i> Michx.	--	--	1.1	4.1
Naiad, slender	<i>Najas flexilis</i> (Willd.) Rostk. & Schmidt.	--	--	0.4	--
Pond lily, yellow	<i>Nuphar</i> sp.	--	1.9	--	--
Pondweed, curly leaf	<i>Potamogeton crispus</i> L.	--	0.6	6.5	4.1
Pondweed, horned	<i>Zannichellia palustris</i> L.	--	--	0.4	--
Pondweed, leafy	<i>Potamogeton foliosus</i> Raf.	--	--	1.1	--
Pondweed, sago	<i>Potamogeton pectinatus</i> L.	61.0	0.6	30.7	7.4
Water celery	<i>Vallisneria americana</i> Raf.	--	17.2	0.8	--
Water lily, white	<i>Nymphaea</i> sp.	--	14.0	8.0	--
Water milfoil, Eurasian	<i>Myriophyllum spicatum</i> L.	23.4	26.1	16.5	19.8
Water stargrass	<i>Zosterella dubia</i> (Jacq.) Small	--	5.6	1.9	5.8

¹Data from 1976-1994 reported in Winkelman (1995a).

²Includes *C. demersum* and *C. echinatum* Gray.

Macrophytes were more dense in 1995 and grew in deeper waters than in 1994. Mean density ratings on a scale of 0 to 5 were calculated for each depth interval from all transects. In 1994, a

whole-lake peak density of 0.8 occurred at 2-3 feet, but quickly declined to 0.0 at 5 ft (Fig. 8). Peak density was even lower in the 7 transects that were resurveyed in 1995. Mean density ratings were higher at all depths in 1995, with a peak density of 1.5 at 2.5 ft. Plants were still relatively abundant at 4.5 feet and occurred as deep as 7.5 ft. Plants were more abundant at all of the transects in 1995 (Fig. 9), particularly transects 2 and 17. Importantly, plants occurred at 3 transects where no plants were found in 1994.

The more abundant plants in 1995 are likely the result of the improved water clarity, which allowed greater rooting depths. However, other factors may have contributed to increased plant recruitment, which in turn enhanced water clarity by holding sediments in place and providing cover for *Daphnia*. Water levels were 0.5 ft. lower than normal in 1994 (Sesing, pers. comm.), perhaps allowing greater areal coverage despite the poor water clarity. In 1995, plants may have responded to these lower water levels and become established more quickly than in previous years. Cool temperatures in the spring of 1995 may have favored early macrophyte establishment.

F. Sedimentation and resuspension

Gross sedimentation rates among the four sites varied between $68.3 \text{ g m}^{-2} \text{ d}^{-1}$ and $180.6 \text{ g m}^{-2} \text{ d}^{-1}$ for the period from 12 July to 12 Oct. (Table 9). Sedimentation was greater in the shallower sites (East and South Basins) indicating that particles reached the sediment surface at a greater rate. Sedimentation rates are generally higher in shallow lakes than in deep lakes (Evans 1994), and thus higher rates would be expected in shallow areas than in deep areas. However, the sedimentation rates at all sites were much higher than rates observed in other lakes (Evans 1994).

Table 9. Mean sedimentation and resuspension rates ($\text{g m}^{-2} \text{ d}^{-1}$) for the period of July 12 - Oct. 12, 1995 as measured by paired sedimentation traps (see text). Minimum/maximum values are given in parentheses.

	<u>East Basin</u>	<u>South Basin</u>	<u>North Basin</u>	<u>Deep Hole</u>
Gross Sedimentation	180.6 (94.5/265.7)	147.6 (56.0/355.6)	116.8 (41.4/188.6)	68.3 (19.2/126.3)
Net Sedimentation	140.3 (41.2/234.4)	85.6 (25.1/157.0)	55.5 (6.5/115.2)	25.8 (3.1/59.4)
Resuspension	40.3 (-8.3/81.0)	62.1 (25.4/198.6)	61.2 (33.6/95.6)	42.5 (11.8/66.9)
Resuspension (% of Gross)	22.7 (-8.7/66.3)	40.5 (22.3/56.3)	57.7 (38.9/84.4)	66.8 (53.0/89.6)

Resuspension rates were relatively uniform among sites ($40 - 60 \text{ g m}^{-2} \text{ d}^{-1}$), but represented a larger proportion of gross sedimentation in the Deep Hole and North Basin (Table 9). While these rates are high, one would expect higher rates of resuspension in shallow areas where waves impinge upon the sediment surface more frequently. For example, Evans (1994) found that

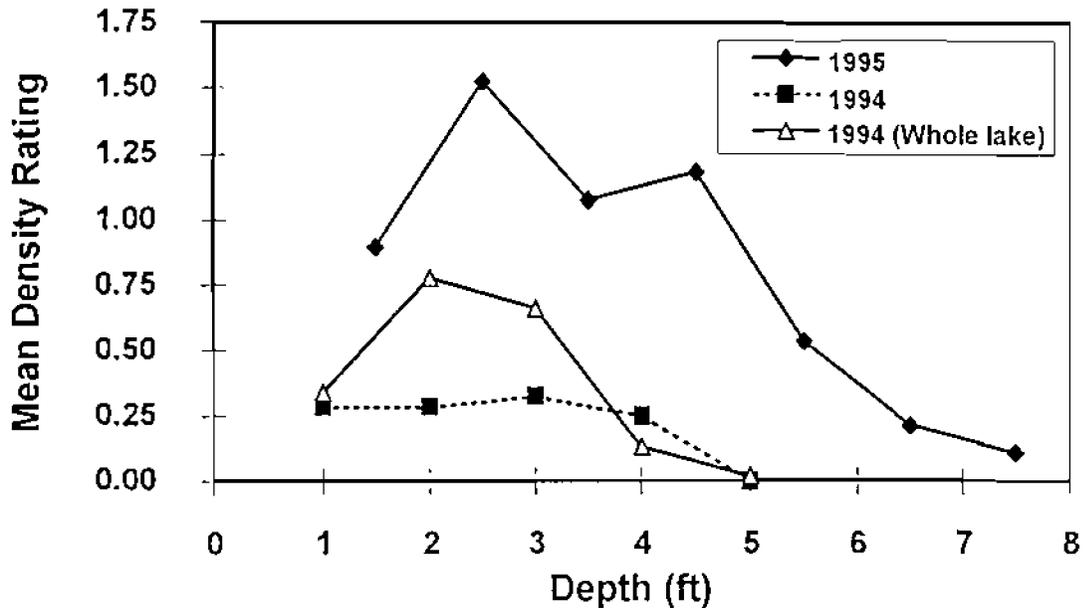


Figure 8. Mean density ratings by depth for all plant species found in macrophyte surveys in 1994 and 1995. The "1995" and "1994" lines are for the 7 transects indicated in Fig. 1. The "1994 (Whole lake)" line is for all 25 transects surveyed in 1994. Density is rated on a scale of 0 (no plants) to 5 (head of rake completely covered with plants).

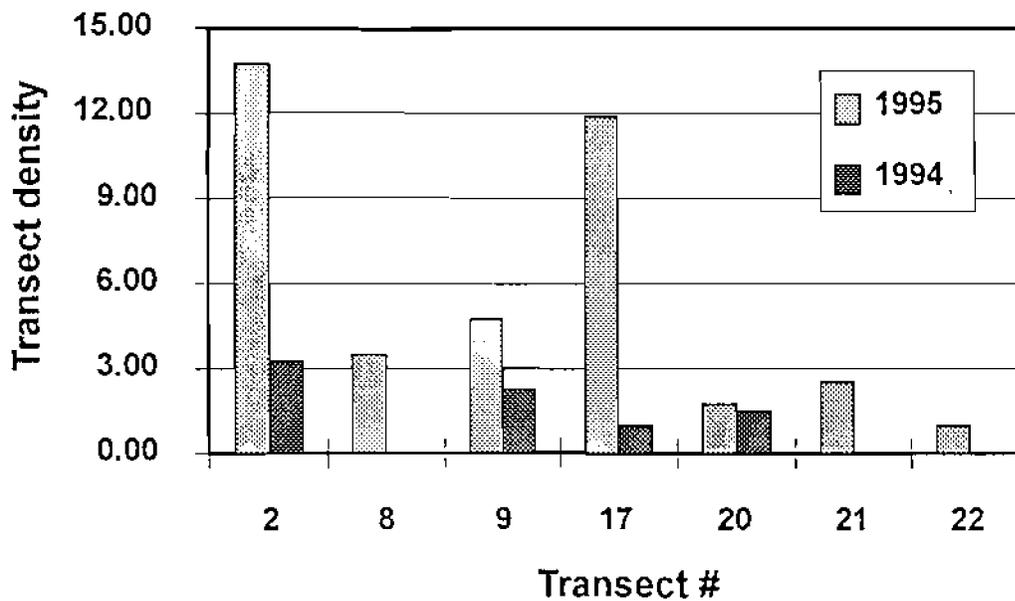


Figure 9. Transect density of all plant species found in 7 transects in 1994 and 1995. Location of transects is given in Fig. 1. Transect density is the sum of all density ratings obtained along a transect and can range from 0 to 5 times the number of depths surveyed.

resuspension typically accounts for 80-90% of gross sedimentation. A possible explanation for this discrepancy is that particles may stay in suspension for a longer period of time in the deeper sites as compared to the shallower sites, following a period of strong winds. Thus, if traps are retrieved shortly after a wind event, less sediment material would be found in the deeper sites. Alternatively, the higher sedimentation and lower resuspension rates in the shallow sites may be due to the presence of macrophytes at these sites. Macrophytes can serve to trap sediment particles as well as stabilize sediments (Zieman 1976; James and Barko 1994). Thus even though rates of sedimentation and resuspension are quite high compared to other lakes, the macrophytes may be preventing even higher rates.

In late September and early October, sedimentation was greatest at the North Site, though overall sedimentation rates were lower than the previous periods (Fig. 10). Sediment resuspension generally increased from late July to early October in the two deepest sites, while declining in the shallow sites. Higher sedimentation rates in the shallow sites in August may reflect settling of algal cells as well as sediments. Most of the temporal variability is likely due to varying weather conditions. Wind velocity increased on average from late summer into fall, and may have caused the greater rates of sediment resuspension. Wind direction also shifted slightly more to the east, possibly affecting the effective fetch and resultant wind mixing at the different sites.

G. Sediment phosphorus dynamics

Sediment resuspension has been implicated in the decline in water clarity of Fox Lake, both in terms of the amount of sediment material reaching the lake from the watershed (Sesing et al. 1991) and the loss of aquatic vegetation which has decreased sediment stability (Winkelman 1995a,b). Concurrent with the increased sediment resuspension is the recycling of phosphorus in the lake which represents a large proportion of the P budget (Winkelman and Garrison 1996). Ongoing work indicates that wind events do increase TP concentrations in the lake, associated with increased suspended solids and turbidity (Asplund, unpub. data). Unclear is whether these increases in TP translate into increased algal growth and what role this mechanism plays compared to other mechanisms, such as the release of P from oxic and anoxic sediments.

Sediment P concentrations in the two shallow sites (East and South Basins) were 1300 mg kg^{-1} dry wt. (Table 10), relatively high compared to other shallow hard water lakes (Asplund 1996). NH_4Cl extractable P, corresponding to loosely bound P, was also relatively high (Søndergaard et al. 1992; Asplund 1996), representing about 11% of the TP. NaOH-P for the sites was 453 and $423 \text{ } \mu\text{g g}^{-1}$ dry wt. respectively, representing about 33% of the total P in the sediments. This P fraction has been found to be roughly equivalent to the amount of P available for algal uptake (Sagher et al. 1975; Williams et al. 1980). However, sediment assays resulted in very low amounts of algal growth, with algal-P concentrations at less than 2% of TP (Table 10).

Asplund (1996) has documented low rates of algal uptake in lakes with high Ca concentrations, while others have shown that algal uptake is lower in sediments with high organic matter (Klapwijk et al. 1982). The Fox Lake sediments were high both in Ca and organic matter (Table

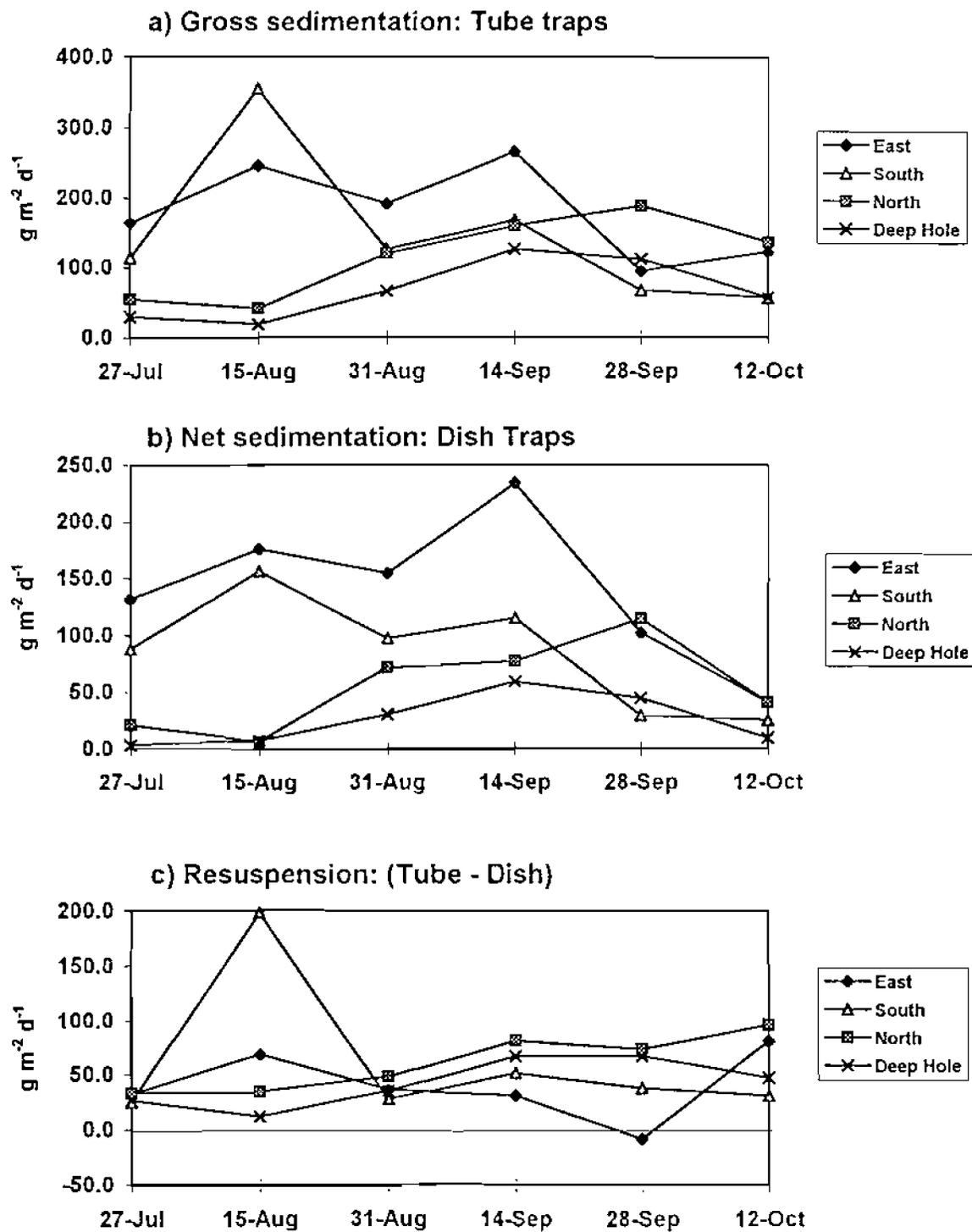


Figure 10. Sedimentation and resuspension rates in 4 areas of Fox Lake (see Fig. 1) as measured by sediment traps sampled biweekly from 12 July - 12 Oct. 1995. a) Gross sedimentation (total amount of sedimented material collected in narrow tube traps); b) Net sedimentation (amount of material collected in shallow dish traps); and c) Resuspension (difference between gross and net sedimentation).

Table 10. Surface sediment characteristics of two shallow sites and the Deep Hole. Deep Hole sample obtained from a March 1994 core. All values except % moisture given on dry weight basis.

	East Basin	South Basin	Deep Hole
% moisture	89.4	91.2	95.5
% organic	47.8	46.8	34.3
% sand	25	17	--
% silt	64	69	--
% clay	11	14	--
pH	6.9	7	--
TKN ($\mu\text{g g}^{-1}$)	23000	25000	12000
NH ₃ -N ($\mu\text{g g}^{-1}$)	490	500	--
Fe ($\mu\text{g g}^{-1}$)	8300	9800	4500
Ca ($\mu\text{g g}^{-1}$)	120000	110000	94000
TP ($\mu\text{g g}^{-1}$)	1300	1300	1300
Mill-Q P ($\mu\text{g g}^{-1}$)	130.0	156.8	--
NH ₄ Cl-P ($\mu\text{g g}^{-1}$)	145.7	146.2	--
NaOH-P ($\mu\text{g g}^{-1}$)	453.0	422.7	--
Algal-P ($\mu\text{g g}^{-1}$)	3.5	23.9	--

10), suggesting that much of the TP was tied up as apatite Ca-bound P or organic P. Thus while wind mixing in the shallow areas of Fox Lake may stir up sediments, the amount of P released may be relatively minor and essentially unavailable for algal growth.

These findings differ from work by Winkelman and Garrison (1996), who simulated oxic release of P in the lab with cores from the East Basin and Deep Hole. Rates of P release were typical of shallow lakes in the East Basin core, but very high in the Deep Hole core (Kirstensen et al. 1992, Søndergaard et al. 1992). Thus the sediments would appear to be a major source of P to algae, rather than a minor source as suggested by the assays. Two reasons may account for this discrepancy. First, the two methods are really measuring different mechanisms of P dynamics and may not be directly comparable. The assays were measuring algal stimulation from mixed sediment material, while the core method was measuring P release from the quiescent sediment surface. Second, James et al. (in press) have found that P release rates are highly dependent upon pH, nearly doubling with an increase in pH from 8.5 to 9.0. Thus when photosynthetic rates are

high, increased pH may increase the amount of oxic P release in shallow areas of Fox Lake (Winkelman and Garrison 1996). We do not know what the pH levels were in our assays, but they may very well have been lower than 8.5. Increased pH monitoring in Fox Lake may be warranted to better understand the importance of sediment P release.

When the lake stratifies, P concentrations can reach very high levels due to the anaerobic conditions near the sediment surface, as occurred in June of 1995 (Fig. 4). Subsequently, DRP and TP increased after the lake mixed at the end of June (Fig. 3). Stratification in Fox Lake is infrequent, however, and likely occurs only over a relatively small area of the lake. Winter anoxia may be an important source of P cycling as larger areas of sediment may become anoxic. High levels of P have been measured near the bottom in February (Sesing, unpub. data). It is unclear what effect this increased P under ice may have on summertime algal populations as much of the P precipitates back to the bottom at ice out. More detailed information on winter oxygen levels and P concentrations is needed.

In summary, sediment resuspension appears to be an important mechanism for increasing TP in Fox Lake, but more important sources of P for algal uptake may be 1) anoxic release of P through iron reduction in deeper areas of the lake which are subsequently mixed up into the water column and throughout the lake; and 2) oxic release of DRP under high pH conditions where hydroxide is exchanged for phosphate. Both of these mechanisms occur independent of wind mixing, but result in the transport of P to the water column which is exacerbated through wind mixing.

IV. Conclusion: Alternative Stable States - 1994 vs. 1995

Shallow lakes such as Fox Lake exist in one of two alternative stable states (Scheffer 1990; Blindow et al. 1993). At low nutrient concentrations, shallow lakes tend to have clear water, high macrophyte growth, and a balanced fishery. At high nutrient levels, shallow lakes tend to be turbid, experience sustained algae blooms and poor macrophyte growth, and are dominated by planktivorous or rough fish. Many lakes shift from one state to another over time, or even from year to year depending upon nutrient levels or more complex biotic interactions (Hosper and Jagtman 1990; Scheffer et al. 1993). Fox Lake has shifted between these two alternative stable states over time (Garrison and Hurley 1996; Winkelman and Garrison 1996), but with increased nutrient levels in the last decade, has tended to persist in the turbid, algal-dominated state.

In 1995, Fox Lake shifted back to a clear-water, macrophyte dominated state, although it is likely that this shift was temporary. Water clarity was much greater (Fig. 3), macrophytes were more abundant and more widespread (Fig. 8), and chl *a* concentrations were much lower than in 1994 or the 10 years prior (Fig. 2). Blue-green algae blooms did not occur until late in the summer (Table 3), and zooplankton were very large and abundant through the middle of August (Fig. 6). All of these changes occurred despite the fact that total P concentrations remained high and comparable to 1994 (Fig. 3).

A combination of unusual climatic events coupled with biotic interactions likely accounted for the

shift to a clear state in 1995. Lakes often exhibit a clear water phase in late spring and early summer, characterized by high zooplankton abundance which graze on the algae and keep the water clear (Lathrop and Carpenter 1992; Vanni et al. 1992). This clear water phase usually ends when the zooplankton either starve from low food supply or are preyed upon by planktivorous fish. In addition, warmer water temperatures foster the growth of algae. Thus as zooplankton are declining and algae are increasing, the clear water phase ends.

In 1995 this clear water phase was maintained in Fox Lake until the middle of August. A variety of factors likely contributed to the extended clear water phase. Water temperatures in April and May were cooler than normal and may have limited algal productivity and delayed fish spawning so that zooplankton were able to thrive and stay abundant. Macrophyte growth was encouraged by the clear water and cool spring and may have provided a refuge for zooplankton from fish predation. In addition, the increased macrophytes and relatively calm weather in June may have reduced sediment resuspension and maintained relatively good water clarity. Predation on zooplankton may have been reduced due to late spawning, poor recruitment of planktivorous fish, or the availability of a refuge. Lower numbers of blue-greens and the availability of more edible diatoms and cryptophyte species in June and July may have contributed to the higher zooplankton biomass. Unfortunately, many of these factors are interconnected and it is difficult to discern what factor was most important or which came first.

Poor year classes or low populations of planktivorous fish could have been responsible for the increase in zooplankton biomass and extended clear water phase in 1995. However, most of the planktivorous fish populations did quite well in 1995 (Congdon, unpubl. data). White crappie were quite abundant in the lake, particularly in the larger size classes. Fall seining indicated an established year class, but there is no past data to make a qualitative assessment. Bluegill experienced a very large hatch in 1995, but existing numbers and sizes of adults are moderate. Largemouth bass and walleye also experienced relatively good recruitment in 1995. Ironically, zooplankton thrived in the lake despite this relatively good fish recruitment. Indeed the good recruitment may have been enhanced by the abundant food source, clearer water, and more extensive macrophyte growth. Fish did not appear to limit the zooplankton community until mid-August, when zooplankton crashed and phytoplankton increased.

The fact that blue-greens were suppressed until the middle of August despite the high amounts of nutrients is curious and difficult to explain. Blue-green algae blooms sometimes occur with high abundances of large zooplankton due to their high grazing efficiency on other algae groups (Lynch 1980). However, Lynch (1980) also noted that large *Daphnia* were able to graze individual blue-green cells, specifically *Aphanizomenon flos-aquae*, but that colonies were largely inedible. *Daphnia* and other zooplankton have also been observed to eat *Microcystis incerta* and other blue-greens (Haertel 1977), although often blue-greens are avoided by zooplankton (Paerl 1988). In Fox Lake, blue-greens did not take off until after the zooplankton began to die out. It is possible that the large and abundant *Daphnia* were able to graze on *Microcystis* cells and to keep it from forming colonies through most of June and July. As their numbers declined at the end of July, however, colonies of *Microcystis* began to develop which quickly became dominant.

In earlier years, low *Daphnia* biomass has likely allowed *Microcystis* to become widespread much earlier in the summer.

Because of high P values, the clear water state exhibited in 1995 is likely not the beginning of a long term stable state shift, but was rather an anomalous year driven by unusual weather conditions and reduced fish predation. P levels over 200 $\mu\text{g L}^{-1}$ are thought to be too high for lakes to maintain a stable clear water state (Hosper and Jagtman 1980). However, these events serve as a good example of the possibilities for Fox Lake if macrophyte growth can be encouraged and P levels reduced.

V. Recommendations

1. Increasing the number and size of the zooplankton community may be a major step toward improving water clarity in Fox Lake. While unique climatic events may have contributed to the extended clear water phase in 1995, several management options exist which can enhance zooplankton biomass. For example:

- Reduce planktivorous fish in the lake through harvesting or biomanipulation. YOY carp, crappie, and other panfish readily prey upon zooplankton. Increased harvesting of carp, or stocking of northern pike to prey upon crappie and bluegill may help to reduce the predation upon zooplankton and restore a more balanced food web in the lake.

- Restore macrophytes to provide a refuge for zooplankton and enhance their growth. Clear water promotes macrophyte growth and vice versa. Establishing macrophytes through a drawdown or planting may also help zooplankton avoid predation and encourage more abundant macroinvertebrate sources of food for fish.

2. Macrophyte reestablishment is needed in South and East Basins to reduce sedimentation rates and resuspension. Even though macrophytes were more abundant and widespread in 1995, sedimentation rates were very high, particularly in shallow areas. A partial drawdown may help to establish submerged macrophytes deeper into the lake and to make the sediments more resistant to resuspension through compaction.

3. pH monitoring should be a part of routine monitoring. Total phosphorus concentrations give only part of the picture for predicting algal growth and internal P loading. Measurements of pH can help determine when P is being released from sediment.

4. Investigate the feasibility of using the aeration system to prevent stratification and maintain oxic conditions at the sediment surface. Temporary stratification in Deep Hole results in high P levels, which become available to algae when the lake mixes. Keeping the sediments aerated in the Deep Hole may help to reduce this source of P; however, it is unclear whether this source is significant. Maintaining adequate oxygen concentrations may also help to reduce the dominance of blue-green algae. Low winter oxygen levels need to be investigated as a mechanism of P release.

5. Reducing phosphorus loading from the watershed still needs to be a primary focus. Despite the focus of this report on potential food web manipulations and managing internal P loading, P loading from the watershed is the major reason for the poor water quality in Fox Lake. Annual estimates of P loading range from 7,000 to 18,000 kg P yr⁻¹ (WRM 1984; Sesing et al. 1991), well above the level needed to sustain the current high P concentrations in the lake (WRM 1984). In-lake management techniques will not work if external sources of P are not actively curtailed. Likewise, reduction of external loading alone will not be effective without concurrent in-lake management. Both approaches need to be applied to effectively improve the water quality and aquatic habitat of Fox Lake.

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