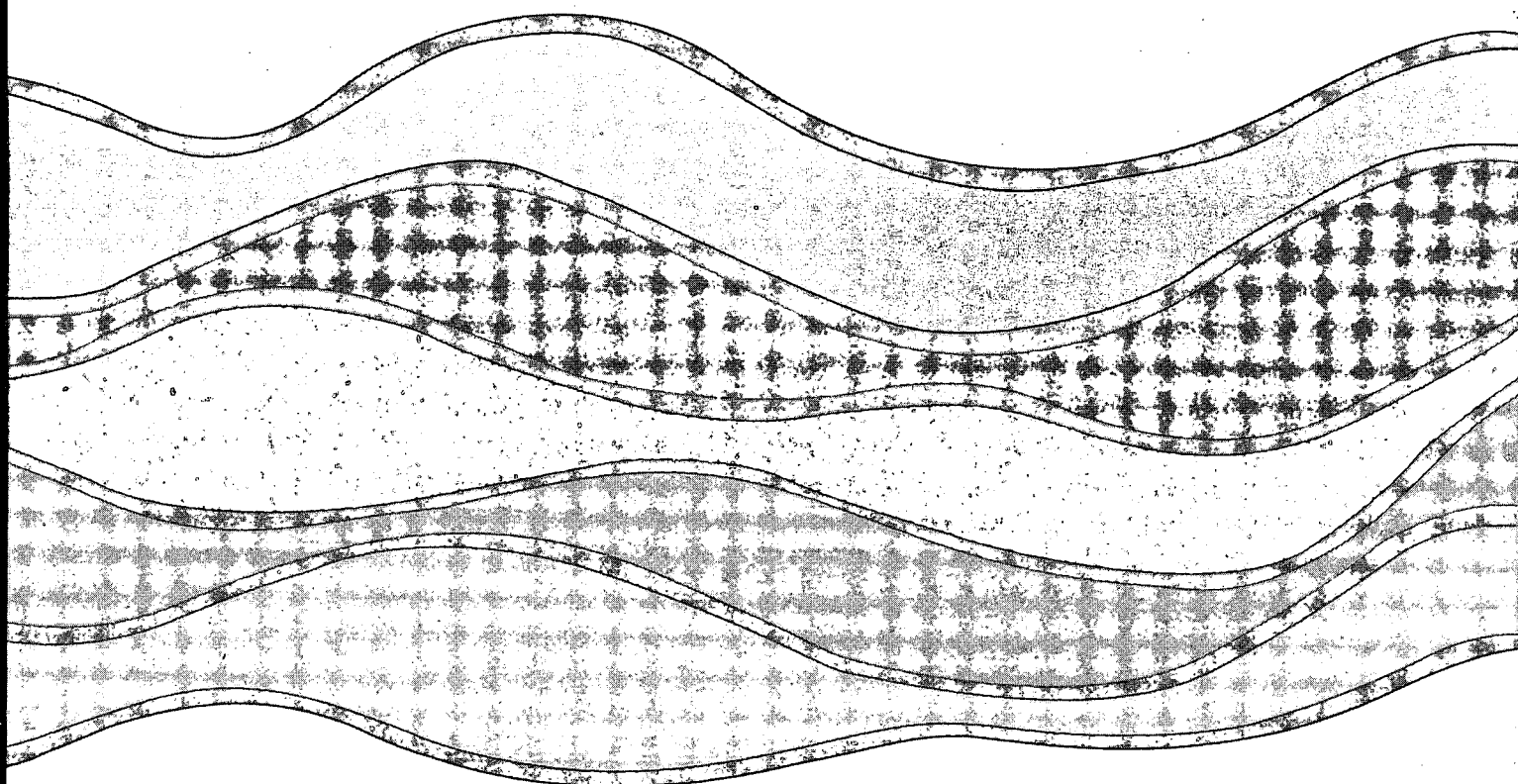NATIONAL WATER RESEARCH INSTITUTE

INSTITUT NATIONAL de RECHERCHE sur les EAUX

**LIMNOLOGY OF
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EFFECTS OF 1986 AND 1987
LIME TREATMENTS ON
WATER QUALITY**

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Management Perspective

The Lakes Research Branch and the University of Alberta collaborated to rehabilitate eutrophic hardwater Figure Eight Lake, Alberta. The object of the research was to develop a cost-effective replacement for copper sulphate use in lakes; copper is now banned as an algicide in Alberta. Lime treatment is an alternative solution which costs approximately $1,500 a hectare. In this lake, treatments will be required every two years.

As with many prairie lakes, source control of nutrients was impossible because the soils are naturally rich in phosphorus. Although undeveloped crown land surrounds Figure Eight Lake, the phosphorus concentration in the inlet water can exceed 1.0 mg/L. Under these conditions dense algal blooms form which result in fish kills.

Lime (calcium carbonate or calcium hydroxide) was applied to the surface of the lake a total of four times during the summers of 1986 and 1987. The decrease in phosphorus concentration and algal biomass led to greater water clarity and higher winter oxygen concentrations. Oxygen consumption rates under the ice were 59% of pretreatment rates. Fish survived the winter, and for the first time in years, _Gammarus_, an important food for trout , were common. Fishing was much better than other lakes in the area.

Lime treatment is a good example of improving the water quality of a lake by enhancing a fundamental geochemical process to a degree which results in clear water and an uncontaminated aquatic ecosystem.

PERSPECTIVES DE LA DIRECTION

La Direction de la recherche sur les lacs et l'université de l'Alberta ont travaillé de concert pour régénérer le lac Figure Eight eutrophique à eau dure, en Alberta. L'objet de la recherche était de trouver une solution de remplacement efficace, à un coût raisonnable, pour le sulfate de cuivre utilisé dans les lacs; l'emploi du cuivre comme algicide est maintenant interdit en Alberta. Le traitement à la chaux, coûtant environ 1 500 dollars l'hectare, constitue une solution de remplacement. Il faudra traiter ce lac tous les deux ans.

Comme pour beaucoup de lacs des Prairies, il était impossible d'éliminer les agents nutritifs à la source car les sols sont naturellement riches en phosphore. Bien que le lac Figure Eight soit entouré de terres de la Couronne non exploitées, la concentration de phosphore dans l'eau à l'entrée peut dépasser 1,0 mg/L. Dans ces conditions, il y a prolifération d'algues, qui entraîne la mort de poissons.

On a appliqué de la chaux (carbonate de calcium ou hydroxyde de calcium) à la surface du lac quatre fois en tout pendant les étés de 1986 et de 1987. La diminution de la concentration de phosphore et de biomasse algale a rendu l'eau plus claire et a augmenté les concentrations hivernales d'oxygène. Le taux de consommation d'oxygène sous la glace avait passé à 59 % du taux avant traitement. Les poissons ont survécu à l'hiver et, pour la première fois depuis des années, Gammarus, une importoute source de nourriture pour la truite, était tout à fait commune. La pêche était nettement meilleure que dans d'autres lacs de la région.

Le traitement à la chaux est un bon exemple de méthode d'amélioration de la qualité de l'eau d'un lac, car il permet d'activer un processus géochimique fondamental jusqu'à clarifier l'eau et obtenir un écosystème aquatique non contaminé.

Abstract

In the early summer, the water quality of Figure Eight Lake was excellent. The clarity of the lake was high, chlorophyll a and phosphorus concentrations were low, and fishing was good. A moderate algal bloom developed (40 μg/L Chla) but the precipitation of 50 mg/L of calcium carbonate sedimented the algae to the sediments. The decay of the algae resulted in anoxic sediments, the release of phosphorus from the sediments, and the development of an intense Aphanizomenon bloom (150 μg/L Chla). The decay of algae under the ice resulted in low oxygen concentrations and a fish kill. All of the added lime dissolves in winter and precipitates in early summer; thus, a long-term water treatment has been established. However, this process does not result in a significant net loss of phosphorus via permanent burial in the sediments. Increased phosphorus retention in sediments could be achieved by either maintaining annual treatments with a moderate dose of lime, or by using less frequent but larger doses of lime.

RÉSUMÉ

Au début de l'été, la qualité de l'eau du lac Figure Eight était excellente. La clarté de l'eau du lac était très bonne, les concentrations de chlorophylle a et de phosphore étaient faibles, et la pêche s'est révélée fructueuse. Il y eu prolifération modérée d'algues (40 µg/L de chl. a), mais la précipitation de 50 mg/L de carbonate de calcium a entraîné la sédimentation des algues aux sédiments. La décomposition des algues a entraîné la formation de sédiments anoxiques, la libération de phosphore à partir des sédiments et la prolifération d'Aphanizomenon (150 µg/L de chl. a). La décomposition des algues sous la glace a résulté en une faible concentration d'oxygène, ce qui a tué les poissons. Toute la chaux ajoutée se dissout en hiver et précipite tôt en été; on a ainsi pu mettre en oeuvre un traitement de l'eau à long terme. Cependant, ce processus n'entraîne pas une perte nette significative de phosphore par enfouissement permanent dans les sédiments. On pourrait obtenir une plus grande rétention de phosphore soit en maintenant les traitements annuels, mais avec une dose modérée de chaux, soit en utilisant des doses moins fréquentes, mais plus fortes, de chaux.

1   INTRODUCTION

Figure Eight Lake is a naturally productive lake in the northern prairies of Alberta (Prepas et al. 1987). Frequent algal blooms reduce the clarity of the water so that swimming is both unpleasant and unsafe. The decay of algae has resulted in periodic fish winterkills which have hampered the establishment of a recreational fishery. Figure Eight Lake was treated with lime (calcium carbonate ($CaCO_3$) and calcium hydroxide ($Ca(OH)_2$)) in 1986 (Prepas and Murphy 1987) and $CaCO_3$ in 1987 (Prepas et al. 1988) to precipitate phosphorus and algae.

Earlier studies had resulted in a long-term improvement in water quality from lime treatment (Murphy et al. 1988). However, the earlier work was conducted in a stratified mountain lake with poor road access and relative to Figure Eight Lake, few samples were collected. The objective in the 1988 study of Figure Eight Lake was to determine if the water quality improved since the pretreatment years. No lime was added to the lake in 1988. Because Figure Eight Lake is similar to many shallow productive lakes on the Canadian prairies, a successful treatment method could be applied to many other Alberta lakes.

1.1 Mechanisms Producing Effect of Lime Treatment

The large reduction in algal biomass in Figure Eight Lake in 1987 relative to 1986 was correlated to lower concentrations of phosphorus and iron. Phosphorus is the major nutrient that regulates algal growth (Schindler 1977, Schindler 1987). The suppression of phosphorus recycling from the sediments of Figure

Eight Lake during the winter of 1986-87 and 1987-88 by lime treatments was a very effective mechanism to suppress algal growth. Long-term suppression of algal growth would most likely be mediated via a suppression of sediment phosphorus release.

The lime treatments have increased the calcium concentration of Figure Eight Lake by approximately 10 mg/L. The increased calcium concentration has resulted in the lake water exceeding the solubility product of calcite (calcium carbonate) by more than tenfold during algal blooms when the pH of the water increases above 9.0. Calcite precipitation is stimulated most by an increase in Ph but the warming of the water also enhances its precipitation (Stumm and Morgan 1981). Calcite precipitation suppresses algal growth by enhancing algal sedimentation (Koschel et al. 1983, Stabel 1986, Koschel et al. 1987). Algal growth is also restricted by the calcite precipitation of phosphorus, a process which has been demonstrated in laboratory studies (Otsuki and Wetzel 1972, Berner and Morse 1974, Stumm and Morgan 1981) and in lakes (Rossknecht 1980, Avnimelach 1983, Murphy et al. 1983a). Calcite precipitation appears to be the agent responsible for the low productivity of marl lakes (Wetzel 1975).

The primary mechanisms of lime treatment may be phosphorus limitation or enhanced algal sedimentation but other factors influence algal growth in hardwater lakes. Iron limitation has often been observed in hardwater lakes (Lange 1971, Murphy and Lean 1975, Murphy et al. 1976, Elder 1977, Elder and Horne 1977, Murphy et al. 1983b, Wurstbaugh and Horne 1983, Storch and Dunham 1986).

Adsorption of iron to sedimenting calcite is the most widely cited
mechanism producing iron limitation (Schelske 1961, Schelske 1962,
Schelske et al. 1963, Wetzel 1965, Wetzel 1966, Wetzel 1968).
Calcite precipitation also enhances oxygen depletion in the
hypolimnia of lakes; thus calcite precipitation could enhance the
formation of pyrite (Manning et al. 1988) and thus reduce the
concentration of iron in the water column. The lime treatments of
Figure Eight Lake should influence the long-term bioavailability of
iron.

Another reaction that could enhance iron limitation is the
coprecipitation of iron chelators or siderophores with calcite
precipitation. Siderophores are organic compounds excreted by
microbes to dissolve and assist in the assimilation of iron
(Neilands 1967, Neilands 1981). Blue-green algae are the only
algae that have consistently been shown to excrete siderophores
(Murphy et al. 1976, Simpson and Neilands 1976, Bailey and Taub
1980, Murphy 1987). Since blue-green algae appear to have a
special iron assimilation system and perhaps a higher requirement
for iron, shifts in iron availability should impact upon the types
of algae present in lakes (Lange 1974, Morton and Lee 1974).

The theory that changes in iron availability would shift the
composition of microbial communities was first proposed by O'Brien
and Gibson (1970) and has since been demonstrated in many
ecosystems (Emery 1982). Enhanced iron availability can result in
the dominance of a pathogen. Toxin production by blue-green algae

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that blue-green algal growth can be controlled by iron availability.

2   METHODS

2.1 Research Site

Figure Eight Lake is a small (36.8 ha), shallow (mean depth 3.1 m) eutrophic lake located 48 km northwest of Peace River, Alberta (Figure Eight Lake: lat. 117° 54' long. 56° 18'), at a surface elevation of 683 m, and situated in glacial till. The drainage basin is small (4.5 km^2, J. Crosby, Alberta Environment pers. comm.) and annual precipitation and lake evaporation average 446 and 522 mm, respectively (Environment Canada 1951-80; Fisheries and Environment Canada 1978). Runoff in the only stream flowing into the north end of the lake (Fig. 1) is limited to a brief period in April; estimated lake water residence time is > 4 yr. The lake is surrounded by a mixture of aspen and spruce forest and grazing land.

2.2 Sampling Techniques

Lake surface area was determined from a 1:2000 topographic map (Alberta Environment). In May 1986, bathymetric surveys were conducted with a Furuno model Fe-400 depth-sounder, and morphometric data were calculated after Hutchinson (1957). From May 24, 1988 until February 22, 1989 Figure Eight Lake was visited 15 times. With the exception of samples for chlorophyll a analyses, all other samples were collected from the south basin

(Fig. 1). Temperature was measured at 0.5 to 1.0-m intervals from the surface to within 0.2 m of the sediment-water interface with a Montedoro-Whitney resistance thermometer accurate to 0.1°C. During the open water period, the depth of the euphotic zone was defined as twice the Secchi disk reading or 1% penetration of surface irradiance, as measured with a Protomatic photometer.

Water samples were collected with a 1.5-L aluminum drop-sleeve water bottle from 0.5 to 2.0-m intervals for analyses of dissolved oxygen, nitrogen (NO_2 and NO_3, TKN, NH_4), Ph, total dissolved phosphorus (TDP), total phosphorus (TP), total iron (TFe), chlorophyll a (Chl$a$), alkalinity, calcium (Ca), magnesium (Mg), potassium (K), sulphate (SO_4), and conductivity. From May until August 1988 samples were also collected from the euphotic zone at five stations (Fig. 1) and pooled to estimate euphotic zone chlorophyll a and phosphorus (TDP, TP) concentrations. All water samples were stored on ice in coolers and then refrigerated at 4°C until they were analyzed.

Water samples for NH_4, TKN, Fe, Mn, Ca, Mg, and K, were placed in 250-mL polystyrene containers. Samples for TKN analyses were acidified with 0.25 mL of concentrated H_2SO_4; samples to be analyzed for total Ca, Fe, K, Mn, and Mg were acidified with 0.33 mL concentrated HNO_3; samples were acidified within 1 h of collection. Water samples for all other analyses were placed in 1 or 2-L Nalgene polyethylene bottles (opaque bottles were used for Chl$a$) which were completely filled. The containers for Ca, K, Fe, Mg, TKN, NH_3, and NO_3 analyses were cleaned with double-distilled water

(DDW) only; all other containers were acid-washed in 2% HCl and rinsed with DDW.

Within 24 h of collection, water samples for TDP, and Chl$\underline{a}$ analyses were filtered under low pressure (-50kPa). Samples for TDP analyses were filtered through prewashed 0.45 μm HAWP Millipore membrane filters and transferred to culture tubes (Prepas and Rigler 1982). Water samples for Chl$\underline{a}$ analyses were filtered through Whatman GF/C filters. The filters were placed in petri dishes, wrapped in aluminum foil, and stored in a freezer.

2.3 Sample Analyses

Dissolved oxygen was determined on duplicate water samples which were preserved in the field, chilled, and analyzed within 24 h of collection by Carpenter's (1965) modified Winkler technique. A Beckman Expandomatic SS-2 pH meter was used to measure pH in the laboratory within 5 to 12 h. Total alkalinity was measured within 24 h by the potentiometric titration method (Environment Canada 1979). Samples to be analyzed for Ca, Mg and K were filtered through prewashed Whatman GF/C filters within 15 to 30 d to six months after collection, and read three times on absorption or emission mode on a Perkin-Elmer model 3030 atomic absorption spectrophotometer. To avoid chemical interference, 1 mL of lanthanum chloride buffer (58.65 g lanthanum oxide with 250 mL concentrated HCl diluted to 1 L with DDW) was added to each 10 mL of water for Ca and Mg analyses. Conductivity was measured within

seven days with a YSI model 31 conductivity meter on water samples at 20°C.

NH$_4$ and TKN were analyzed within 48 h by Solorzano's (1969) phenolhypochlorite method as modified by Prepas and Trew (1983). NO$_3$ + NO$_2$ were determined within 48 h, after filtration through a prewashed 0.45 µm HAWP Millipore membrane filter, by the cadmium-copper reduction method of Stainton et al. (1977). All nitrogen analyses were performed in triplicate.

Duplicate samples for TP and TDP were digested and analyzed within seven days by Menzel and Corwin's (1965) potassium persulfate method as modified by Prepas and Rigler (1982).

Chlorophyll $\underline{a}$ was determined in duplicate within two weeks with a spectrophotometric technique based upon the ethanol extraction procedure of Ostrofsky described by Bergmann and Peters (1980).

Samples to be analyzed for total Kjeldahl nitrogen, particulate nitrogen, dissolved organic carbon, particulate carbon, dissolved inorganic carbon, chloride, sulphate, calcium, magnesium, silica, and potassium were prepared in a field laboratory, and shipped on ice to a laboratory for analysis using Technicon autoanalyzer methods (Environment Canada 1979).

2.4 Calculations

The computer program PCWATEQ was used to calculate the saturation values of calcite, hydroxyapatite and other minerals. The program is the 1984 version of the U.S. Geological Survey

release of WATEQF (Plummer et al. 1976) that has been modified by Rollins (1987) to run on IBM compatible microcomputers. The critical variables were all obtained from analysis of samples collected in 1988; however, analysis of chloride had been discontinued. To make the calculations more robust, chloride measurements from the 1987 study of Figure Eight Lake were used. The average charge balance error was 11%.

For calculations of sediment phosphorus release between two sampling dates, the mean areal concentration was derived using morphometric data (Prepas et al. 1989) and phosphorus data from depths of 1.0, 3.0 and 5.0 m. Mean chlorophyll _a_ data for the summers (May–August) was calculated by integrating the area under a plot of daily mean chlorophyll _a_.

2.5 Primary Production

Primary productivity response to iron (200 µg/L as $FeCl_3$), ammonium (500 µg/L N as NH_4Cl), and phosphorus (200 µg/L as NAH_2PO_4) was measured by algal uptake of 1.48 x 10^6 Bq of $^{14}C-HCO_3$ in 300-mL BOD bottles that were incubated in the lake. Relatively long incubations (36 h) were used to avoid misleading signals that short-term incubations can produce (Lean and Pick 1981). Dark bottles were used for controls. Samples were filtered (0.45 µm Millipore filters), treated with 0.2 mL of 0.5 N HCl for 24 h, dried (110°C), dissolved in Bray's fluor, and counted with a Beckman scintillation counter. One mL of sample was treated with 0.025 mL of ethanolamine prior to counting with fluor for a

measurement of total radioactivity. All samples were processed in duplicate.

2.6 Iron-Binding Assay

Samples from the summer of 1987 were frozen within hours of collection and subsequently thawed for study in the spring of 1988. The iron-binding capacity (FeBC) of lake water was determined with a radioisotope assay (Murphy et al. 1983b, Murphy 1987). In this assay, any unchelated iron was precipitated with magnesium carbonate. The chelators were calibrated with a siderophore chelator desferal (desferrioxamine-B, Ciba-Geigy) and the FeBC was expressed in equivalents of desferal (μM).

A typical iron-binding experiment consisted of 2.0 mL of algal filtrate, 0.5 mL of ^{55}Fe-$FeCl_3$ (7.4 x 10^4 Bq in 0.01 N HCl), 0.5 mL of 0.01 N NaOH, 1.0 mL of buffer, and enough double distilled water to make a final volume of 10.0 mL. One-mL samples were then taken for determination of total ^{55}Fe. After an initial 1 h incubation with the metals, $MgCO_3$ (60 mg) was added to each flask. After a second 1 h incubation, the solutions were filtered through 0.2 μm Nuclepore filters and 1.0 mL of filtrate was collected for determination of ^{55}Fe remaining in solution. Between experiments, the algal filtrates were frozen.

3   RESULTS

In the early summer of 1988, the aesthetic quality of Figure Eight Lake was high. The camp sites were busy and many families enjoyed catching fish. The relatively high water clarity (Secchi disk depth) in May and June (Table 1) assisted the fishermen by enabling the fish to see the bait and by preventing their fishing lines from becoming fouled with algae. The rainbow trout were fat and had grown to as large as 1.0 kg within a year. Presumably, the observed recovery of the amphipods and the high oxygen concentrations contributed to this pronounced growth. The oxygen concentrations remained high throughout the summer (Fig. 2). The 1988-89 winter oxygen concentrations were slightly lower than those of 1987-88 when the trout survived the winter (Fig. 2).

Until July 23, the high oxygen concentrations were reflected by an increase in sulphate concentrations (Table 2) over those observed in 1986 and 1987. Sulphate concentrations are regulated by sulphate reduction to pyrite and the most plausible mechanism resulting in higher sulphate concentrations is the suppression of reductive power production (algal biomass) through lime treatments.

Relative to 1986, the algal biomass was low throughout most of 1988 (Fig. 3, Table 3). A moderate algal bloom developed in June and July (Chl$\underline{a}$ approximately 40 µg/L). Although the mean algal biomass in June-August 1988 (43 µg/L) was much lower than in 1986 (92 µg/L), it was higher than in 1985 (26 µg/L) or 1987 (12 µg/L). The dense algal bloom in late August 1988 of 150 µg/L Chl$\underline{a}$ was primarily composed of <u>Aphanizomenon flos-aquae</u>.

The dense <u>Aphanizomenon</u> bloom was preceded by a release of phosphorus from the sediments (Figs. 4, 5). On August 7 during the field trip prior to the bloom, the phosphorus concentration in the bottom water had increased by approximately 40 µg/L. By August 29, the total phosphorus in the water column had increased by approximately 230 µg/L. Most of the phosphorus in the surface water was particulate and most of the phosphorus in the bottom water was in solution (Table 2) indicating that the sediment release of phosphorus was not due to the emergence of algal cells or other biota.

The sediment release of phosphorus in Figure Eight Lake was preceded by the decay of an algal bloom. Signals of the algal decay on July 23 include the decrease in chlorophyll <u>a</u> concentration of 7 µg/L in 12 days (Fig. 3, Table 3), the decrease of particulate epilimnetic nitrogen by approximately 340 µg/L (Table 3), the decrease of surface pH by 0.8 units (Fig. 6, Table 4), and the reduction of approximately 25 mg/L of sulphate in the bottom water (Table 2). Sulphate reduction only occurs in the absence of oxygen (Stumm and Morgan 1981). Since the oxygen content of the lake remained relatively high, the observed reduction must have occurred in the surface sediments which must have been anoxic. The sediment release of phosphorus in 1988 occurred approximately two months later than in 1986 or 1987 and approximately one month later than in 1985.

The release of phosphorus from the sediments occurred about two weeks after the lake had stopped precipitating calcium

(Fig. 7, Table 5). The calcium concentration was approximately 47 mg/L in late winter and the concentration had decreased to approximately 40 mg/L by May 24. The period of most intense calcium precipitation was around July 11. Note that the particulate carbon on July 11 of 5870 µg/L had an unusually low nitrogen content (7%); by using the nitrogen content of August 7, and assuming that the calcium precipitate was calcium carbonate, it can be calculated that about 35 mg/L of calcium carbonate was in suspension in the surface water. The precipitation of an average of 20 mg/L of calcium is at least 12 mg/L more than was observed in pretreatment years.

A geochemical analysis of the water column indicates that the lake water was supersaturated with calcite (calcium carbonate) throughout the summer of 1988 (Fig. 8). Calcium concentrations reached a minimum about August 7 but the lake water remained over tenfold supersaturated with calcite for another month until the water cooled (Fig. 9). Other discrepancies were observed in the geochemical analysis. The lake water was ten to twenty-fold supersaturated with aragonite (calcium carbonate and dolomite (calcium magnesium carbonate)), but the former compound is rarely observed and the latter is never observed in lakes (Kelts and Hsu 1978).

Since the calcium precipitate was likely calcite, the precipitation of 20 mg/L of calcium indicates that approximately 50 mg/L of calcium carbonate precipitated. By comparison, the calcium carbonate treatments of 1986 and 1987 were 14 and 18 mg/L,

respectively. The calcium precipitation of 1988 is equivalent to treating the lake with 56 tonnes of calcium carbonate which is almost the equivalent quantity of calcium carbonate (58 tonnes) that the lake was actually treated with in 1986 and 1987. The excellent calcium budget is partly a coincidence. Some of the lime must have been lost via hydraulic flushing. The major error in the calculation (10-20%) is the lack of a precise water budget. Regardless, the calculation indicates that most or all of the added lime has dissolved.

Geochemical analysis indicates that hydroxyapatite should dissolve in early summer and winter, and precipitate in late summer (Fig. 10). In general, the model fits the observed data; however, considerable delays occur prior to precipitation or dissolution. The dissolution of phosphorus occurred in August not June; the precipitation of phosphorus occurred in October not August. By November, approximately 68% of the phosphorus had precipitated from the water column (Table 6). The phosphorus concentration remained relatively constant throughout the winter, but a slight increase of phosphorus was observed in February.

The concentration of phosphorus throughout the winter of 1988-89 was much lower than observed in 1986-87 but it was three to four times higher than observed in the winter of 1987-88. Approximately 87% of the total phosphorus was in solution and presumably available to algae. If the winter phosphorus concentration is an accurate indicator of algal biomass; the algal blooms in 1989 should have been worse than in 1988 but not as intense as in 1987.

Calcium dissolved under the ice to approximately 50 mg/L which is about 4 mg/L higher than observed in March of 1988 (Table 7). The higher calcium concentrations may reflect either more dissolution of lime by a lower pH (unlikely) (Table 8) and lower oxygen concentrations (Table 9) or the freezing out of salts under a thicker ice cover (preferred hypothesis).

3.1 Figure Eight Lake Iron Chelation

The lime treatment in 1987 initially resulted in an increase in the chelation capacity of the lake water (Figs. 11, 12). The effect was transitory; after a week, the V_{max} had returned to pretreatment values. Note that the concentration of dissolved organic carbon (DOC) remained relatively constant (Figs. 13, 14). Only the more labile forms of DOC produced by the microbes changed.

Two peaks of V_{max} values (July 30, August 10) may represent times of highest iron demand/assimilation. The first peak was associated with the beginning of an algal bloom. The second V_{max} peak of August 10 was associated with the highest chlorophyll a concentrations in both basins.

Some aspects of the primary production bioassays are difficult to interpret in that the variability between bottles was high (Table 10). It is obvious that the primary production increased greatly from July 23, 1988 to August 7 (tenfold) and that the productivity on August 7 was extremely high. It is highly unlikely that a nutrient limitation existed on August 7. Sediment release of iron began about July 24 (Figs. 13, 14). It appears that iron

limitation was restricting algal productivity on July 23 but that the sediment release of iron overcame this limitation.

4   DISCUSSION

The lime treatments of 1986 and 1987 have changed the calcium carbonate geochemistry of Figure Eight Lake. The lake currently precipitates approximately 50 mg/L of calcium carbonate. It appears that the precipitation delayed the onset of the algal bloom and that the calcium precipitation or some other aspect of the lime treatment suppressed sediment phosphorus release. Adsorption of phosphorus to sedimenting calcite could have delayed sediment phosphorus release. Another hypothesis to explain this delay is that the lime treatments suppressed algal growth and loading of reduced carbon to the sediments. These interpretations are consistent with hypotheses of Murphy et al. (1983a), Koshel (1983) and Stabel (1986).

In spite of the optimistic direction of the results, the lime treatments were not able to prevent the formation of the intense algal bloom in late August 1988. Resolution of why the bloom formed could lead to either improved methods of lime treatment or determination of the limitations of lime treatment.

The intense sediment release of phosphorus in 1988 of 39 mg m^{-2} d^{-1} (August 7–August 29) was faster than observed in 1985 (July 3 to July 17, 12 mg m^{-2} d^{-1}) or 1986 (June 1 to June 17, 22 mg m^{-2} d^{-1}). With the exception of two days after lime treatment (July 14-16, 46 mg m^{-2} d^{-1}), sediment phosphorus release was not

observed in 1987. Apparently, the rapid decay of algae in the lime treatment stimulated some sediment phosphorus release, but the net effect of the lime treatment was to suppress release of phosphorus from sediment.

If the net effect of lime treatment was inhibition of sediment phosphorus release in 1987, the 1988 results would indicate that a new equilibrium had formed between the sediments and the water column. Spring loading rates of phosphorus are not available for 1988, but the observations and analyses of 1986 and 1987 would support the hypothesis that the phosphorus released from the sediments in August 1988 entered the lake in the spring of 1988. A similar sequence of reactions was proposed by Kennedy et al. (1986). This hypothesis is interesting but the relative proportion of recently sedimented phosphorus and "historic" phosphorus that recycles from the sediments cannot be assessed by a monitoring study.

The concern over sediment phosphorus release is more serious for shallow lakes. In a deep stratified lake, the sequence of reactions that occurred in Figure Eight Lake in 1988 would likely lead to good water quality. When phosphorus is released into the hypolimnion of a deep lake, little of the phosphorus enters the epilimnion during the algal growing period and most of the phosphorus precipitates during the fall or spring.

The possibility of achieving a long-term treatment for lakes similar to Figure Eight Lake exists. Sediments can be an effective sink and trap for phosphorus. Schindler (1987) found that after an

oligotrophic lake was loaded with phosphorus for 15 years the sediment phosphorus release remained insignificant. With an ideal lake treatment, sediment phosphorus release would be blocked. The typical alum treatment utilizes much larger doses (60-120 mg/L) than the lime treatments of Figure Eight Lake; the large alum dose is used to block sediment phosphorus release (Connor and Smith 1986, Morency and Belnick 1987). It is quite possible that earlier lime treatments focussed too much on the water column and not enough on the sediments. Since virtually all of the lime added to Figure Eight Lake has redissolved, there has been no sediment treatment.

A lake with a fishery could not tolerate very large treatments of calcium hydroxide as the resulting high pH would kill fish. However, repeated treatments, a month apart, should achieve the same objective. Further lime treatments to Figure Eight Lake could have an additive effect in both suppressing phosphorus release, increasing winter and spring calcium concentrations, and in turn enhancing long-term calcite precipitation and suppression of algal growth.

The long-term enhancement of calcite precipitation could be more intense than occurred in 1988. In 1988, the precipitation of approximately 50 mg/L of calcite suppressed the first algal bloom but the decay of the bloom led to rapid release of phosphorus from the sediments and in turn to a larger algal bloom. In theory, the calcium concentration could increase to more than 100 mg/L in the winter, but in practice the rate of lime dissolution from the

sediments could be limited by diffusion. Prairie lakes have winter calcium concentrations exceeding 100 mg/L (Barica 1975). The extra 50 mg/L of calcium would increase the amount of calcium carbonate precipitation in Figure Eight Lake to about 250 mg/L. The increased precipitation could restrict algal growth before the organic carbon decay could develop the intensity to stimulate a large sediment phosphorus release.

If further treatments of Figure Eight Lake are conducted and monitored, the role of lake stratification in influencing sediment phosphorus release should be studied. The rapid sulphate reduction in 1986 and 1988 occurred with relatively intense water column stratification, inferred anoxic sediments and intense phosphorus release. The lack of sediment phosphorus release in 1987 was associated with no sulphate reduction and minimal water column stratification.

Further studies should attempt to improve the geochemical data base. A basic model for lime treatment is that enhanced calcium carbonate precipitation and phosphorus adsorption to calcium carbonate will lead to enhanced apatite formation. Limitations such as using total dissolved phosphorus for phosphate are obvious, but the general agreement between predicted apatite formation and the geochemistry of Figure Eight Lake is encouraging. It might be a mistake to use a geochemical model as more than a guide, but testing discrepancies between model predictions and field observations could lead to new insights and to improved lake management.

Accurate calcium analysis is critical to both the geochemistry of apatite and calcite and is probably the simplest geochemical analysis to test. The apparent discrepancy in the lack of calcite precipitation in late summer when the lake should precipitate calcite was also observed in lakes in British Columbia (Murphy 1987). It might be produced by using total calcium values instead of reactive calcium data. Dissolved organic carbon (DOC) can complex calcium and reduce its reactivity. The DOC concentrations in Figure Eight Lake (13 mg/L) are moderately high. The uncertainty associated with using total dissolved calcium data in the model might be resolved by using an ion selective electrode to measure reactive calcium.

The organic chelation of calcium is likely related to the algal excretion of siderophores to chelate iron. Hider at al. (1982) observed that a bacterial siderophore complexed calcium. The production of siderophore like compounds in Figure Eight Lake may serve to both mediate iron availability and to restrict calcite precipitation. Certainly the role of organic matter in regulating iron availability in lakes is well known (Shapiro 1969, Sakamoto 1971). A sediment treatment with lime should restrict both iron and phosphorus release from the sediments and suppress blue-green algae by at least two nutrient deficiencies. The lack of iron may lead indirectly to nitrogen limitation. Blue-green algae require more iron when they fix nitrogen (Carnaham and Castle 1958).

Some changes in treatment protocol (i.e., use of iron or aluminum salts) would confound interpretation of a considerable

amount of long-term data, and likely lead to new uncertainties. We recommend that lime treatments be continued and the biology and geochemistry of the lake continue to be studied. If any additional lake restoration action is taken, we recommend that the winter aeration program be expanded. Although lake aeration in summer would complicate data interpretation, aeration in the winter would assist the study of calcite precipitation. Enhanced aeration would increase oxygen concentrations, decrease sediment phosphorus release, enhance dissolution of calcite and, in turn, enhance precipitation of calcium carbonate when the water warms.

Without further treatment, the lake will likely return to former conditions in a year or two. Earlier lime treatments established a long-term enhancement of calcium carbonate precipitation that could have effectively reduced eutrophication of a deep lake. However, shallow Figure Eight Lake requires annual treatment in May or June with a moderate dose of calcium hydroxide (10-20 mg/L) or perhaps a larger dose of calcium hydroxide (75 mg/L) could maintain good water quality for a number of years. Further lime treatments should be more effective than earlier treatments.

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Table 1. Figure Eight Lake 1988. Physical Parameters - Open water period.
Analyses performed by the Univ. of Alberta.

Date	Depth (m)	Dissolved Oxygen (mg/L)	Temperature (C)	Colour (mg/L as Pt.)	Turbidity (NTU)	Conductivity (us/cm)	Secchi disk depth (m)
May 24	0.2		15.5				
	1	8.9	15.5	--	--	295	2.3
	3	8.9	15.5	--	--	296	
	5	8.4	15.0	--	--	297	
June 9	0.2		14.6				
	1	8.9	14.6	--	--	294	2.2
	3	8.3	14.6	--	--	296	
	5	7.6	14.4	--	--	297	
June 29	0.2		21.0				
	1	6.1	20.0	2.5	1.2	290	2.1
	3	4.7	20.0	--	--	280	
	5	4.1	19.0	--	--	295	
July 11	0.2		20.0				
	1	9.0	19.5	--	--	297	--
	3	9.5	18.0	--	--	269	
	5	--	18.0	--	--	--	
July 23	0.2		19.0				
	1	11.6	19.0	11.3	1.7	279	0.8
	3	9.5	--	6.3	4.7	277	
	5	7.9	--	11.3	4.5	285	
August 7	0.2		18.0				
	1	8.4	18.0	22.5	6.7	240	1.1
	3	8.2	17.0	12.5	3.4	239	
	5	6.2	17.0	11.3	2.6	245	
August 29	0.2		17.0				
	1	15.5	19.0	--	--	213	1.0
	3	15.0	19.0	--	--	224	
	5	5.7	17.0	--	--	224	
September 19	0.2		ND				
	1	--	12.0	--	--	--	1.5
	3	--	12.0	--	--	--	
	5	--	12.0	--	--	--	

-- Samples not analyzed.

ND - no data

Table 2 . Figure Eight Lake 1988. Nutrient Concentrations (ug/L) in the water column during open water period. Analyses performed by the Univ. of Alberta except where indicated.

Date	Depth (m)	Total Phosphorus *	Total Dissolved Phosphorus	Nitrite & Nitrate	Ammonium	Total Kjeldahl Nitrogen +*	Silica +*	Sulphate +*
May 24	1	12.5	7.7	--	--	0.934	0.38	28.1
	3	39.7	13.3	--	--	0.964	0.35	28.7
	5	36.1	9.1	--	--	1.001	0.37	28.8
June 9	1	33.0	18.2	--	--	0.996	0.64	26.5
	3	29.7	18.0	--	--	1.084	0.66	26.0
	5	28.9	23.8	16.2	76.6	1.077	0.66	26.0
June 27	1	31.0	77.9	31.2	--	--	0.620	0.66	30.2
	3	293.2	99.2	28.4	--	--	2.653	4.88	29.4
	5	114.9	63.4	--	--	--	0.923	1.10	28.1
July 11	1	42.9	63.3	25.4	10.9	117.0	1.457	0.68	26.4
	3	38.7	55.8	23.0	0.7	81.9	1.065	0.72	25.2
	5	--	--	--	--	--	--	--	--
July 23	1	54.2	39.8	22.8	--	--	2.065	1.29	29.1
	3	61.7	41.6	21.9	--	--	2.233	1.29	28.3
	5	52.1	41.6	20.3	--	--	1.344	0.69	3.1
August 7	1	182.3	36.2	36.0	16.5	118	2.842	2.15	24.2
	3	105.0	44.0	23.6	47.0	124	2.224	2.22	24.2
	5	154.6	88.9	27.5	44.5	224	1.912	2.36	23.7
August 29	1	274.3	274	103	13.9	26.8	4.20	3.27	23.5
	3	219.9	236	104	13.6	33.2	3.63	3.22	23.3
	5	248.8	306	265	36.3	451	1.847	3.64	22.1
September 19	1	260.7	273	173	--	--	2.57	4.67	20.6
	3	276.9	281	161	--	--	3.01	4.57	20.4
	5	216.4	236	175	--	--	1.95	4.58	20.4

* Samples analyzed by CCIW

+ Concentrations in mg/L

-- Samples not analyzed

Table 3. Figure Eight Lake 1988. Biomass Parameters (ug/L) – Open water period.

Date	Depth (m)	Particulate Nitrogen	Particulate Carbon	Chlorophyll a (0-3 m)
May 24	1	105	872	7.33
	3	85	699	
	5	83	686	
June 9	1	37	290	3.17
	3	51	438	
	5	53	462	
June 29	1	109	757	47.1
	3	--	--	
	5	--	--	
July 11	1	417	5940	45.4
	3	310	2650	
	5			
July 23	1	24	241	38.6
	3	21	182	
	5	19	169	
August 7	1	1430	5870	25.7
	3	812	2820	
	5	168	1310	
August 29	1	1130	5210	150
	3	1030	4400	
	5	94	521	
September 19	1	740	3370	53.4
	3	752	3220	
	5	334	1650	

Chlorophyll a analyzed by the Univ. of Alberta.
PN and PC analyzed by CCIW.
-- Samples not analyzed.

Table 4. Figure Eight Lake 1988. Alkalinity Parameters (measured as mmg/L CaCO) - Open water
Analyses performed by the Univ. of Alberta.

Date	Depth (m)	pH	Total Alkalinity	Carbonate Alkalinity	Bicarbonate Alkalinity	* Dissolved Inorganic Carbon (mg/L)	* Dissolved Organic Carbon (mg/L)
May 24 +	1	8.13	127	0.0	127		
	3	8.13	130	0.0	130		
	5	8.06	136	0.0	136		
June 9 +	1	8.22	130	0.0	130		
	3	8.24	129	0.0	129		
	5	8.18	130	0.0	130		
June 27	1	8.70	122	8.2	114	28.3	13.5
	3	7.80	124	0.0	124	29.9	13.6
	5	8.35	122	0.0	122	26.4	13.1
July 11	1	8.94	118	13.4	105	25.6	14.3
	3	8.98	118	16.4	101	26.7	12.5
	5	8.93	115	13.8	101	--	--
July 23	1	8.14	107	0.0	107	23.1	13.9
	3	8.48	106	2.2	104	25.0	13.7
	5	8.46	106	3.0	103	24.1	13.7
August 7	1	9.30	102	25.2	76.4	22.4	14.4
	3	9.30	100	25.6	74.7	20.4	14.2
	5	9.02	102	33.2	85.1	22.6	14.3
August 29	1	9.55	96.3	38.8	57.5	24.8	13.1
	3	9.54	96.0	38.6	57.4	24.3	13.4
	5	8.95	98.6	13.6	85.0	24.4	12.8
September 19 +	1	8.18	96.8	0.0	96.8		
	3	8.46	99.4	3.0	96.4		
	5	8.51	102	4.4	97.1		

* Samples analyzed by CCIW
+ Not analyzed for DIC/DOC

Table 5. Figure Eight Lake 1988. Metal Concentrations (mg/L) in the water column during open water period.

Date	Depth (m)	Sodium	Potassium		Magnesium		Calcium		Iron	Manganese
		* U of A	** CCIW	U of A	CCIW	U of A	CCIW	U of A	CCIW	CCIW
May 24	1	2.91	9.83	10.1	11.7	11.6	40.9	40.5	.054	.015
	3	2.90	9.61	10.0	11.7	11.5	41.2	40.2	.051	.015
	5	3.22	10.5	9.92	11.6	12.2	41.2	40.7	.067	.015
June 9	1	--	9.72	--	11.4	--	40.0	--	.068	.024
	3	--	9.44	--	11.4	--	40.0	--	.068	.025
	5	3.14	10.3	10.0	11.3	12.3	39.5	39.7	.048	.019
June 27	1	3.39	9.39	10.5	11.7	12.9	37.0	37.4	.025	.015
	3	3.15	10.5	10.6	11.9	13.0	42.3	37.7	1.400	.905
	5	3.06	9.45	10.3	11.7	12.8	37.7	37.7	.185	.136
July 11	1	2.88	9.86	10.5	11.6	13.1	35.3	38.5	<.007	<.002
	3	2.77	9.81	10.3	11.5	12.7	35.6	37.9	--	--
	5	--	--	--	--	--	--	--	--	--
July 23	1	2.58	9.86	10.2	11.5	12.2	29.9	28.4	.052	.020
	3	2.62	9.31	10.1	11.6	11.8	30.1	28.2	.074	.030
	5	3.91	13.4	13.7	12.2	12.0	23.8	29.2	.082	.031
August 7	1	2.60	10.7	9.52	11.5	12.6	27.2	26.4	.124	.095
	3	2.56	9.85	9.43	11.5	12.6	27.2	26.4	.126	.092
	5	2.55	9.69	9.26	11.4	11.4	27.6	26.3	.163	.091
August 29	1	2.82	11.1	10.1	11.7	11.9	28.8	28.4	.237	.111
	3	2.82	10.2	10.0	11.5	11.9	28.5	29.3	.234	.105
	5	2.78	10.6	9.73	11.4	12.2	28.9	30.0	.273	.126
September 19	1	2.87	10.5	9.61	11.2	12.1	29.3	31.0	.277	.079
	3	2.90	10.6	9.70	11.2	12.2	29.3	31.1	.289	.080
	5	2.90	10.3	9.48	11.1	12.3	29.3	30.0	.287	.081

* Analyses performed by the Univ. of Alberta.
** Analyses performed by CCIW.
-- Samples not analyzed.

Table 6. Figure Eight Lake 1988. Nutrient Concentrations (ug/L) in the water colummn under ice conditions.

Analyses performed by the Univ. of Alberta.

Date	Ice Thickness (cm)	Depth (m)	Total Phosphorus	Total Dissolved Phosphorus	Nitrite & Nitrate	Ammonium
November 2	9	1	73.3	37.2	--	--
		3	98.6	40.9	--	--
		5	75.8	41.7	--	--
November 15	10	1	89.9	50.7	--	--
		3	73.6	40.5	--	--
		5	64.4	38.1	--	--
November 29	ND	1	78.1	47.1	59.8	105
		3	75.0	45.5	235	--
		5	75.6	44.0	217	--
December 13	23	1	79.1	52.6	242	173
		3	71.6	49.2	231	169
		5	69.3	45.6	208	206
January 11	46	1	84.7	61.9	--	--
		3	77.1	58.7	--	--
		5	71.9	55.7	--	--
January 25	61	1	79.4	66.4	204	228
		3	80.6	66.5	194	228
		5	74.5	53.9	170	260
February 22	71	1	85.8	66.2		
		3	84.9	65.9		
		5	88.7	64.4		

-- Samples not analyzed.

ND - no data

Table 7. Figure Eight Lake 1988. Metal Concentrations (mg/L) in the water column under
ice conditions.
Analyses performed by the Univ. of Alberta.

Date	Ice Thickness (cm)	Depth (m)	Sodium	Potassium	Magnesium	Calcium
November 2	9	1	3.01	10.9	13.0	34.8
		3	2.83	10.4	11.6	33.7
		5	2.92	10.7	12.2	35.0
November 15	10	1	3.01	11.1	13.3	36.5
		3	2.90	10.9	12.6	35.6
		5	2.82	10.7	12.1	35.3
November 29	ND	1	2.97	11.0	12.9	36.6
		3	2.95	10.4	12.4	35.2
		5	3.00	11.0	13.2	37.0
December 13	23	1	2.87	11.0	12.7	38.1
		3	2.82	10.8	13.0	36.4
		5	2.79	10.8	13.1	36.9
January 11	46	1	3.50	11.7	12.8	40.6
		3	3.40	11.8	13.3	40.5
		5	3.19	11.0	12.5	39.4
January 25	61	1	3.37	12.4	12.4	45.8
		3	3.30	11.6	13.1	49.6
		5	3.15	11.2	12.4	48.2
February 22	71	1	3.52	12.2	12.9	52.6
		3	3.32	11.7	12.3	49.6
		5	3.33	11.6	12.5	49.8

ND - no data

Table 8. Figure Eight Lake 1988. Alkalinity Parameters (measured as mg/L CaCO) –
Under ice conditions.
Analyses performed by the Univ. of Alberta.

Date	Ice Thickness (cm)	Depth (m)	pH	Total Alkalinity	Carbonate Alkalinity	Bicarbonate Alkalinity
November 2	9	1	7.94	109	0.0	109
		3	7.84	108	0.0	108
		5	7.92	111	0.0	111
November 15	10	1	7.86	113	0.0	113
		3	7.86	111	0.0	111
		5	7.85	115	0.0	115
November 29	ND	1	7.76	119	0.0	119
		3	7.76	119	0.0	119
		5	7.69	116	0.0	116
December 13	23	1	--	--	--	--
		3	--	--	--	--
		5	--	--	--	--
January 11	46	1	7.36	130	0.0	130
		3	7.43	125	0.0	125
		5	7.50	125	0.0	125
January 25	61	1	7.62	146	0.0	146
		3	7.56	146	0.0	146
		5	7.53	142	0.0	142
February 22	71	1	7.43	149		
		3	7.49	147		
		5	7.60	150		

-- Samples not analyzed.

Table 9. Figure Eight Lake 1988. Physical Parameters - Under ice conditions.
Analyses performed by the Univ. of Alberta.

Date	Ice Thickness (cm)	Depth (m)	Dissolved Oxygen (mg/L)	Colour (mg/L as Pt.)	Turbidity (NTU)	Conductivity (us/cm)
November 2	9	1	11.2	--	--	380
		3	10.9	--	--	390
		5	7.8	--	--	380
November 15	10	1	12.2	20.0	1.95	370
		3	9.8	18.8	2.15	355
		5	6.3	16.3	1.85	358
November 29	ND	1	7.2	12.5	1.80	350
		3	6.5	7.5	1.70	345
		5	5.2	12.5	1.50	350
December 13	23	1	5.5	17.5	2.25	410
		3	5.0	15.0	2.00	410
		5	3.9	17.5	2.45	380
January 11	46	1	4.0	20.0	1.80	415
		3	4.1	20.0	1.85	405
		5	2.8	20.0	2.00	410
January 25	61	1	2.9	16.8	1.95	409
		3	2.9	17.5	1.95	428
		5	1.3	17.5	2.25	408
February 22	71	1	2.0	--	--	--
		3	1.8	--	--	--
		5	0.8	--	--	--

-- Samples not analyzed
ND - no data

Table 10   Primary Production Bioassays

Treatment[*]	Primary Production $(mg\ m^{-3}\ h^{-1})$	
	July 23	August 7
Control-1	30	290
Control-2	35	689
Ammonia-1	47	248
Ammonia-2	38	402
Phosphorus-1	29	169
Phosphorus-2	43	374
Ferric chloride-1	43	176
Ferric chloride-2	50	434
Fe-EDTA-1	--	229
Fe-EDTA-2	--	267
EDTA-1	--	175
EDTA-2	--	196

[*] each replicated treatment was sampled twice and reported
as a mean value

Figure 1
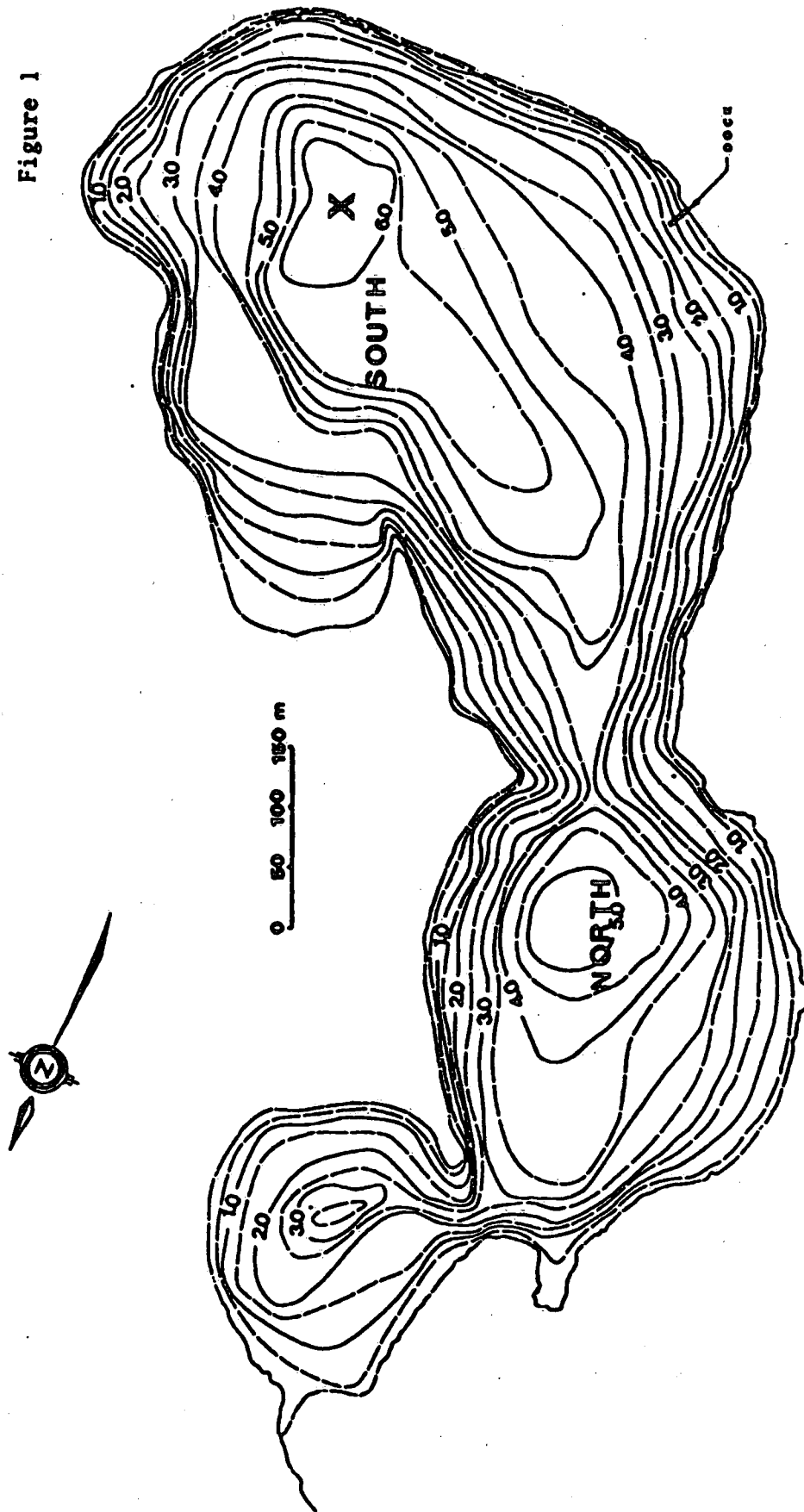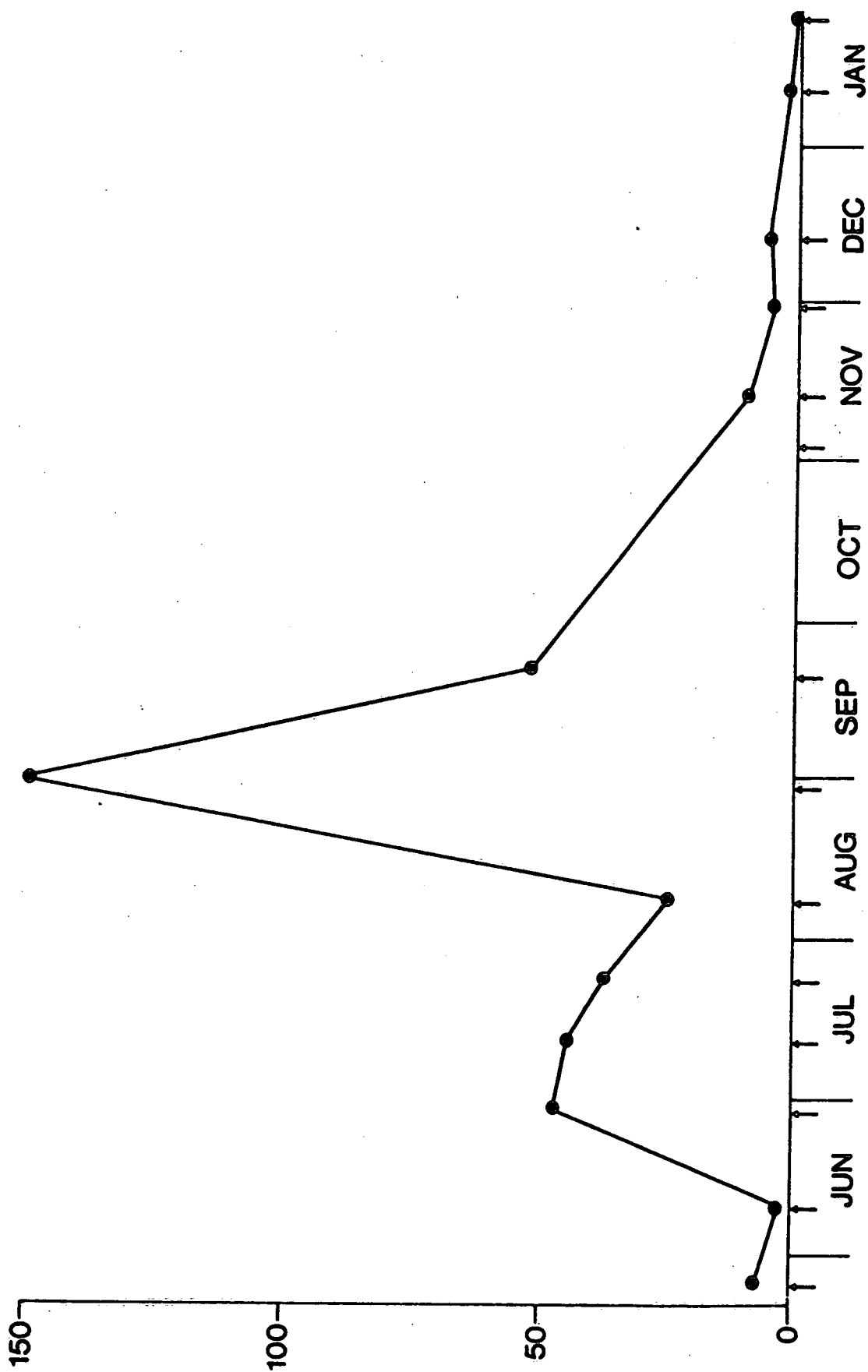
Figure. 8 Lake Chlorophyll a (µg/L) 1988
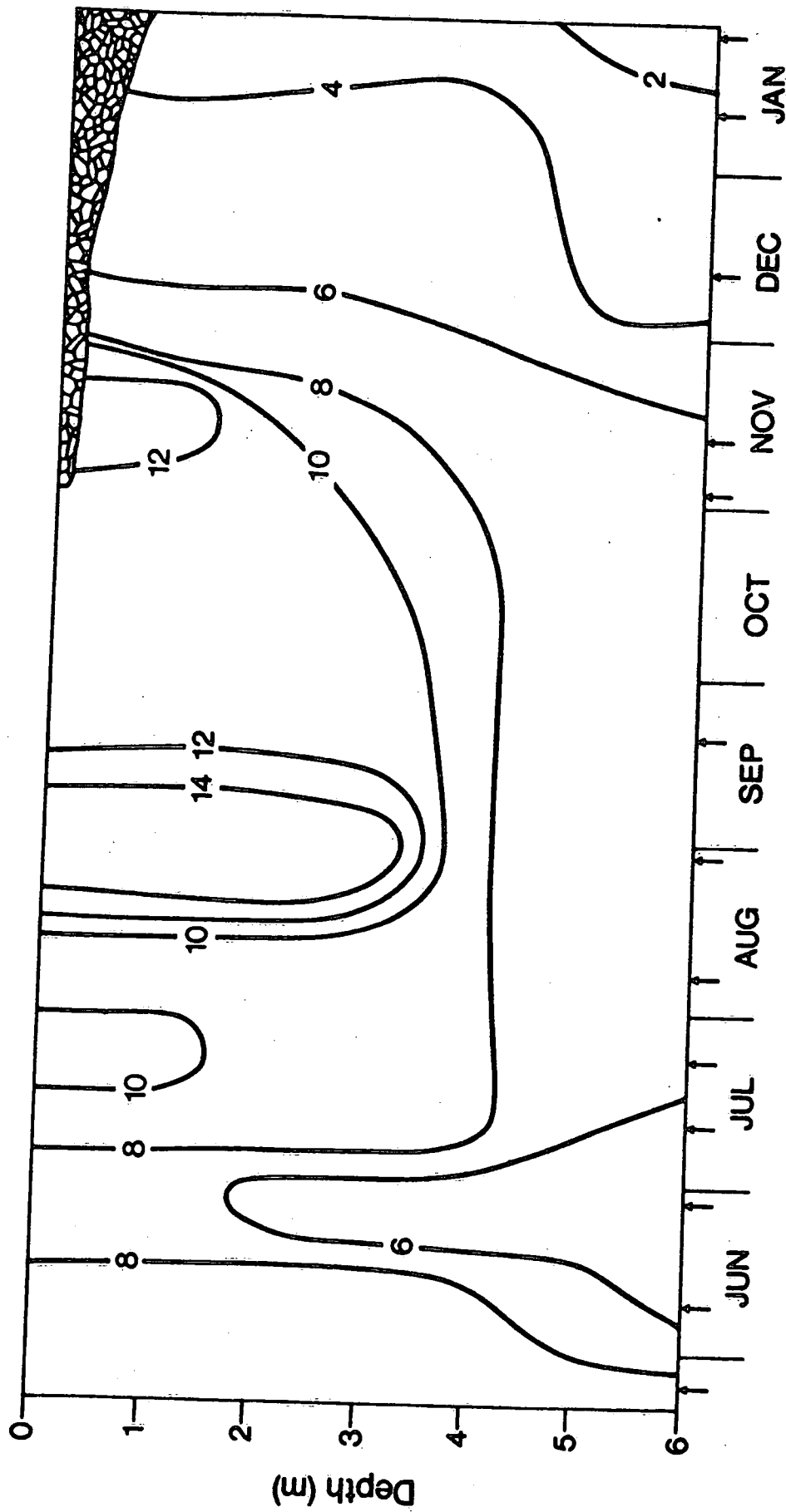
Figure 2

Figure 8 Lake Dissolved Oxygen (mg/L) 1988
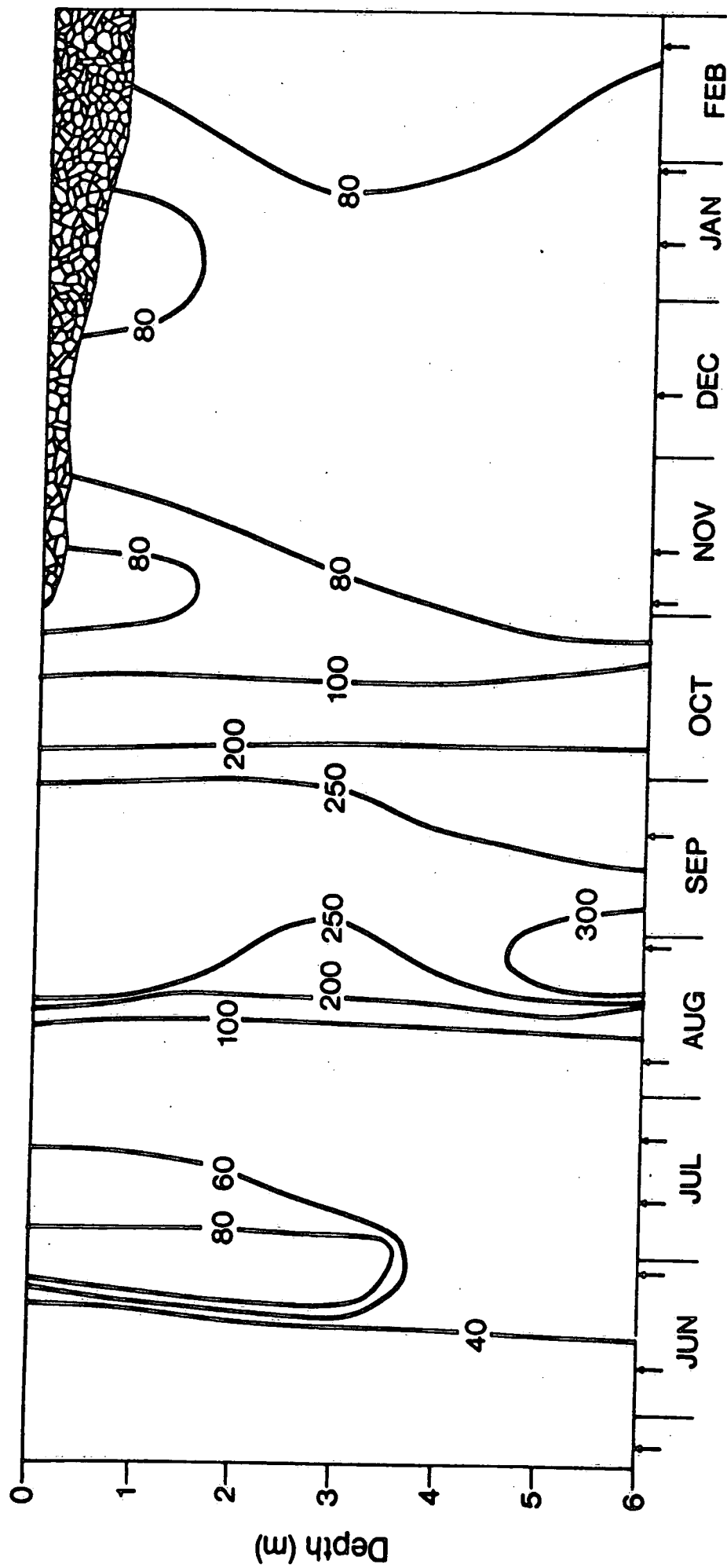
Figure 3

Figure 8 Lake Total Phosphorus (μg/L) 1988
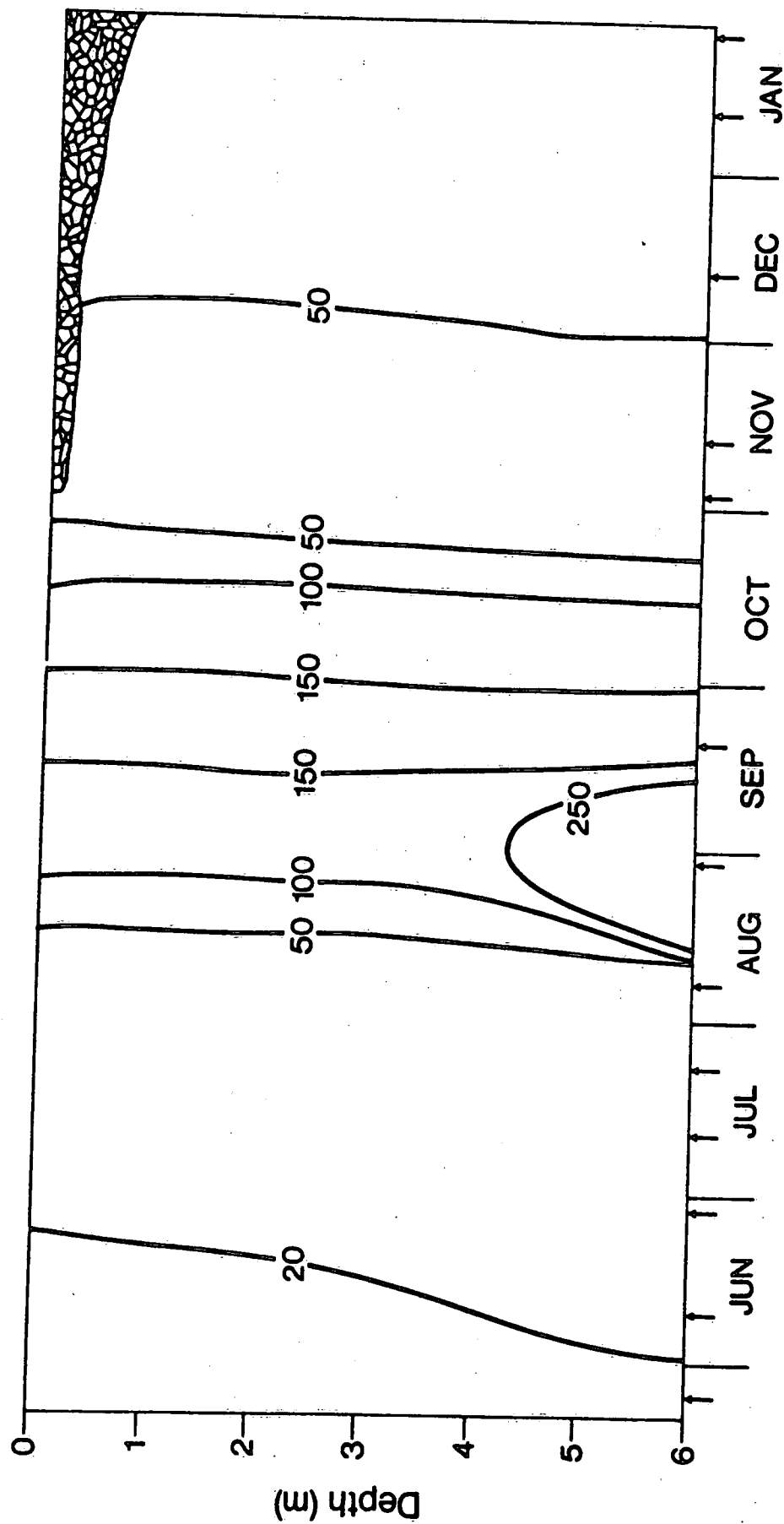
Figure 4

Figure 8 Lake Total Dissolved Phosphorus (µg/L) 1988
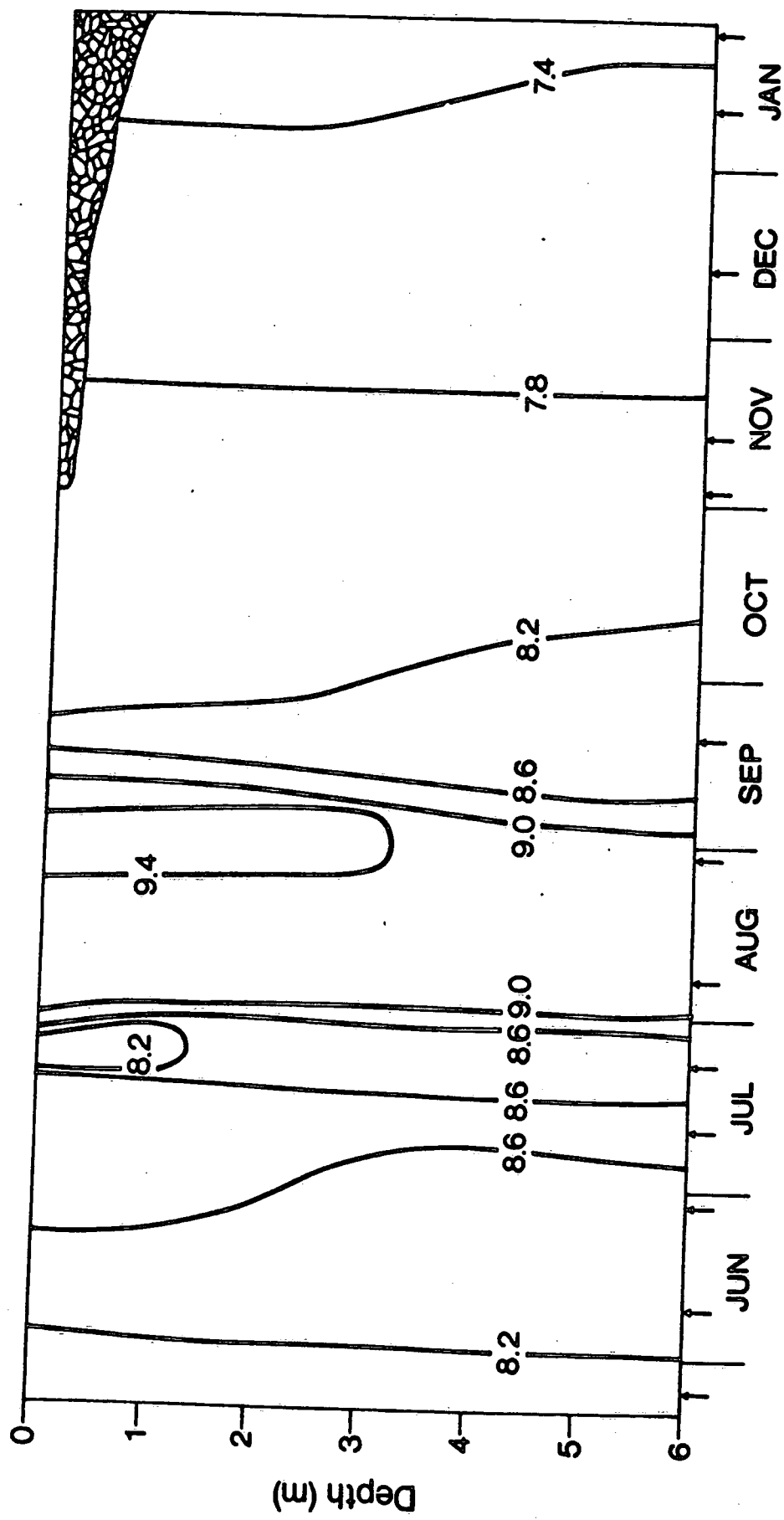
Figure 5

Figure 8 Lake pH 1988
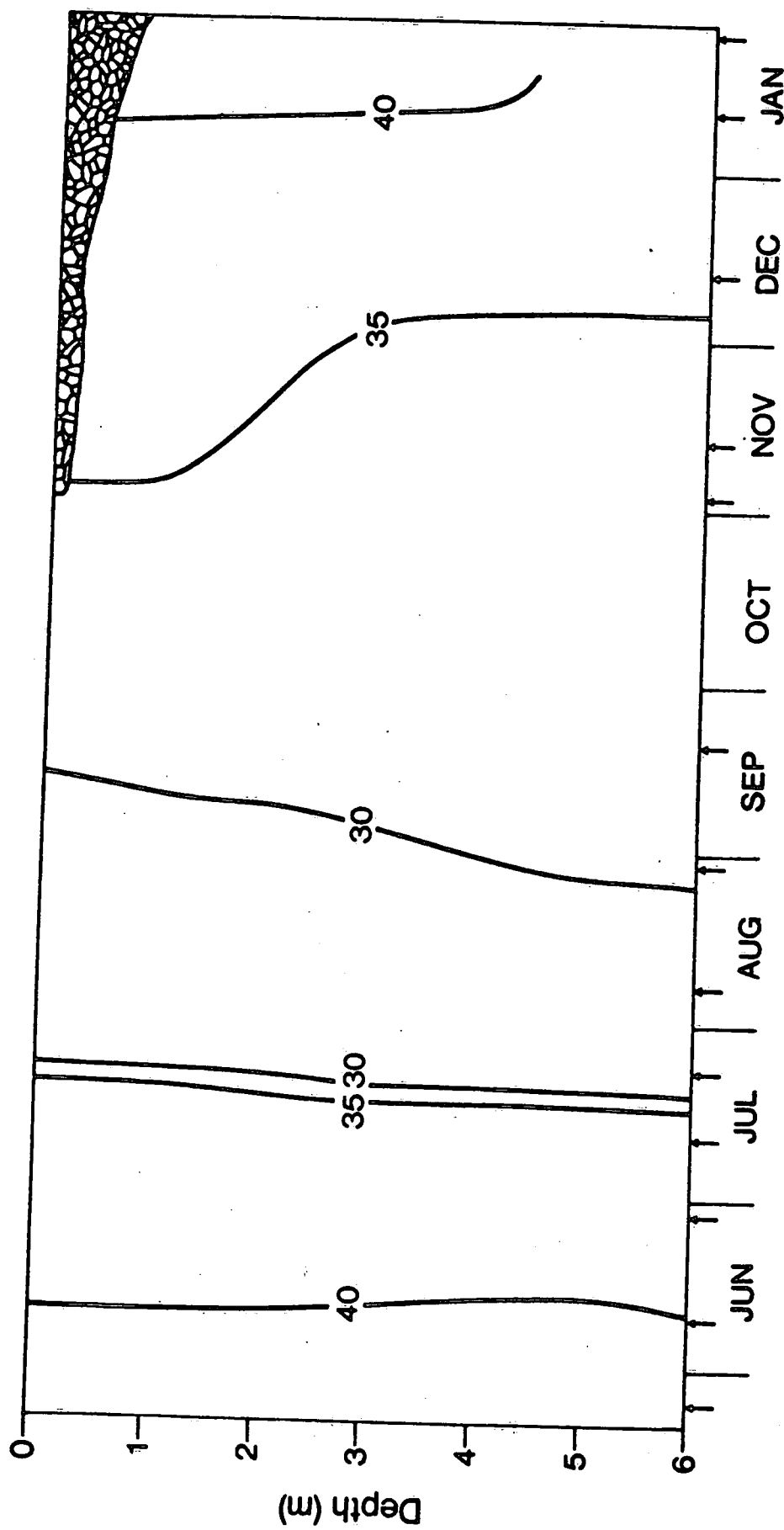
Figure 6

Figure 8 Lake Total Calcium (mg/L) 1988
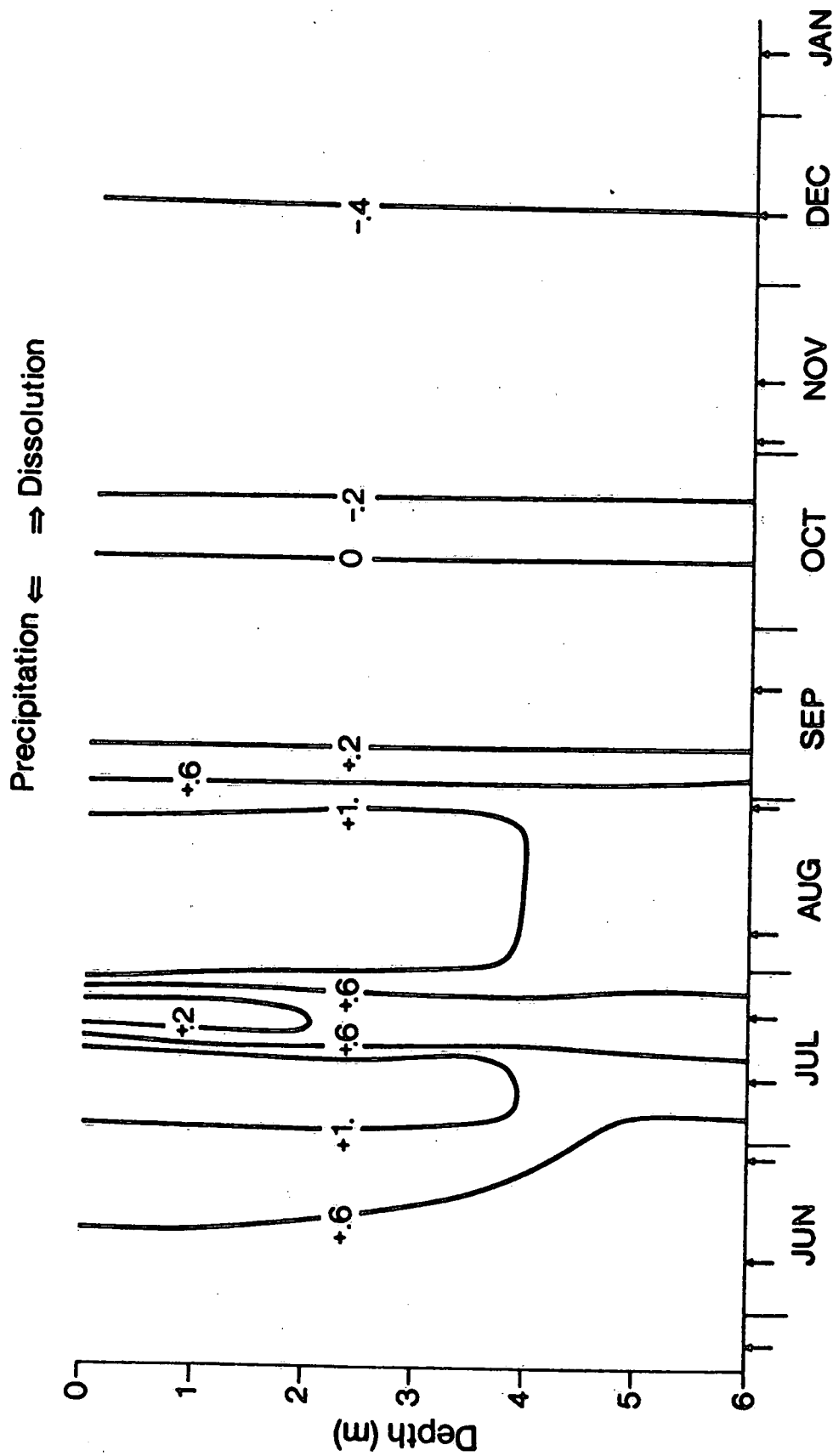
Figure 7

Calcite Supersaturation Log IAP/Kt 1988

Figure 8
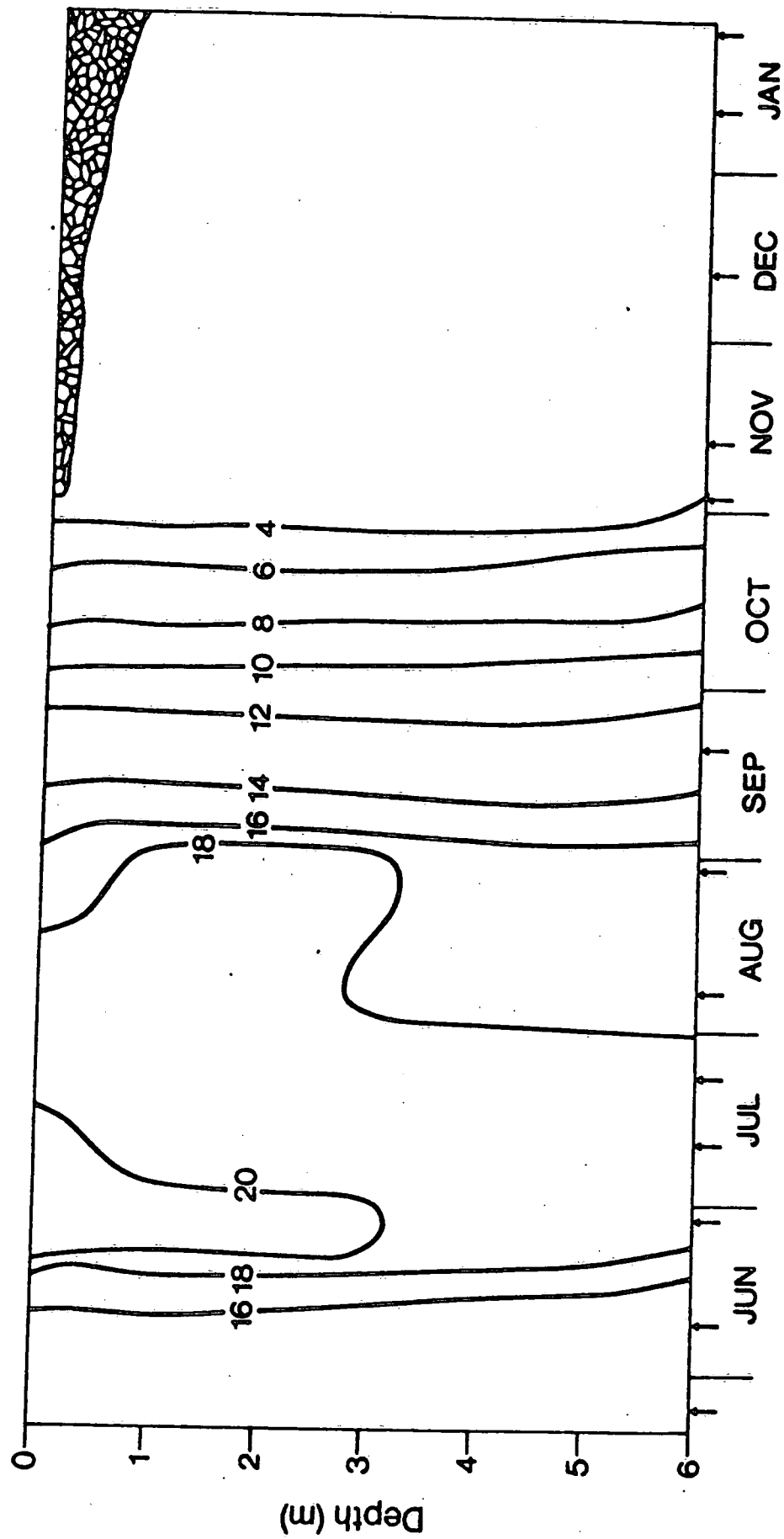
Figure 8 Lake Temperature (°C) 1988
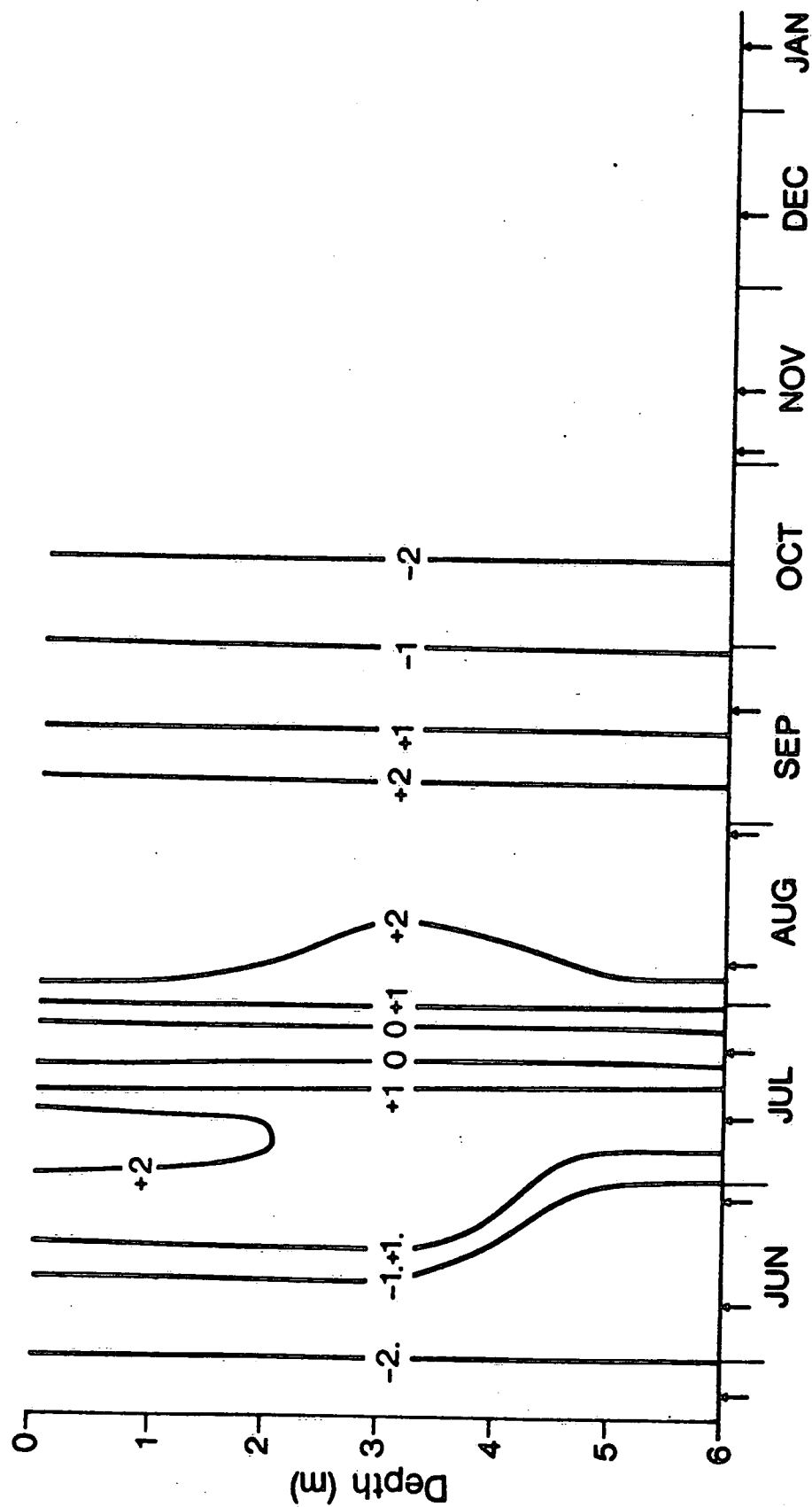
Figure 9

Hydroxyapatite Supersaturation Log IAP/Kt 1988

Figure 10

Fe-55 Binding – Figure 8 Lake

1987 – Vmax – North Basin

Vmax vs Date
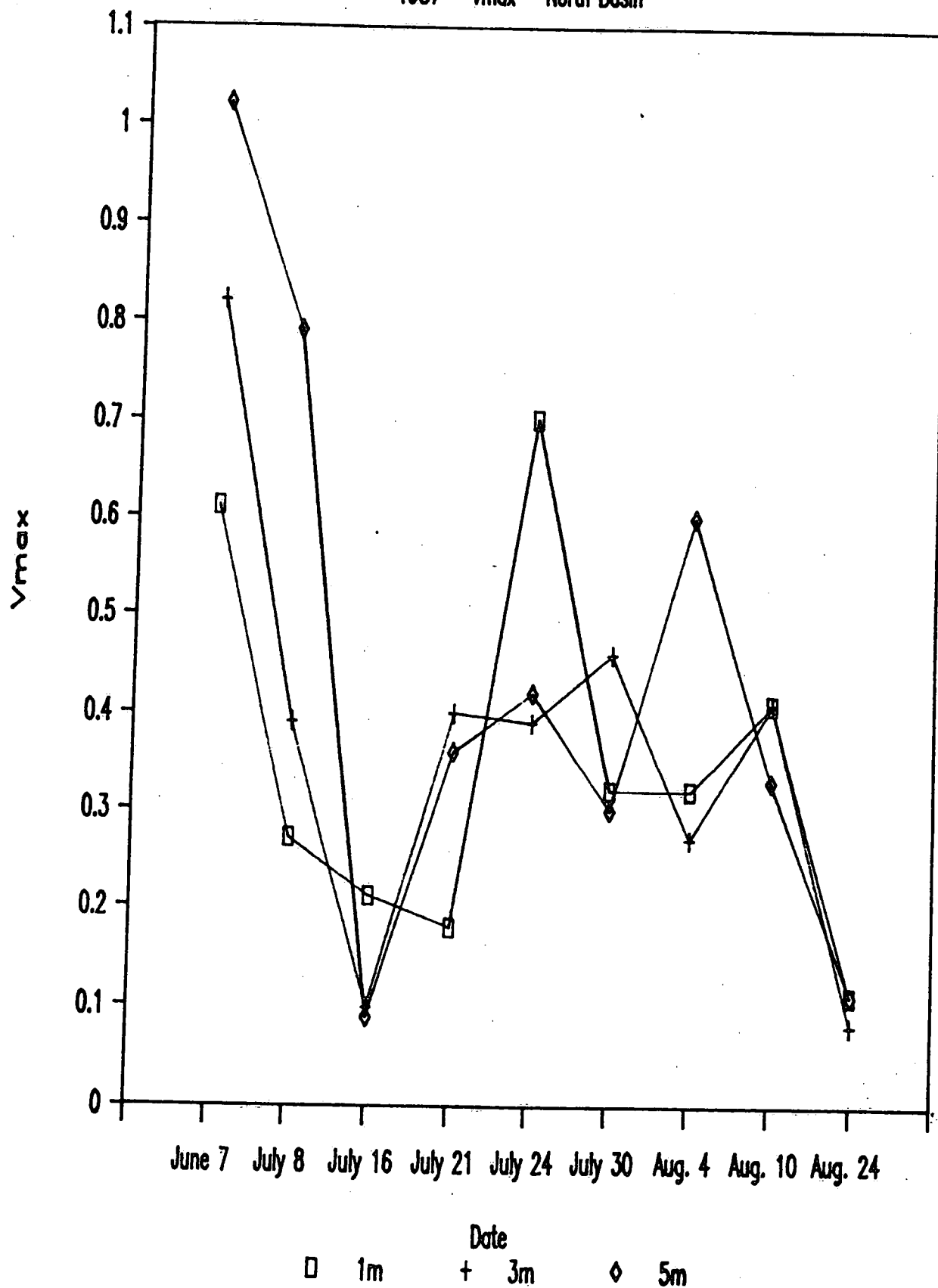
□ 1m   + 3m   ◊ 5m

Figure 11

Fe-55 Binding – Figure 8 Lake

1987 – Vmax – South Basin
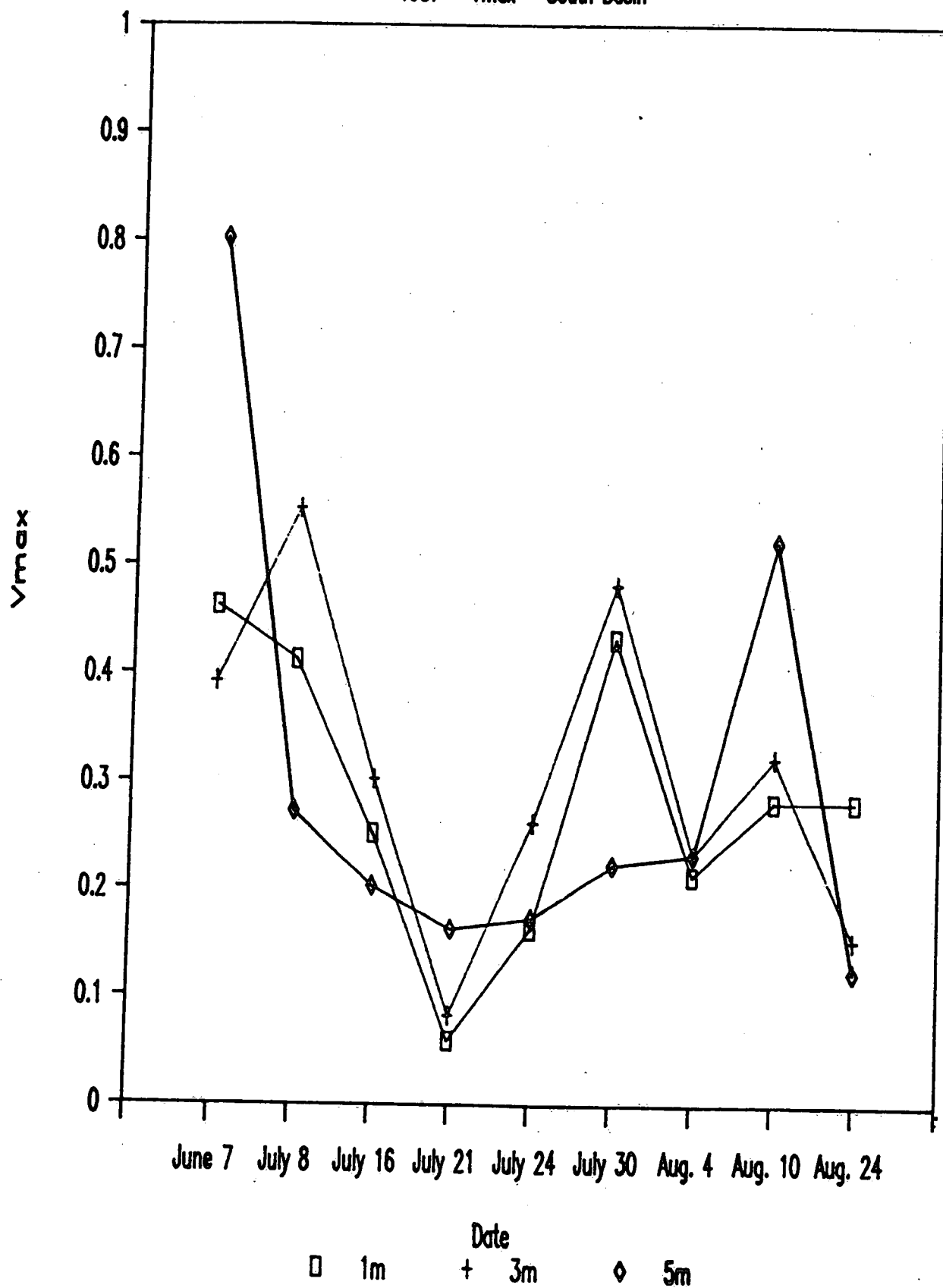
Figure 12

Figure 8 Lake - DIC, DOC, Total Fe

1987 - North Basin
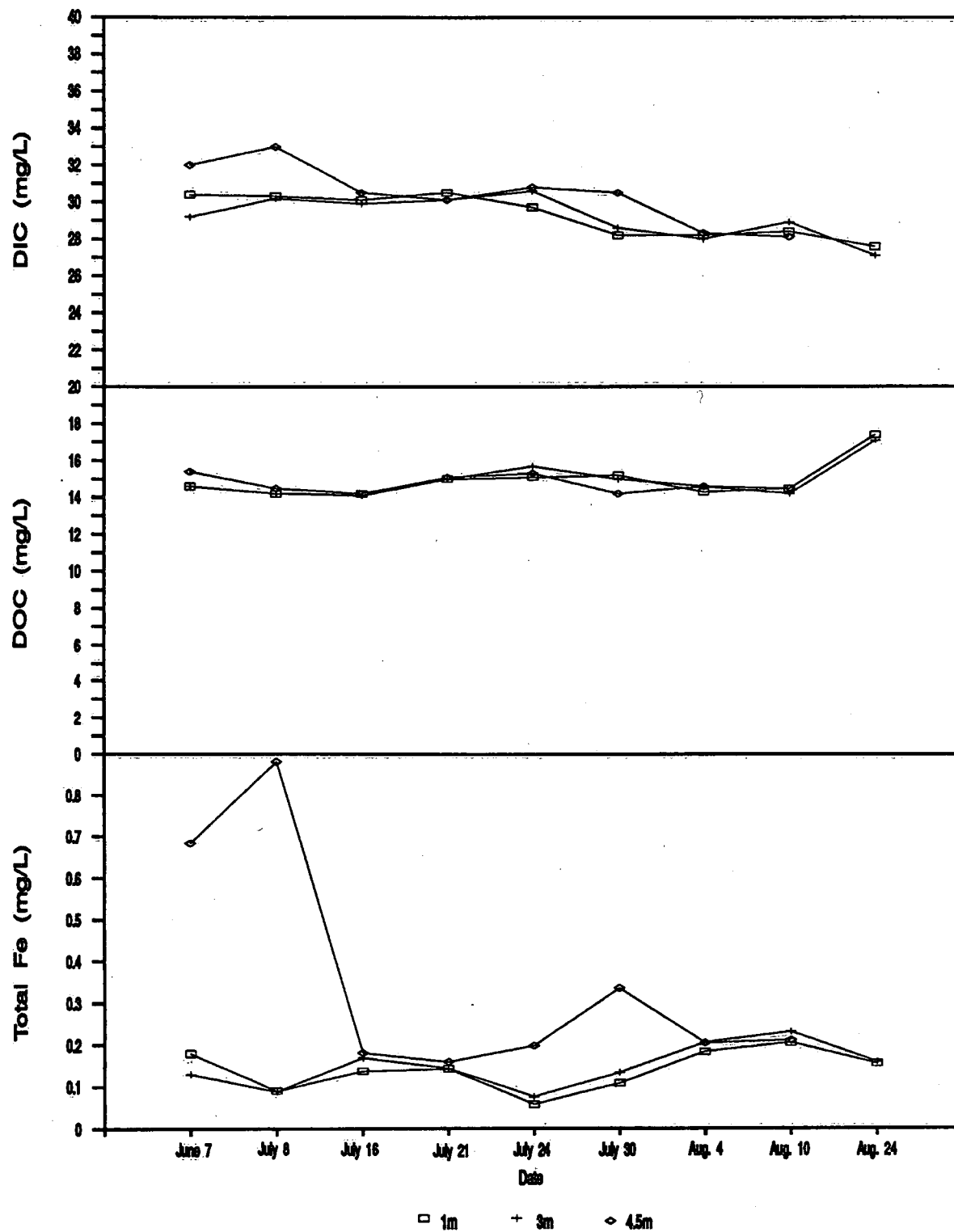
Figure 13

Figure 8 Lake - DIC, DOC, Total Fe

1987 - South Basin

Figure 14

□ 1m   + 3m   ◇ 5m