MINISTRY OF ENVIRONMENT AND PARKS
PROVINCE OF BRITISH COLUMBIA

WOOD LAKE: A PROPOSAL FOR A DEMONSTRATION PROJECT FOR WATER QUALITY IMPROVEMENT

Richard N. Nordin
Water Quality Unit
Resource Quality Section
Water Management Branch
Victoria, B. C.

July 1987

TABLE OF CONTENTS

	Page
SUMMARY	vi
ACKNOWLEDGEMENTS	v
1. INTRODUCTION	1
1.1 Background	1
1.2 Data Base and Previous Studies	8
2. HYDROLOGY AND LAKE MORPHOMETRY	10
2.1 Surface Water	10
2.2 Lake Physical Structure	10
2.3 Groundwater	11
3. WATER QUALITY	16
3.1 General Ions	16
3.2 Nutrients and Oxygen	16
4. NUTRIENTS	26
4.1 Loading Estimates	26
4.2 Trends over Time	28
5. SEDIMENTS	33
6. TREATMENT RATIONALE AND DESIGN	46
7. PROPOSED TREATMENT	64
REFERENCES	73

LIST OF TABLES

TABLE		Page
1	Wood Lake: Morphologic, Hydrologic and Physical Data........	12
2	Hypsographic Data for Wood Lake............................	13
3	Wood Lake - Water Input From Vernon Creek 1970 - 1982........	14
4	Wood Lake Water Chemistry - Summary of Previous Sampling.....	19
5	Spring Overturn Phosphorus and Nitrogen Concentrations 1973-1986..	31
6	Recent Changes in Wood Lake Water Chemistry..................	32
7	Chemical Concentration of Elements in Wood Lake Sediments....	34
8	Phosphorus Fractions of Wood Lake Sediments..................	37
9	Iron Fractions of Wood Lake Sediments.......................	38
10	Phosphorus and Iron in Surface Sediments.....................	40
11	Phosphorus Minerals in Lake Sediments.......................	43
12	Sediment Interstitial Water Estimates.......................	52
13	Sediment-Water Column Experiment (Distilled).................	53
14	Sediment-Water Column Experiment (Wood Lake Water)...........	55
15	Oxygen Concentration and pH in Experimental Columns..........	57
16	Iron Concentrations in Sediment-Water Columns................	58
17	Phosphorus Concentrations in Sediment-Water Columns (low dosages)..	59
18	Chemical Analysis of Tree Island Steel Pickling Liquor.......	66
19	Calculated Increases in Metals in Wood Lake Sediments........	68

LIST OF FIGURES

FIGURE		Page
1	Bathymetry of Wood Lake	15
2	Time-Depth Diagram for Phosphorus in Wood Lake	17
3	Mass of Phosphorus in Wood Lake	18
4	Time-Depth Diagram for Nitrate in Wood Lake	21
5	Time-Depth Diagram for Ammonia in Wood Lake	22
6	Dissolved Oxygen in Wood Lake	24
7	Calcium Concentrations in Wood Lake Epilimnetic Water	25
8	Sediment-Water Experimental Column	50
9	Wood Lake Sediment Treatment Field Experiment	63

ACKNOWLEDGEMENTS

I am very grateful to everyone who took time to read, make comments and suggestions on the first draft of this report. Reviewing a thick report during a heavy schedule of other work was difficult for everyone and I would like to thank everyone on whom I inflicted this task: Bill Kastelen, Dick Nickel, Ron Kawalilak, Jim Bryan, Peter Jarman, Chris Bull, Dave Jones, Ken Ashley, Colin Gray, Tom Murphy, Ron Buchanan, Roland Rocchini, and Colin McKean. Lorna Rounds did the word processing and again tolerated my intolerable handwriting and my seeming unending requests for changes and corrections.

Kevin Devito assisted with the laboratory experiments by fabricating equipment, and running some of the experiments. Tom Murphy provided information and unpublished data which was very helpful.

Ray Kirkland and NWRI, West Vancouver, provided chemical analysis of Wood Lake sediments and provided unpublished data from the 1980-81 work done by NWRI. Colin Gray provided other unpublished data and on numerous occasions was an invaluable source of comments, information, and advice.

SUMMARY

Wood Lake has been identified in a number of previous studies as having poor water quality relative to the other lakes of the Okanagan Valley. This poor water quality (high nutrients, excessive algae, oxygen depletion) prevents the water-based recreation potential from being achieved and affects the sport fishery potential. The water quality of the south end of Kalamalka Lake has also been affected by the inflow of high concentrations of nutrients from Wood Lake.

The high phosphorus concentration in Wood Lake is a result of recycling of phosphorus normally lost to the sediments (so called "internal loading"). In most lakes, phosphorus taken up by biota in the water column settles with the dead biota and ends up in the sediments, bound more or less permanently. In Wood Lake (and some other eutrophic lakes) the phosphorus is not bound in the sediments and returns to the water column as part of an annual cycle. The intent of the project described in this report is to add iron to retain phosphorus in the sediments. The proposal has the advantage of treating the cause of the problem (internal phosphorus loading) rather than any secondary symptoms.

A number of previous proposals have been made to improve Wood Lake water quality, but none at present have been implemented. The proposal presented here is to modify the chemical composition of Wood Lake sediments, by adding iron, to prevent phosphorus release from the sediments. Phosphorus release from sediments appears to be the major mechanism maintaining high phosphorus concentrations in the water column. Evaluations of external phosphorus loadings indicate that these are generally low in comparison to internal loading.

The data and findings of previous studies are reviewed and information relevant to the proposal is presented. A review of the relevant scientific

literature was made and some laboratory investigations were carried out to determine the feasibility of the proposal. Summaries of these aspects are presented.

The initial concept of enhancing iron concentrations in Wood Lake sediments was proposed after it was noted that Wood Lake water and sediment had relatively low concentrations of iron. It was hypothesized that this might be the reason why there is an apparently large movement of phosphorus in late fall and winter from the sediments to the water column. Wood Lake sediments and interstitial water have high concentrations of phosphorus. If this phosphorus could be chemically bound permanently to iron, the water column phosphorus concentrations should be reduced and general water quality should improve. The difficulty with changing the water quality of Wood Lake is its size (9.3 km^2) which makes adding a sufficient amount of iron very expensive if bulk commercial chemical (ferric chloride) were used. The factor which made the proposal potentially feasible was the availability, free of charge, of large quantities of an iron solution from an industrial process. The iron is in the form of a waste product ("pickling liquor") from a steel plant in the Vancouver area.

Although pickling liquor is used at three sewage treatment plants to remove phosphorus from effluent, there are a number of potential problems associated with its use in Wood Lake. Since the iron material is a waste product, an extensive series of chemical analyses for heavy metals, organics and other constituents was done. Bioassays were run with fish and zooplankton.

Laboratory experiments were used to evaluate likely effects in the lake. The result of these evaluations was that the use of pickling liquor in Wood Lake appeared to be a favourable course to pursue. The bench-scale experiments showed that iron additions slowed movement of phosphorus from lake sediments to the water column even under low oxygen conditions.

An outline of the proposed application technique and details of the logistics of the project are described. The project is to be undertaken in August and September when the lake is most strongly stratified. By using a subsurface addition, there appears to be very little risk of undesirable changes in water chemistry, sediment, or toxicity to biota. Although the pickling liquor shows some toxic effects to fish and zooplankton, by dispersing it 20 metres below the surface during the period of maximum lake stratification, there would be no exposure of the pelagic biota to the pickling liquor. There are virtually no benthos in Wood Lake deep sediments according to recent surveys. As a consequence, toxicity to benthos is not a major concern. The iron solution is to be distributed on transects over the deep sediments by pumping the pickling liquor solution from a boat down a hose to a diffuser 20 metres below the surface. Approximately 4.5 km^2 of the lake bottom sediments is proposed to be treated.

Prior to undertaking the full scale treatment, it is proposed that a small scale field experiment will be undertaken. This field experiment will provide additional information on the practicality of the full scale project and check the conclusions drawn from the laboratory experiments. The field experiment will also provide the opportunity to assess possible effects on lake biota.

This report provides details of the background of the project, its feasibility, and presents the results of a number of investigations undertaken to evaluate this proposal.

1. INTRODUCTION

1.1 BACKGROUND

A report was prepared in 1985 by the Water and Waste Management Branches (Ministry of Environment 1985) which was a review of phosphorus loading to the Okanagan Valley Lakes. The report was used as the basis for a cabinet submission which requested additional funding to deal with the problem of nutrient inputs (specifically phosphorus), the very high costs of advanced treatment of sewage, and control of non-point sources. A fund of $26 million was subsequently established to assist with protection of the lakes. The money was to be used to cover 75% of costs for municipalities making improvements to discharges as well as investigations of non-point source contributions. Waste Management Plans will be the basis of funding for Municipalities by encouraging them to have an integrated, long-range perspective of problems and solutions. The funding is to apply over a three-year period (1985-1988) and will be guided through the creation of the Okanagan Water Quality Control Program (OK Water). Two small projects suggested in this 1985 report are also to be funded. One proposal is to investigate the reduction of phosphorus loading from septic tanks by pilot scale in-tank phosphorus removal systems. The other is a proposal to improve Wood Lake water quality by reducing the internal phosphorus loading through treatment of bottom sediments. This latter proposal is the subject of this report.

Since the first evaluation of the Okanagan Lakes was done, Wood Lake has been identified as having relatively poor water quality, particularly in comparison to the adjacent lakes (Kalamalka and Okanagan). The need for improvement of Wood Lake and the unsatisfied public concern is documented in previous reports which have evaluated Wood Lake. In the Okanagan Basin Study, which had a socio-economic component, Wood Lake was described in the following manner (Canada-British Columbia, Okanagan Basin Agreement, Annual Report March 31, 1972, P.17). Under the advantages of Wood Lake, general lake conditions of "warm water" and "safe beaches" are listed. The disadvantages listed were "virtually no fishing, algal growth detracts seriously from recreational opportunities". The warm water temperature of Wood Lake is important since the descriptions for both Okanagan and Kalamalka contain the comment "cold for swimming".

The Kalamalka-Wood Lake Basin Water Resource Management Study (1974) had an excellent public involvement program which should have reflected public opinion. The study listed among its final recommendations that "immediate steps be taken to improve the quality of Wood Lake by reducing nutrient concentrations in this lake. Consideration should be given to alum, aeration or similar treatments". The Okanagan Basin Study Implementation Agreement Summary (1982) stated that "improvement of (Wood Lake) water quality would require reduction of phosphorus loadings and/or use of in-lake restoration methods".

Immediate improvement of the water quality of Wood Lake is not an item of high public profile. As noted above, the poor water quality for swimmers is a major consideration. Given the choice between turbid, green Wood Lake and clear, blue Kalamalka (or Okanagan Lake), the swimmers (as might be phrased) "stay away in droves". The lack of developed access points or improved beach areas also reduces potential use. This latter circumstance, however, is unlikely to change until water quality improves, thus much hinges on the water quality.

Because of the heavy algal growth and consequent poor water quality, the high potential use for recreation has not been realized. Wood Lake is smaller than Kalamalka or Okanagan, has a higher surface water temperature, and should be preferred for swimming over the cooler water of the larger lakes. The poor water clarity (caused by high nutrients), however, prevents many people from using the lake who would likely otherwise do so. Water clarity has improved over the last ten years but it is still much poorer than any of the other Okanagan main-stem lakes.

The recreational fishery is also negatively affected by the hypolimnetic oxygen depletion. Oxygen depletion and the eutrophic conditions appear to be a major constraint to salmonid fishery production (kokanee and rainbow trout). Recreational fishing effort has increased over the past two or three years; however, it is not clear whether this is due to a change in the fish populations or the discovery by fishermen of a previously unexploited fishery resource. Prior to 1985 few fishermen fished in Wood Lake and there are no detailed data on salmonid populations presently available. The question of fisheries and the relationship to water quality and the proposed project is an important one. Quoted above was the comment from the Okanagan Basin Study that little fishing activity was present in Wood Lake in 1971. The 1972 annual report also shows a figure (p.18) giving the relative abundance of fish in the mainstem lakes as measured by a netting program. The abundance (fish standing crop - all species) in Wood Lake was lowest of all the lakes sampled. The standing crop given for Wood Lake was less than half that given for Okanagan Lake and less than one third of Skaha. The most intensive fisheries work done on fisheries of Wood Lake was done as part of the Kal-Wood Study. This 1972 study showed higher fish standing crop in Wood than Kalamalka but that the potential yield, on a per area basis, should be much larger in Wood Lake (13-fold in terms of sport fish, 24-fold in terms of all fish). In light of current knowledge these estimates are probably far too high. However, the principle is valid and Wood Lake should yield more fish production than it does. In the discussion of fisheries and water management in the Kal-Wood report (p. 174), the decline of the Wood Lake kokanee fishery is attributed to eutrophication of the lake. It is noted that a decrease in eutrophy would probably improve conditions for kokanee and other salmonids.

The question of what the quantitative objectives for future fisheries are is also important. Without good data to estimate present populations it is difficult to determine what changes in population might occur, particularly without details of whether the populations are limited by food availability, spawning habitat, predation, or a number of other factors. However, the water quality is sufficiently poor that, if the summer oxygen depletion were reduced then a substantial portion of the bottom waters would then be made available for fish to use as habitat and for fish food organisms to recolonize, and some improvement in fish productivity would be inevitable.

A third consequence of the poor water quality of Wood Lake is the impact on Kalamalka Lake. In recent years, there has been a measurable deterioration in the water quality of Kalamalka, particularly in the south portion of the lake where it might be expected that the influx of Wood Lake water might have the most marked effect. There are certainly a number of other likely sources of nutrients in the watershed but the net flow of poor quality water from Wood Lake has been identified on several occasions as a significant loading to Kalamalka Lake. Kalamalka Lake is an extraordinary lake and a very valuable resource which needs to be protected. At present, the lake has a spring phosphorus concentration of about 10 µg/L. The water quality objective for Kalamalka Lake given in the Ministry of Environment (1985) report is 8 µg/L. Earlier, the Okanagan Basin Study recommended that the phosphorus concentration not exceed 5 µg/L. Clearly some immediate action is necessary to reduce phosphorus loading to Kalamalka Lake, and reducing the concentration of phosphorus in Wood Lake is one means of achieving this.

The long-term average spring phosphorus concentration for Wood Lake is 75 µg/L. The objective proposed in the 1985 report is 15 µg/L representing a compromise between the requirements for recreation and fisheries. For purely recreational use, it would be advantageous to have as low a concentration of phosphorus as possible, probably less than 10 µg/L, since this would result in high water clarity and best aesthetic appeal. However, most lakes have several uses which may have conflicting requirements. In a lake with recreational fisheries use it is necessary to have sufficient basis for biological production which means a reasonable supply of nutrients. Too high a supply of nutrients is not desirable, since for good salmonid production, a lake with a cool oxygenated hypolimnion is necessary and lakes with phosphorus concentrations greater than 15 or 20 µg/L run the risk of hypolimnetic oxygen depletion depending on the lake morphometry (see Nordin

1986). For Wood Lake, the typical spring concentration of 75 µg/L phosphorus is too high to allow use of the hypolimnion of the lake in summer because of the low oxygen concentrations associated with this high nutrient level. A reduction of phosphorus to a level (probably in the 20-30 µg/L range) which gives an acceptable oxygen depletion results in water quality which is not ideal for recreational use (swimming, boating, etc.). The objective proposed for Wood Lake in the 1985 report was 15 µg/L phosphorus. This value represented a compromise between these two major water uses.

Determination of an optimal range of nutrients which would result in the best conditions for fish production is presently being investigated with particular application to Wood Lake. In principle the optimal range would be high enough so that food supply is sufficient (particularly zooplankton production) but not so high as would result in an oxygen depletion in summer. The species of primary importance in Wood Lake is kokanee. Most lakes in British Columbia with significant kokanee recreational fisheries have relatively low concentrations of phosphorus e.g., Okanagan (10 µg/L), Skaha (15 µg/L), Kootenay (5 µg/L). No studies have been carried out on any of these lakes to indicate that food limitation is a major constraint to fish production. In any case, this important question of nutrient level relationship to food supply of kokanee will receive attention in the future.

With Wood Lake below its potential for both recreation and fisheries, a number of proposals have been made to improve water quality. The Kalamalka-Wood Lake basin Study (1974) made recommendations for several possible actions which would improve Wood Lake water quality. These included alum treatment, aeration, mixing Wood and Kalamalka Lakes together, constructing a tunnel between Wood and Okanagan Lakes to pump Okanagan Lake water into Wood Lake, as well as watershed activities to reduce phosphorus input (set-backs, green belts, zoning, removing or improving septic tanks). The option which appeared to be the most promising (alum treatment) was investigated by B.C. Research (1976). The objective proposed by B.C. Research was to reduce lake phosphorus to 15-20 µg/L. On the basis of laboratory jar tests, a dosage of 1 mg/L Al/cm^2 was calculated to be sufficient to achieve that objective. The intent was removal and immobilization of water column phosphorus (as contrasted to treatment of sediments). To treat the lake, 1100 tonnes were to be required at a cost of $100/tonne (1975). Field experiments were conducted and it was concluded on the basis of results obtained that 1 mg Al/cm^2 was not a sufficient dosage, that 2-5 mg/cm^2 was required and this made the project economically impractical.

The second water quality improvement technique considered was hypolimnetic aeration. A quote was obtained by the Okanagan Implementation Program from Atlas-Copco in 1980 for aeration of Wood Lake. A cost of $1,151,000 was tendered, and this cost was considered too high to be practical. Destratification aeration was determined to be inappropriate in this situation.

A number of other lake restoration techniques (as well as alum treatment noted above) were put forward as suggestions in the Kal-Wood report. A tunnel between Wood and Okanagan Lakes to enable high quality Okanagan water to be fed into Wood Lake was suggested; however, the costs were so high ($4.75 million 1974 dollars) that it was never seriously considered. Ironically, the pumping of Okanagan Lake water by Hiram Walker, its use for distillation cooling and subsequent discharge to Wood Lake is a small scale version of this proposal. The effects on Wood Lake water quality are discussed in section 4.2. Also proposed was the forced mixing (by pumping) of the entire volumes of Kalamalka and Wood Lakes using the rationale that the difference in volumes would result in a marked improvement in Wood Lake and only a minor deterioration in Kalamalka Lake. The risk of damage to Kalamalka Lake was a consideration as well as the fairly large cost ($340,000) and this idea never passed the concept stage. Other suggestions were concerned with techniques other than in-lake restoration. These included setback and greenbelt regulations for creeks, land-use zoning to minimize nutrient input and the sewering of residential areas which were at the time on septic tanks (Winfield).

Gray and Jasper (1982) also considered some options for Wood Lake and recommended fertilization with ammonium nitrate in the spring as a means of reducing summer blue-green algal concentrations and increasing summer water clarity.

Despite the possibilities noted above, no action to improve Wood Lake water quality has been undertaken. The major impediment is the size of the lake (9.3 km^2). Most lake restoration projects involving in-lake treatment which have been undertaken have been on relatively small lakes (generally less than 1 km^2). The difficulty involved in manipulating a lake of this size for a reasonable cost remains the single most challenging aspect of Wood Lake.

The basis of this proposal is that a major portion of the water column loading in Wood Lake originates from the sediments and that by increasing the iron content of the sediments, the internal loading could be reduced. The key aspect to the proposal was that a free source of iron was available in the form of a waste product from a steel mill. Because of the size of the lake, the iron chemical costs would be very high if iron were to be purchased commercially. The technical merits of the proposed treatment are discussed later in the report.

It is difficult to evaluate cost-benefit factors for this project. There has been no study done in this regard. However, even on the most simplistic basis, the large benefits which would accrue from the relatively small cost ($50,000) would be very favourable. It can be shown that the present proposal is the most cost-effective option available. McNiel (1982) concluded that there was a significant relationship between beach use and water quality for the Okanagan Lakes. He did not consider Wood Lake but did calculate the benefit of a minor improvement in water quality (meso-eutrophic to mesotrophic) for Osoyoos Lake. The improvement after a ten-year period was calculated to be $6.07 million in annual gain value. He calculated "present value" of the gain to be $44.65 million. Wood Lake is not comparable to Osoyoos Lake's recreational use but even if 10% (or even

1%) of this benefit occurred in Wood Lake, the return is very large and makes for a very favourable cost/benefit comparison.

1.2 DATA BASE AND PREVIOUS STUDIES

Wood Lake in the Okanagan Valley has been the subject of several specific examinations of water quality over the past 20 years. As early as the 1930's, Rawson reported data on Wood and other Okanagan Lakes (Clemens *et al*. 1939). They reported that, at that time, Wood Lake had a hypolimnetic oxygen depletion (oxygen concentration 1.7 mg/L at 30 m on August 13, 1935). The water transparancy (Secchi disc) was reported to be 2.0 to 2.5 m with a heavy bloom of *Aphanizomenon* being present. The bottom sediment was described as a very black organic ooze below 15 m with a very dense fauna of oligochaete worms and midge larvae.

More detailed data were reported by Stein and Coulthard (1971) for samples taken in 1969 and 1970. The first comprehensive examination of Wood Lake took place during the Okanagan Basin Study (1969-71) and was reported in Pinsent and Stockner (1974). Some additional sampling of Wood Lake was done as part of the Implementation Study, with samples obtained in 1976-78. The most thorough examination of Wood Lake was done in 1980 by the National Water Research Institute and reported in Gray and Jasper (1982), Jasper and Gray (1982), Gray and Jasper (1986 MS), Wiegand (1984), and Wiegand and Chamberlain (1987).

A long-term data set has been collected by the regional office of the Ministry's Waste Management Branch which provides some information as to the trends in Wood Lake Water Quality. Data exist from approximately 1970 to the present.

Although the lake has received some investigations, there are considerable gaps in the understanding of important processes which operate in Wood Lake. Some of these unknown areas are discussed in the text of the report. Some information can be gained from the experience of other investigators working on other similar lakes. Calcareous lakes appear to share a number of characteristics and this information can be useful. One lake which has undergone many years of intensive investigation which has a similar water chemistry is Lake Mendota in Wisconsin (Brock 1985). Mendota has a similar concentration of total dissolved solids (total residue 200 mg/L, specific conductance 320 µS/cm) as Wood (190 and 330 µS/cm respectively). Alkalinity is similar (about 150 mg/L). Some of the anions and cations are similar but Wood Lake has higher sulphate (26 versus 8 mg/L) and sodium (15 versus 6 mg/L) but lower chloride (4 versus 14 mg/L). The watershed of Lake Mendota is highly agricultural and this is apparently reflected in the nutrient concentrations with total phosphorus at spring overturn of about 116-144 µg/L (Stauffer 1985, 1986). In contrast, the historical spring overturn concentration for Wood Lake is about 75 µg/L although this has been considerably lower in the past three years.

2. HYDROLOGY AND LAKE MORPHOLOGY

2.1 SURFACE WATER

One of Wood Lake's important features is the relatively small input of water in comparison to the lake volume. The filling time is now approximately 17 years and is considerably reduced since 1971 when Hiram Walker's distillery released cooling water from Okanagan Lake into Vernon Creek which flows into Wood Lake. Prior to 1971, the lake filling time was estimated to be 30 years. The main input to Wood Lake is from Vernon Creek at the south end. Vernon Creek drains 151 km^2 of the watershed with a mean annual discharge of 15 480 dam^3 (station 08NM009). There are only a few other small creeks flowing into the lake (Winfield, Hayton, Ribbleworth) which contribute relatively little water to the lake. The outlet flow from the lake is through the Oyama Canal to Kalamalka Lake. The canal was excavated in 1908 to provide boating access between the lakes. It is reported that the Wood Lake water level decreased by 60 cm as a consequence. The net annual flow between Wood and Kalamalka would be expected to be about 8 500 dam^3 based on a loss of about 7 000 dam^3 from evaporation (76 cm/yr). Although the net flow is to Kalamalka Lake, wind may cause reverse flow at some times of the year. The best discussion of the hydrology of Wood Lake is in Water Investigations Branch (1974).

A summary of morphometric, hydrologic, and physical measurements is given in Table 1. Hypsographic data are given in Table 2. Recorded Vernon Creek inflows are given as Table 3. A bathymetric map is given as Figure 1.

2.2 LAKE PHYSICAL STRUCTURE

The stratification pattern of Wood Lake is described best in Jasper and Gray (1982) and Gray and Jasper (1986 ms). The stratification begins in late April and a strong vertical gradient is established by June with upper thermocline at 5 - 6 metres and the lower boundary at approximately 18 metres. The maximum stratification exists in August and September with the thermocline centred at about 12 - 15 metres. Autumn cooling erodes the thermocline and fall overturn is usually complete in early November. The lake typically freezes 80 to 90 percent of winters. The lake did not freeze the winter of 1980-81.

The only detailed examination of the stratification and internal water movements was made in 1981 by the National Water Research Institute and reported in Wiegand and Chamberlain (1987) and Wiegand (1984).

2.3 GROUNDWATER

Groundwater may contribute a significant water and nutrient load to lakes. The most thorough examination of groundwater in the Wood Lake basin was done for the Kal-Wood Study (Water Investigations Branch 1974). The estimate given at that time was that approximately 23 kg/year of phosphorus was transported to the lake in this way. In the total P budget (estimated to be 3.3 tonnes in 1980) this is insignificant.

One interesting feature of groundwater adjacent to Wood Lake, at least in some areas, is that it can have relatively high concentrations of iron. This is in contrast to the low concentrations of iron in lake water and sediments and is a key point of discussion considered in section 5.

TABLE 1

WOOD LAKE: MORPHOLOGIC, HYDROLOGIC AND PHYSICAL DATA

Watershed area	-	190 km^2
Surface area	-	9.3 km^2
Maximum and mean depths	-	34.0 and 21.5 m
Lake Volume	-	199.5 x $10^6 m^3$ (199,500 dam^3)
Lake water input (filling time)	-	15 480 dam^3/yr (17 years, 30 years pre 1971)
Lake water output (estimated)	-	8 500 dam^3/yr (23.5 years emptying time)
Mean annual input from Vernon Creek	-	15,480 dam^3 (range 1,930 - 31,500)

TABLE 2

HYPSOGRAPHIC DATA FOR WOOD LAKE

Depth (m)	Area (km^2)	Volume of slice ($10^6 m^3$)	Cumulative Volume ($10^6 m^3$)	
0	9.3	18.3	18.3	
2	9.0	17.7	36.0	
4	8.7	17.2	53.2	
6	8.5	16.7	69.9	
8	8.25	16.2	86.1	
10	7.9	15.5	101.6	z_{V50}=11.7M
12	7.6	14.8	116.4	
14	7.2	14.0	130.4	
16	6.75	13.0	143.4	
18	6.25	11.9	155.3	
20	5.6	10.5	165.8	$\bar{z}$=21.5m
22	4.9	9.2	175.0	z_{A50}=23.0m
24	4.3	7.9	182.9	
26	3.6	6.6	189.5	
28	3.0	5.4	194.9	
30	2.4	3.9	198.8	
32	1.45	0.7	199.5	
33	0			

from Jasper and Gray (1982)

TABLE 3
WOOD LAKE: WATER INPUT FROM VERNON CREEK 1970 - 1982

	Inflow at 08NM009 $dam^3 x 10^3$	Relative Input	Residence Time (yr)	% Lake Volume
1970	1.9	Low	105	1.0%
1971	4.9	Low	40.7	2.5%
1972	20.8		9.6	9.6%
1973	6.8		29.3	3.4%
1974	26.6	High	7.5	13.3%
1975	12.0		16.6	6.0%
1976	19.2		10.4	9.6%
1977	13.1		15.2	6.6%
1978	17.4		11.5	8.7%
1979	10.3		19.4	5.2%
1980	6.6	Low	30.2	3.3%
1981	23.5	High	8.5	11.8%
1982	27.7	High	7.2	13.9%
1983	31.5	High	6.3	15.8%
1984	18.7		10.7	9.4%
1985	6.7	Low	29.8	3.4%
mean	14.48		22.4 16.9 (71-85)	7.8%

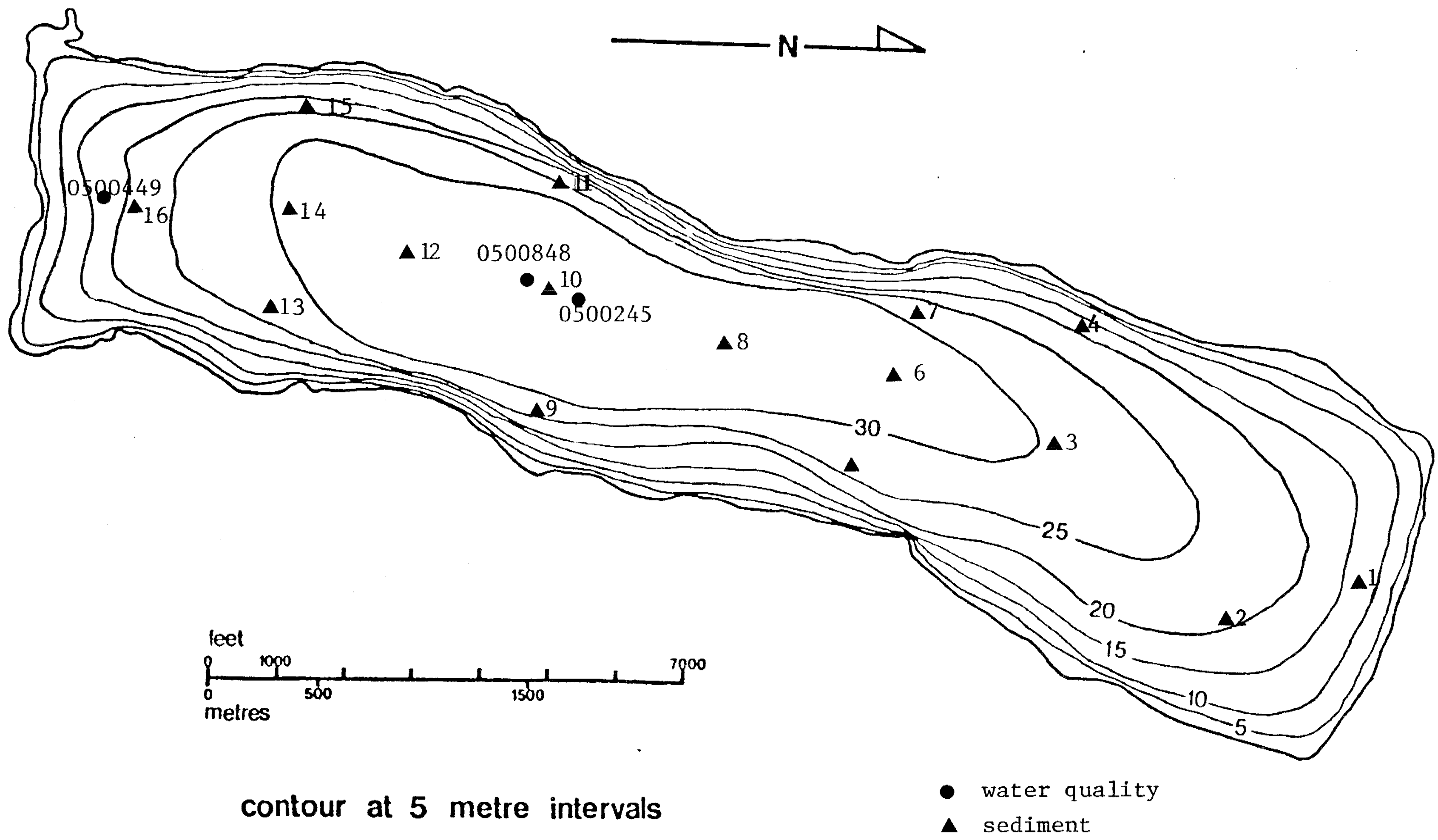

Figure 1 Bathymetry of Wood Lake showing sampling stations.

3. WATER QUALITY

3.1 GENERAL IONS

Some consideration of the general water chemistry characteristics is essential and bears directly on the important nutrient concentrations and cycles discussed in detail below. Table 4 gives the general characteristics of Wood Lake water.

Wood Lake would be considered to be a calcareous hardwater lake with total dissolved solids of about 200 mg/L, specific conductance of about 330 µS/cm, alkalinity of 140 mg/L, and hardness of 135 mg/L. The dominant cations are calcium, magnesium, and sodium (26, 16, 19 mg/L respectively) and the dominant anions are bicarbonate and carbonate (TIC 36 mg/L) and sulphate (26 mg/L).

3.2 NUTRIENTS

A number of water chemistry characteristics are influenced by the annual cycles of biological growth, physical factors, and stratification pattern. The annual cycle involves a number of interrelated factors; however, a key consideration is nutrients. Late winter-early spring concentrations of total phosphorus are generally in the 60-90 µg/L range, averaging about 75 µg/L. At spring overturn in most years, 90% of the phosphorus is dissolved and readily bioavailable. As light levels increase in spring, phytoplankton numbers increase and phosphorus is transferred from the dissolved form to the particulate (as algal cells). During the spring, much of the algal biomass (diatoms with relatively fast sinking rates) sinks out of the photic zone into the deeper depths of the lake. The lake begins to stratify in April so the phosphorus is trapped in the hypolimnion. Phosphorus increases in the hyplimnion through the summer and remains low in surface waters through the summer (Figure 2). More important is the mass balance of phosphorus in the lake. There is a loss of 4-5 tonnes of phosphorus from the water column between March and September. The water column regains this phosphorus mass between October and February (Figure 3).

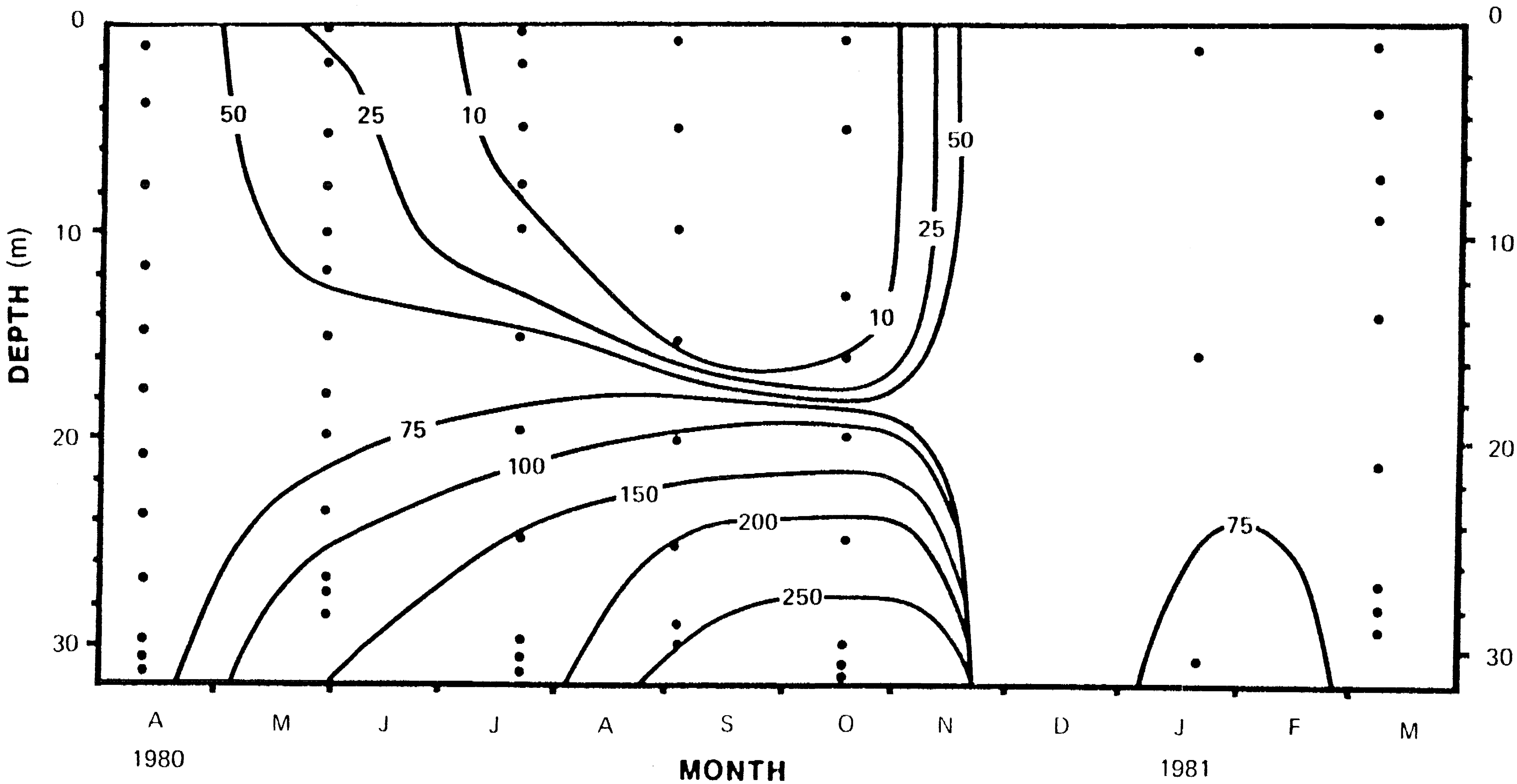

Figure 2 Time-depth diagram of dissolved phosphorus (µg/L) in Wood Lake 1980-81

From Jasper and Gray 1982

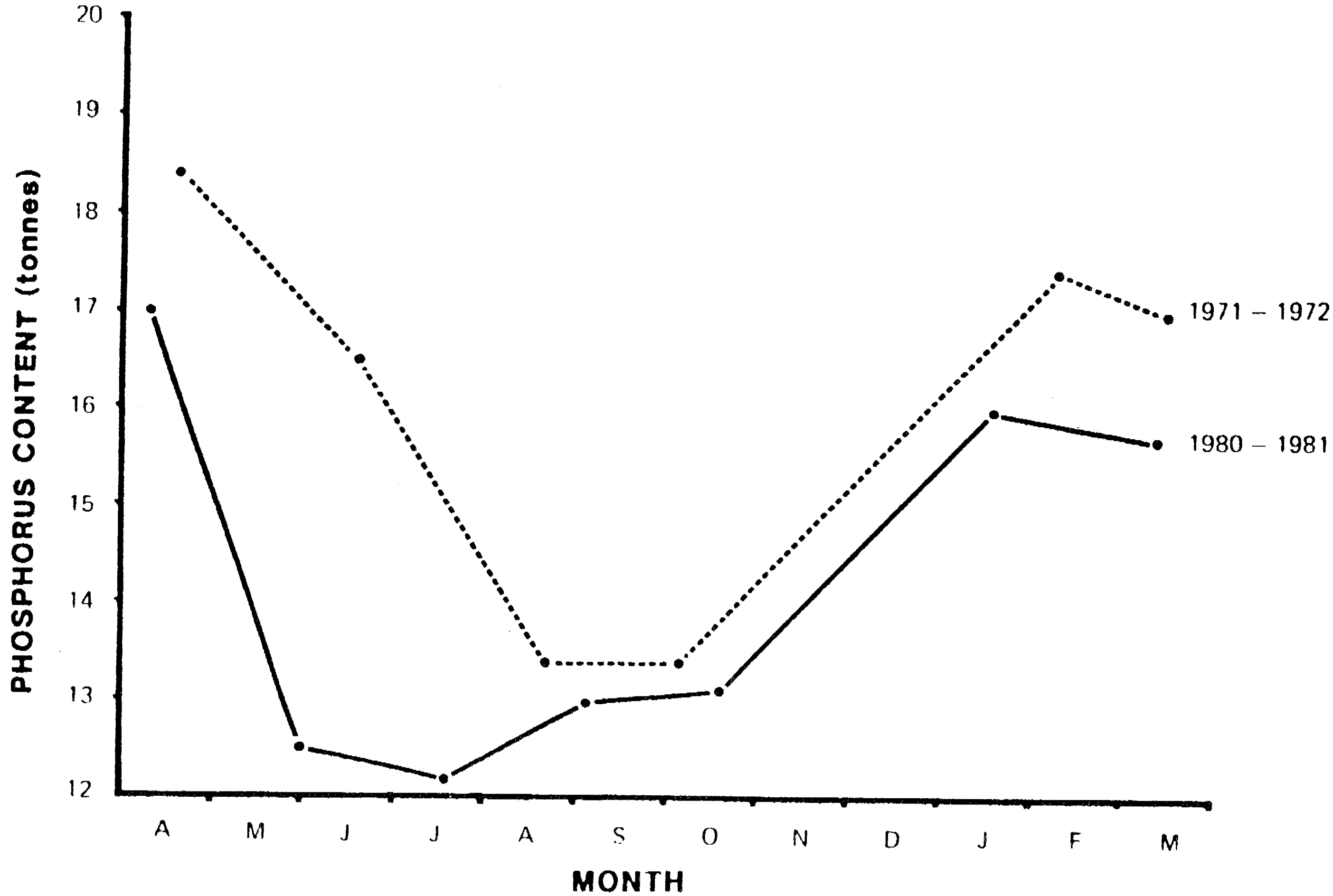

Figure 3 Mass of phosphorus in Wood Lake. From Jasper and Gray 1982.

TABLE 4

WOOD LAKE WATER CHEMISTRY - SUMMARY OF PREVIOUS SAMPLING

Station 0500449 Wood Lake - south end, east of Vernon Creek 1975-1980

		n=	max	min	mean	std dev.
pH (field)		34	9.2	7.0	8.3	0.53
pH (lab)		41	9.0	7.6	8.3	0.37
res 550 C	mg/L	3	136	114	124	11.1
res 105 C tot	mg/L	11	224	184	206	11.3
res filterable	mg/L	33	222	178	202	10.0
spec. cond.	µS/cm	41	360	281	329	19.1
ext. depth	m	38	8.4	1.0	3.48	2.22
alkalinity	mg/L	3	154	137	143	9
organic carbon	mg/L	39	14	2	6.7	2.8
chloride	mg/L	32	3.4	2.6	3.0	0.2
hardness	mg/L	3	146	128	135	9.6
ammonia-N	µg/L	41	580	16	76	120
nitrate & nitrite-N	µg/L	41	610	20	165	107
organic nitrogen	µg/L	41	3420	310	607	470
C.O.D.	mg/L	3	23	11	17.7	6.1
ortho P	µg/L	3	149	<3	51	84
total diss. P	µg/L	41	195	<3	58	57
total P	µg/L	41	222	12	78	54
silica	mg/L	41	5.9	<0.5	3.2	1.7
sulphate	mg/L	33	28	24	26	1.1
inorganic carbon	mg/L	33	43	27	36	4.1
calcium	mg/L	36	33	18	26.4	2.9
magnesium	mg/L	35	17.2	14.9	16.2	0.7

A similar pattern occurs with nitrogen. Spring concentrations of total nitrogen average 600 µg/L with 300 µg/L as dissolved organic and 200 µg/L as nitrate.

Nitrate decreases rapidly in surface waters in spring and generally remains below detection limits until fall overturn. As with phosphorus, there is an increase in nitrogen (both nitrate and ammonia) in the hypolimnion during summer (Figures 4 and 5). More detailed discussions of annual nutrient dynamics may be found in Jasper and Gray (1982).

Silica concentration is also affected by phytoplankton uptake. Spring concentrations are generally 2-3 mg/L but decrease very rapidly with the spring phytoplankton bloom. By May, silica is generally <0.5 mg/L and it would be expected that diatom growth would be limited through the summer months by the availability of silica.

At fall overturn, nitrogen, phosphorus, and silica concentrations are generally returned to levels close to those present in spring. Very little is known about the winter dynamics of these parameters. However, biological production is low during that period and changes in nutrient concentrations would be expected to be minor. Ice cover in the past ten years has been the usual case. For Wood Lake to remain ice free through the winter is an infrequent occurrence, although it may have been more frequent in the earlier part of the century. Ice cover has two major effects. First, sedimentation rates of algae and particulates are increased. Second, gas exchange is drastically changed, the supply of oxygen to the lake is reduced, and oxygen at the sediment water interface is decreased causing increased mobilization of nutrients from the sediments.

The hypolimnion of Wood Lake is isolated from any significant input of oxygen after stratification is established. The lake represents a good system for examining the components of nutrient supply and Gray and Jasper (1986) have documented this aspect of Wood Lake. The sedimentation of phytoplankton into the hypolimnion, the decomposition of its biomass, and

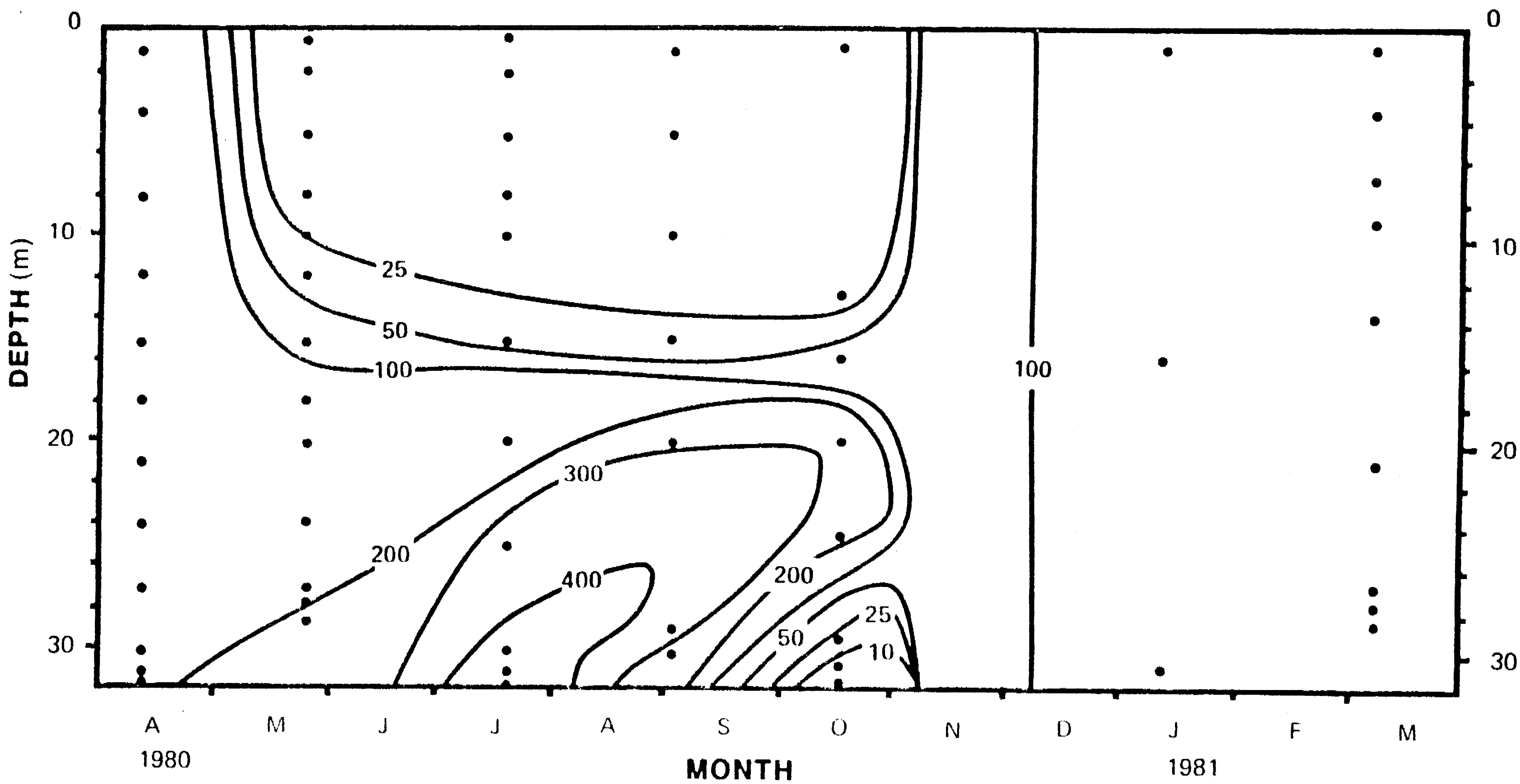

Figure 4 Time-depth for nitrate plus nitrite (μg/L) in Wood Lake. From Jasper and Gray 1982.

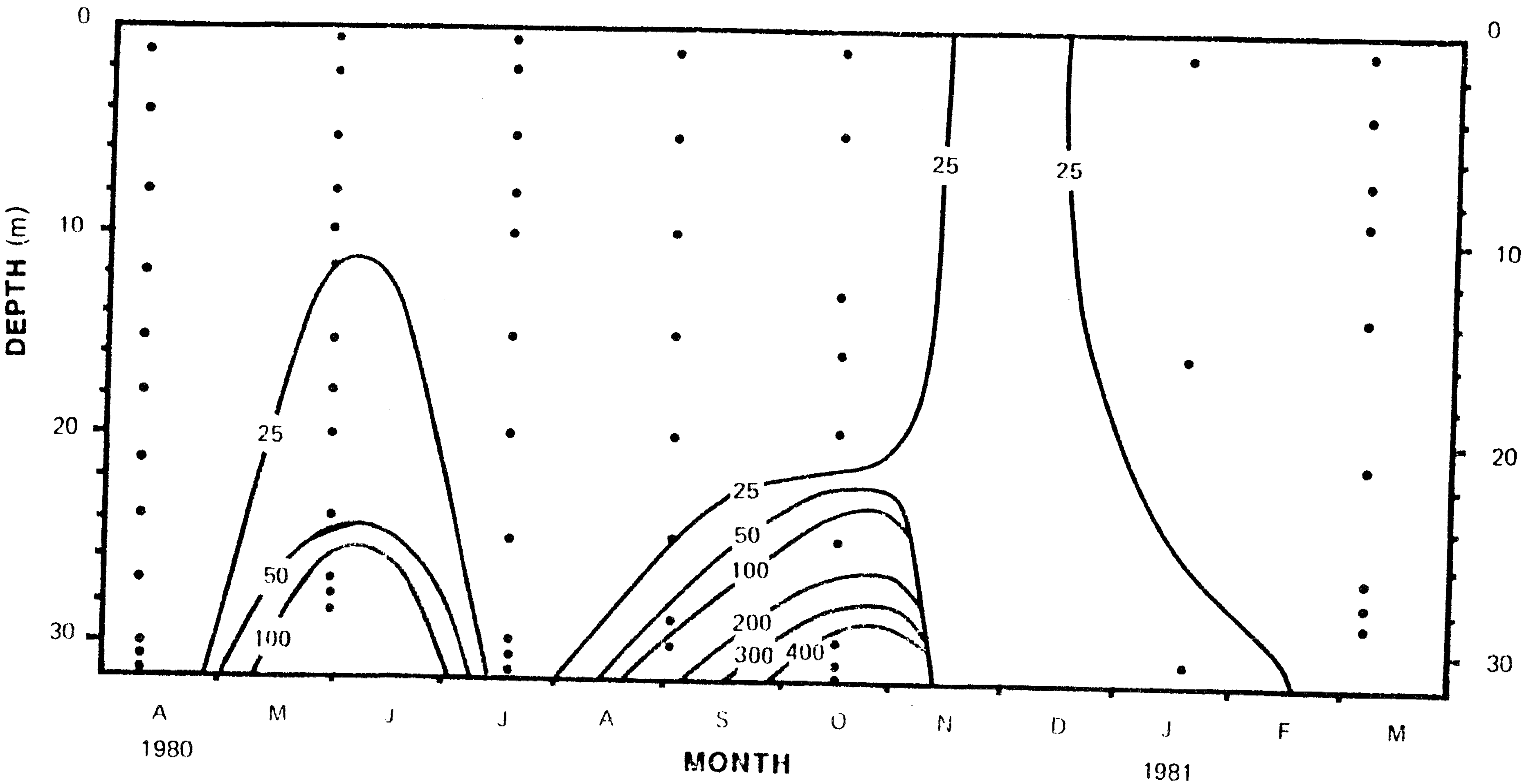

Figure 5 Time-depth diagram for ammonia (μg/L), Wood Lake. From Jasper and Gray 1982

the accumulated organic material in the sediment cause the dissolved oxygen to be progressively used and, as a consequence, oxygen concentrations fall (Figure 6). Concentrations less than 1 mg/L at the sediment interface occur by mid-August and concentrations less than 1 mg/L are prevalent below 22-23 m by late October. By fall overturn (late November) the lake mixes down to the bottom and high oxygen is restored. The oxygen content of the lake increases over the winter period. Coincident with the low oxygen in the hypolimnion from July through October, the near-sediment waters undergo a dramatic increase in ammonia (to 500 µg/L), dissolved phosphorus (to 300 µg/L), and manganese (to 500 µg/L). No significant increase in soluble iron occurs in near sediment waters (Jasper and Gray, 1982).

One chemical process which has been identified as having a likely important role in nutrient cycling, but has not been evaluated, is the calcium carbonate (marl/calcite) system. Jasper and Gray (1982) measured a decrease of 800 tonnes in the calcium content of the epilimnion and meso-limnion between May and September. Total calcium concentration in surface water shows a consistent decrease of 3-7 mg/L in the period between April and October (Figure 7). It can be presumed that fall overturn returns the surface water calcium to higher concentrations by re-mixing the accumulated hypolimnetic calcium which generally increases over the summer period. There are few winter data to confirm this assumption. The calcium cycle in Wood Lake should receive closer scrutiny to determine its significance. It is interesting to note that Kalamalka Lake, which is assumed to have a significant marl precipitation cycle (so far undescribed), shows far less fluctuation in annual calcium concentration and much less vertical calcium gradient than Wood Lake.

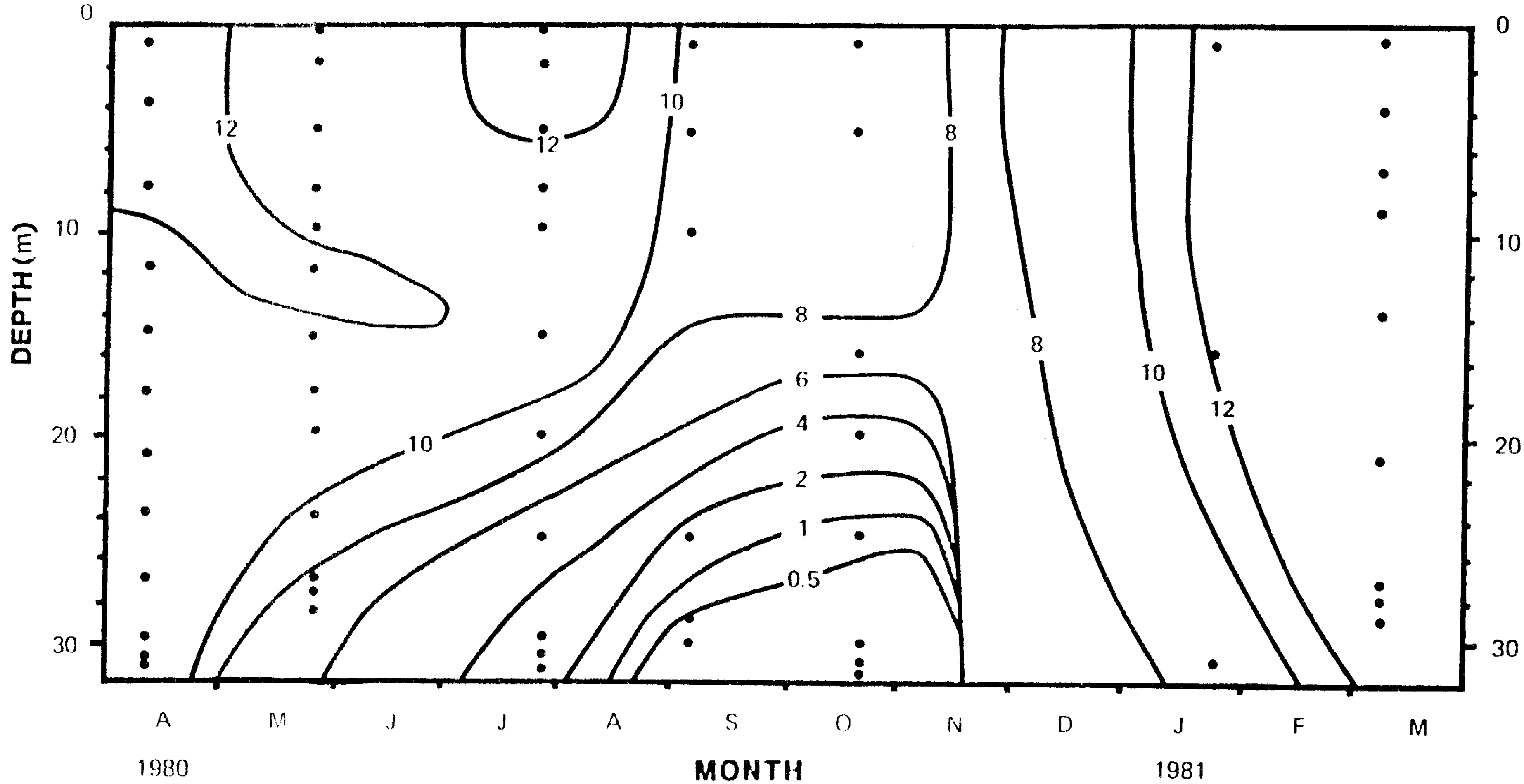

Figure 6 Dissolved oxygen in Wood Lake (mg/L). From Jasper and Gray 1982.

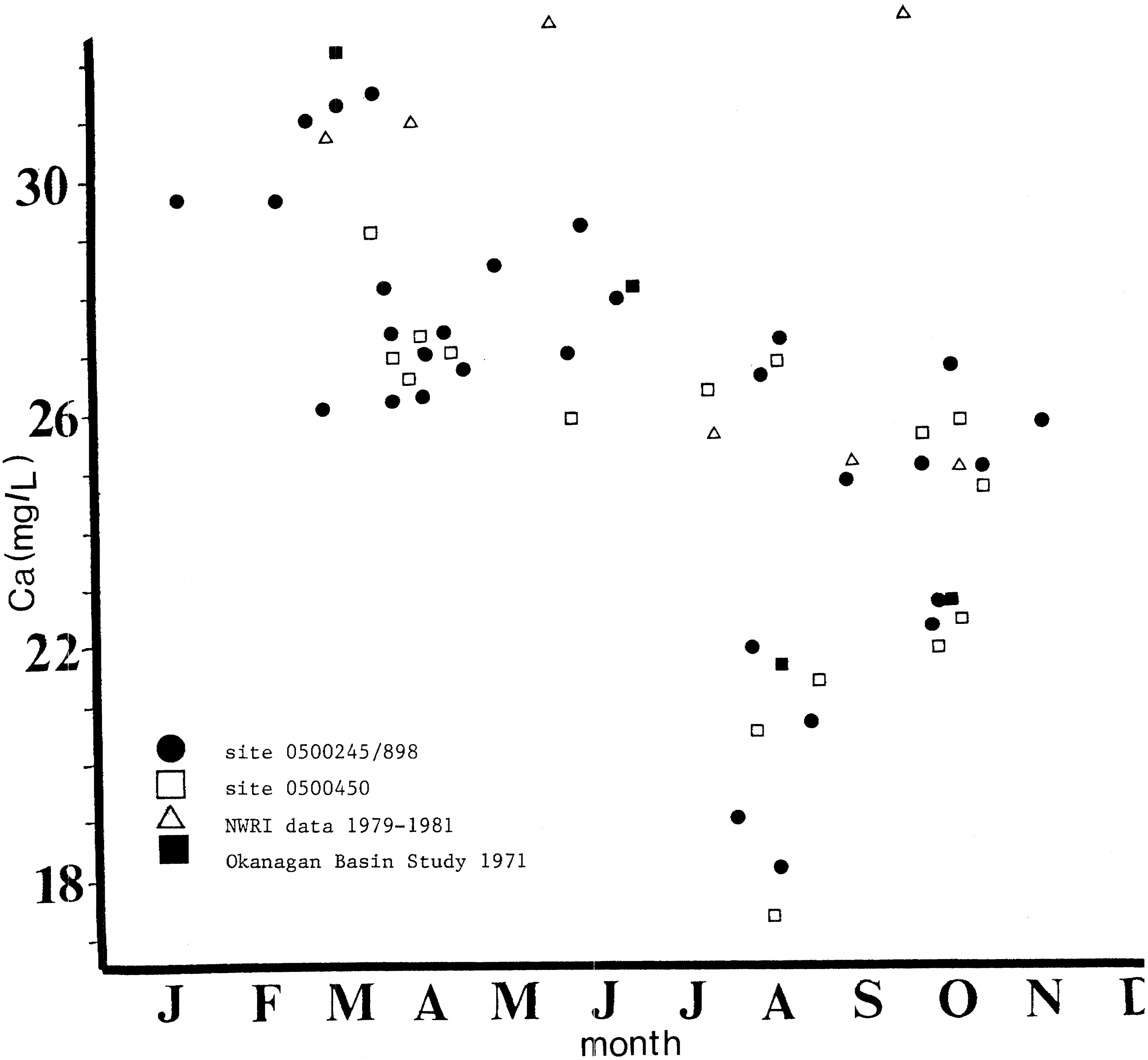

Figure 7 Calcium concentrations in Wood Lake epilimnetic water

4. NUTRIENTS

4.1 LOADING ESTIMATES

A number of studies have been carried out to estimate the amount of nitrogen and phosphorus which enter Wood Lake on an annual basis. A summary of loading estimates is given below.

Loading Estimates to Wood Lake

Okanagan Basin Study (1970) (Pinsent and Stockner 1974)	1.5 tonnes total phosphorus 24.7 tonnes total nitrogen
Kalamalka Wood Basin Study (Water Investigations Branch, 1974)	2.3 tonnes total phosphorus 3.3 tonnes total nitrogen
Okanagan Implementation Study (1982) (Alexander 1982)	1970: estimated 2.8 tonnes bioavailable phosphorus
	1980: estimated 3.3 tonnes bioavailable phosphorus
	1990: estimated 4.3 tonnes bioavailable phosphorus

Estimates of external loading are extremely difficult projects and require a variety of assumptions. As a consequence, estimates in general tend to be subject to wide ranges of error. The three estimates given above for Wood Lake would be expected to be increasingly accurate. The most recent loading estimate benefits from the work of Gray and Kirkland (1982) which gave estimates of the important bioavailable fractions in inflows to the Okanagan lakes.

In evaluating these estimates, it appears that the amount of loading is very low in comparison to the concentration maintained in the lake. Stauffer (1985) considered that this was characteristic of calcareous lakes and proposed a number of reasons for this pattern. There have been a number of mathematical relationships established between loading and concentration which can be used to evaluate the Wood Lake loadings. The equations given in Vollenweider (1976), Reckhow and Simpson (1980), and Canfield and Bachmann (1981) are inappropriate to estimate loadings accurately since they were derived from a data set of predominantly small, short water-residence-time lakes. Stauffer used the Dillon and Rigler, and two other predictive equations to evaluate the accuracy of these models for calcareous lakes and determined that they were of little utility. The three equations noted above were used in a similar way, to evaluate the accuracy of the loading estimates for Wood Lake. The equations give estimates of 6.5 to 13.5 tonnes annual loading to maintain a spring overturn phosphorus concentration of 75 µg/L. In the absence of any reasonable equation which describes the relationship between loading and concentration for calcareous lakes, it is difficult to evaluate the accuracy of the loading estimates. However, one of the reasons Stauffer has stated that calcareous lakes display a pattern different from other lakes is that there is relatively poor retention of P in bottom sediments with P being returned to the water column on an annual basis.

Gray and Jasper (1982) give information on seasonal phosphorus content of the lake. It shows an increase of phosphorus of approximately 3-4 tonnes between October and January when little external loading is taking place (Figure 3), giving some indirect support to the possibility of a significant internal source of P.

Murphy et al. (1983) concluded that the main source of phosphorus to Black Lake, a small hypereutrophic in the southern Okanagan, was from weathering of phosphorus-rich volcanic rocks in the watershed. They noted that Wood Lake had a large deposit of Eocene volcanic rock similar to Black Lake and suggested that these deposits might be a source of phosphorus to the lake. Stream loadings in the studies done to date do not support this idea since Black Lake's inflow stream P concentrations are considerably higher than any inflow stream to Wood Lake.

4.2 TRENDS IN WATER QUALITY

Prior to 1970, there exists little information to quantify the condition of Wood Lake. The only direct useful observation was made by D.S. Rawson in August 1935 (Clemens et al. 1939). The lake, as noted earlier, had low hypolimnion oxygen conditions with 1.7 mg/L being present at 30 m depth. Pinsent and Stockner (1974) calculated that in August 1935 the percent oxygen saturation was 21% in the hypolimnion, but decreased to 5% in August 1971, implying an increase in hypolimnetic oxygen depletion over that 36-year period. Other comparisons made by Pinsent and Stockner were an increase in phosphorus loading from 1.58 tonnes in 1935 to 4.65 tonnes in 1971; however, the basis for the 1935 loading is not given. They also note that zooplankton standing crop (settled volume) doubled in this comparison (15 mm^3/cm^2 for 1935, 31 mm^3/cm^2 for 1971). Data for zooplankton settled volume for 1979-80 (Jensen 1981) show lower zooplankton biomass (10 mm^3/cm^2), although the dates do not correspond and it is unclear which data were used to calculate the 1971 value. Infrequent samples collected from 1980 to 1986 have settled volumes averaging 15 mm^3/cm^2 (Bryan 1986). It would appear that no easy comparison can be made with the 1935 data and no trend can be easily discerned. As well, insufficient phytoplankton data are available from 1935 for comparison to present information. In August, 1935, a bloom of Aphanizomenon was present but was not quantified. However, it shows that cyanobacteria (blue-green algae) were present in fairly large quantities in 1935.

One aspect of Wood Lake biology which appears to have changed significantly is the benthic community. Rawson observed in 1935 that bottom samples from 15-30 metres had a very dense concentration of oligochaete worms and midge larvae. In most samples there were more than 1 000/m^2 and one sample had 23 000/m^2. The standing crop for the profundal sediments was 8.7 g/m^2. Intensive sampling carried out in 1971 was in vivid contrast. Saether and McLean (1972) described the bottom as being "practically a biological desert". They note that triplicate samples at two stations yielded a single chironomid and the disappearance of the benthic fauna was very dramatic and puzzling. They speculated that the change might be due to toxic chemicals but gave no evidence to support this contention. Sampling of sediments conducted in January 1986 at 16 stations showed no macroscopically visible benthic animals present in the samples. The samples obtained did have a noticeable surface layer of greyish filamentous bacteria which contrasted against the black sediment surface. The change in benthos is one strong piece of evidence that the lake has changed over the past 50 years. The loss of benthic production is a loss of potential food base for fish production. If the 1935 estimates of 8.7 g/m^2 dry weight - or 50-90 g/m^2 live weight - over an area of 7.2 km^2 (area below 14 m) is used, then 360-650 tonnes of benthic standing crop has been lost.

There has been a significant change in Wood Lake water quality over the past 10-15 years. The first noticeable change was an increase in water clarity during the late 1970's (Nordin 1980) and this has continued through the present (Bryan 1986, pers. comm.). The most likely reason for this change is the input of good quality cooling water from the Hiram Walker distillery. The distillery pumps water from Okanagan Lake to use as cooling water which is then discharged into Vernon Creek. The water has changed the theoretical water residence-time of the lake by half (30 to 17 years), but with some increase in phosphorus loading the net effect should still be an improvement in water quality. Water clarity, at least, has apparently responded to this input of low nutrient water. Other indices of changed water quality (algal standing crop, phosphorus or nitrogen concentrations) have not yet shown trends which are as definite, although spring overturn phosphorus in the past three years (1985 to 1987) has been unusually low (Table 5).

One other possibly significant change is the change in nitrogen composition. Early data show 20-55 µg/L ammonia nitrogen at spring overturn. After 1982 ammonia is generally below detection limits. Nitrate shows considerable variation from year to year ranging from 40-355 µg/L. One interesting pattern is that in years of relatively high total dissolved phosphorus (>70 µg/L) there is correspondingly high nitrate (>200 µg/L). The reason for this pattern is not clear at this time.

Another notable change has occurred in the chemistry of general ions. The water chemistry of Okanagan Lake is different to that of Wood Lake, and the effect of the input of Okanagan Lake water since 1970 can be noted (Table 6). Okanagan Lake is generally lower in concentration of most dissolved water quality constituents than Wood Lake. This apparent dilution effect is notable for total residue, specific conductance, alkalinity, chloride, potassium, and sodium with lower values in recent years than occurred prior to 1983. The effect would probably be even more marked if, for example, 1970-75 data or pre-1970 data were compared to 1985-87 data. Calcium has increased in Wood Lake since Okanagan Lake has higher calcium concentrations. Sulphate has apparently decreased in recent years in Wood Lake; however, this is unexpected since sulphate concentrations are quite similar in both lakes.

TABLE 5
SPRING OVERTURN PHOSPHORUS (AND NITROGEN) CONCENTRATIONS FOR WOOD LAKE 1973 - 1986 (in µg/L)

	TDP	TP	NO_3-N	NH_3-N	TK - N
1973 05 01		55			
1974 04 03		81			
1975 04 24	4.5	82	60	33	700
1976 04 14	19.5	70	215	35	580
1977 04 04	40.5	68	155	24	850
1978 04 12	74	91	355	22	490
1979 04 18	31	54	53	44	
1979 04 19	41	56	39	55	515
1980 03 27	75	82	225	32	340
1980 03 31	77	85	215	52	580
1981 03 30			95	36	493
1981 04 14	43	61	58	45	410
1982 03 31	64	79	165	<5	420
1983 02 24	72	76	240	<5	345
1984 03 13	70	79	225	9	350
1985 04 11	36	54	80	7	430
1986 03 26	40	51	180	<5	325
1987 04 01	25	37	70	<5	370

TABLE 6

RECENT CHANGES IN WOOD LAKE WATER CHEMISTRY

Parameter	Wood Lake 0500245 1970-1983	Wood Lake 0500848 1985-1987	Okanagan Lake 0500236 1973-1983
residue total (mg/L)	212	191	162
specific conductance (µS/cm)	334	324	263
total alkalinity (mg/L)	144	138	108
total organic carbon (mg/L)	5.5		2.0
chloride (mg/L)	3.0	4.3	1.4
sulphate (mg/L)	26.7	21.5	27.7
calcium (diss) (mg/L)	26.5	30.1	32.6
magnesium (diss) (mg/L)	16.9	15.4	8.3
potassium (diss) (mg/L)	3.8	3.1	2.1
sodium (diss) (mg/L)	16.5	14.6	9.4

5. SEDIMENTS

The project proposed is keyed to modifying the chemical composition of the sediments to achieve a higher phosphorus retention. To accomplish this successfully, it is necessary to have some understanding of the characteristics of the sediments of Wood Lake and the processes which occur in sediments.

In Wood Lake (and most other lakes) production of organic biomass by the plankton exceeds the decomposition rate, and organics accumulate over time in the sediment. The physical and chemical characteristics of the sediments as well as the environment in which the sediments exist are variable from lake to lake and can vary over the annual cycle within an individual lake. Documentation of the physical environment and analysis of the chemical composition of the sediment are important first steps in understanding the dynamics of the sediment-water interaction and if, when, and how much of important sediment constituents such as phosphorus are released back into the water column.

Wood Lake sediments can be characterized as having a high moisture content (90%), relatively low volatile component (17%), a high ratio of organic to inorganic carbon (70 mg/g : 13 mg/g), and high calcium content (63 mg/g). Jasper and Gray (1982) felt that marl precipitation from the water column might be an important factor in the development of lake sediments and a determinant of overall sediment character. In sediment cores they noted a band, presumed to be calcite, at the 6-7 cm interval, showing a different physical appearance as well as increased inorganic carbon content.

Table 7 lists the general chemical characteristics of Wood Lake sediments.

TABLE 7

CHEMICAL CONCENTRATION OF ELEMENTS IN WOOD LAKE SEDIMENTS (μg/g)

	Mean	Std. Dev.	Mean of B.C. Lakes (n > 300)
Aluminum	10 072	2 577	13 780
Calcium	63 662	26 193	29 440
Cadmium			1.3
Chromium	3.778	1.00	38.2
Copper	21.44	13.6	45.3
Iron	26 883	643.8	27 250
Mercury	<0.05		0.154
Inorganic carbon	12 744	6 795	9 820
Kjeldahl nitrogen	8 050	3 606	10 550
Manganese	1 641	757	1 064.2
Magnesium	7 212	1 471	8 360
Organic carbon	70 055	27 513	128 900
Phosphorus	1 356	242.9	1 301
Lead	42.22	14.22	36.0
Sulphur	7 638	2 543	3 614
Volatile (%)	16.84	5.7	31.4
Zinc	68.33	15.5	86.3

Determined by methods used by the Environmental Laboratory of the Ministry of Environment and Parks, Vancouver. Mean of 15 samples taken at depths between 22-32 m, January 1986.

5.1 PHOSPHORUS

The emphasis in this discussion is on phosphorus although Wood Lake does not appear to be strongly phosphorus-limited. Biological production appears to be limited by phosphorus or nitrogen depending on the time of year and other circumstances (nutrient supply, weather). However, phosphorus is amenable to reduction (nitrogen is not) and the lake appears to be close to general phosphorus-limitation with a minor reduction in phosphorus supply. The emphasis on the sediments and internal supply is a consequence of evidence that internal supply of phosphorus appears to be much more important than external loading. Concentrations of phosphorus in inflowing suspended sediments are lower than lake sediment concentrations, implying a strong internal cycling (Jasper and Gray 1982). The external loads, when compared to loadings which would likely be necessary to maintain lake concentrations, are sufficiently different to suggest that internal supplies of phosphorus are important (see section 4.1).

Phosphorus concentrations in the sediments and interstitial water of Wood Lake are quite high. Table 12 (section 6.1) shows the results of extractions done on Wood Lake sediments. Concentrations were generally estimated at 1-3 mg/L for total and up to 1 mg/L for SRP in interstitial water.

In water and the sediment, phosphorus can be bound to iron, manganese, and carbonates in a variety of mineral forms. Wood Lake is a calcareous system and it has been stated (Williams et al. 1971, Stauffer 1985) that calcium is relatively ineffective as a means of binding phosphorus in sediments. Shukla et al (1971) felt that non-calcareous sediments sorbed phosphate better than calcareous sediments. The iron-phosphorus reactions, particularly in calcareous lakes, appear to be the most important feature in controlling phosphorus supply from sediments. This may partially be a result of the relatively high pH of Wood Lake and other calcareous lakes where reactions such as calcium-phosphorus, aluminum-phosphorus and iron-phosphorus are markedly affected by pH.

Phosphorus and iron occur in a number of forms. A number of fractionation procedures have been proposed and the general methods of Williams et al. have been generally accepted. Tables 8 and 9 list the fractions of phosphorus and iron respectively for Wood Lake surface sediments. Table 7 gives a breakdown of fractions of phosphorus in sediments of Wood Lake. The separation of organic and inorganic phosphorus is useful and shows that phosphorus is associated primarily with the inorganic fraction. Apatite phosphorus (AP) is mineral-bound and not likely to be biologically available within any short-term time period. Non-apatite inorganic phosphorus (NAIP) is a reasonably good estimation of phosphorus likely to be of importance in the cycling of material between sediment and water column. Sodium hydroxide extractable phosphorus is a fraction of NAIP and represents the most biologically available form of phosphorus.

Phosphorus is held in the sediments by being bound primarily with several elements: calcium, aluminum, manganese, and iron. There are a variety of mineral forms in which phosphorus can be bound. The most overwhelmingly important reactions (in terms of phosphorus quantity) involve iron. Calcium is the predominant cation in apatite; however, in most lake sediments, apatite is inert and of little consequence in the phosphorus cycle. Marl formation ($CaCO_3$) in surface waters can bind calcium but when the marl sinks to the hypolimnion, re-dissolution of the marl precipitate occurs in large part. Calcium has been shown to have little correlation to phosphorus in lake sediments (Williams et al. 1971). However, the use of lime as a means of retarding P release from sediments has been recommended by Lofgren and Ryding (1985). Murphy et al. (1983) reported some success in using lime to reduce water column concentrations of phosphorus in Frisken Lake.

The formation of marl (calcite) has been shown in a number of cases to be a mechanism for removal of phosphorus from the water column (Otsuki and Wetzel 1972, Murphy et al. 1983) Co-precipitation of phosphorus with calcium does not, for a variety of reasons, appear to be a means of sedimentation and long-term binding of phosphorus. Marl precipitate can be resus-

TABLE 8

PHOSPHORUS FRACTIONS OF WOOD LAKE SEDIMENTS
MEANS OF EIGHT STATIONS, 0-5 cm SEDIMENT DEPTH (µg P/g d.wt.)

Station/depth (see Fig. 1)	TP	TIP	AP	NAIP	OP	NaOH-P	% NaOH-P / TP	% NaOH-P / NAIP
2/20	1420	1268	926	342	152	116	8.2	34
6/32	1281	784	423	361	497	135	10.5	37
7/25	1590	746	396	350	844	178	11.2	51
8/32	1231	779	382	397	452	166	13.5	42
10/32	1407	796	399	397	611	170	12.1	43
11/32	1691	996	568	428	695	270	16.0	63
12/32	1112	705	426	279	407	102	9.2	37
13/32	1602	1006	647	359	596	170	10.6	47
mean	1417	885	417	364	532	152	11.4	44

TP = total phosphorus
TIP = total inorganic phosphorus
AP = apatite phosphorus
NAIP = non-apatite inorganic P
OP = organic phosphorus
NaOH-P = NaOH extractable P (0.1 N)

TP = AP + NAIP + OP
TIP = AP + NAIP

These data were provided by Ray Kirkland and Colin Gray

TABLE 9

EXTRACTABLE IRON FRACTIONS OF WOOD LAKE SEDIMENTS (μg/g)

station	Fe(total)	Fe(pyrophosphate)	Fe(dithionite)	Fe(oxalate)
3	23 571	2 770	4 458	-
4	17 490	2 100	3 570	5 907
5	10 908	4 684	7 228	-
8	10 138	2 409	6 812	6 641
9	13 495	4 582	8 953	-
14	12 159	2 424	5 243	6 090
15	8 547	4 594	8 209	9 793
16	12 866	2 115	5 368	5 748
mean	13 647	3 210	6 230	6 836

* Analysed using the methods of the soils laboratory of the Ministry of Agriculture

Other Wood Lake Sediment Characteristics (μg/g)

station	pH	Mg (extractable)	Ca (extractable)	SO_4 (extractable)
3	6.7	472	6061	310
4	6.9	522	4597	216
5	6.7	313	3671	219
8	6.8	444	7661	248
9	6.5	397	3688	298
14	6.9	487	7283	217
15	6.6	381	4620	236
16	6.9	542	7910	242
mean	6.75	445	5686	248

pended at spring or fall overturn (White and Wetzel 1975), calcite can redissolve in deeper colder waters, and the bond with calcium appears to be a weak surface adsorption reaction (Avnimelech 1980) which is easily broken. Murphy et al. (1983) noted relatively good retention of P in sediments with added lime.

Aluminum has negligible natural interaction with phosphorus in water or sediment (Stauffer 1981). However, additions of alum to lakes can be very effective since amorphous aluminum ($Al(OH)_3$) is very effective in adsorbing phosphate. Manganese can bind phosphorus in sediments; however, it is rarely present in sufficient amounts to bind a significant amount of phosphorus. As lakes become progressively more eutrophic, the presence of manganese in hypolimnetic water during low oxygen conditions is an indication of manganese re-dissolution from sediments. This is a stage which precedes iron release from sediments as dissolved oxygen and redox decrease.

It is important, in terms of phosphorus-iron reactions, to consider the amounts of phosphorus and iron in the sediments, particularly "available" forms. Iron fractions of Wood Lake sediments are given in Table 9 to provide a basis of comparison. Both dithionite (CDB) and oxalate fractions have been used to estimate available iron, and for Wood Lake it appears that varying proportions of the total iron are "available", depending on the depth of sediments. The ratio of Fe:P for Wood Lake is an important indicator of the relative availability of iron to bind phosphorus. For Wood Lake, Table 10 gives some data for the surface layer of sediments showing very low extractable iron concentrations at the immediate surface (0-1 cm layer) compared to deeper layers. The ratio of CDB-extractable iron to NAIP phosphorus is 1.1:1 by weight. Even if organically-bound phosphorus is included, the Fe:P ratio of "available" iron and phosphorus is only 1.8:1 (by weight - by atomic weight this ratio is 3.3:1).

Williams et al. (1971) give Fe:P ratios of 21-85 from shallow sediments in Wisconsin. They state that high ratios such as these would be extremely unfavourable for desorption of P. Deep water sediments had ratios of 3.3 -

TABLE 10

PHOSPHORUS AND IRON IN SURFACE SEDIMENTS AT 31 m DEPTH, OCTOBER 17, 1980.

Depth (cm)	Total Phosphorus	Total Inorganic P	Apatite P	Non-Apatite Inorganic P	Organic P	Citrate Dithionite Bicarbonate Extractable Fe
0 - 1	2 944	1 544	170	1 374	1 400	1 500
1 - 2	1 935	844	273	571	1 091	7 100
2 - 3	1 692	748	298	450	944	8 400
3 - 4	1 416	790	375	415	626	9 200

All concentrations μg/g dry weight sediment.

(Data provided by Colin Gray, NWRI, Environment Canada)

9.7. They noted that in calcareous lakes specifically the ratios were generally low (<10:1) and did not vary as significantly with depth as in non-calcareous systems, although overall concentrations of both increased with increasing water depth in lakes. Stauffer (1981) gives atomic ratios for calcareous lakes of 2.1 to 7.8 and notes that the higher ratios tend to be from lakes which are relatively unproductive. Lower ratios are from lakes with significant watershed disturbance or in an advanced state of eutrophication.

Allan and William (1978) hypothesized that low ratios of extractable Fe to P in the surface sediments combined with a rapid decrease in the ratio with depth are indicative of an overloading of P relative to the ability of Fe to sorb and retain available P in sediments. In Table 10 this pattern is quite evident with CDB-Fe:NAIP ratios of about 1:1 in the 0-1 cm depth, 12:1 in the 1-2 cm depth, and 22:1 in the 3-4 cm depth. The implications of low Fe:P ratios is that there is insufficient iron to provide binding sites for the available phosphorus. Baccini (1985) felt that the stoichiometric ratio of Fe:P in the waters of anaerobic hypolimnia was an important factor in binding of sedimented phosphorus. The ratio of Fe:P in various mineral forms differs and some of these are listed in Table 10. In some forms Fe:P is very low (1.5:1). In other cases phosphorus may be bound to amorphous hydrous iron at ratios of approximately 5:1 (Einsele 1936, 1938 cited in Stauffer 1981). In water column experiments, McQueen et al. (1986) recorded a Fe:P ratio of 10:1. Other Fe:P ratios show a wide range of variation: Lijklema (1977), 20:1; Manning (1977), 15:1. Non calcareous lakes, for instance the ELA Lakes, show high Fe:P ratios and generally do not exhibit any P release from sediments.

The low iron content of Wood Lake sediments may be a reflection of the low input of iron from the watershed because of low rainfall and porous soils (Stauffer 1981). The low available iron does not appear to be a result of export from the lake (long water residence time) or due to pyrite formation. The lake does not have noticeable H_2S presence in deep water although the sediments have a relatively high sulphur content.

Allan and Williams (1978), after examining sediment iron and phosphorus results from a number of Canadian lakes, felt that low ratios of extractable iron:phosphorus reflected an overloading of the normal geochemical balance between iron and phosphorus, generally caused by anthropogenic phosphorus inputs.

The mineral forms shown in Table 11 appear to be forms which are relatively stable and would provide desirable end-products. There are several iron compounds formed with carbonate (siderite, $FeCO_3$) and sulphur (pyrite FeS_2, and mackinawite FeS) which are undesirable since no phosphorus is bound and the sulphur minerals are formed before the phosphorus minerals. The absence of data on the present mineral forms of phosphorus and iron in Wood Lake sediments and on the minerals formed as a consequence of addition of pickling liquor is a major gap in knowledge.

The data in Table 10 are very interesting in that they show a distinct gradient in exchangeable iron and exchangeable phosphorus in the surface sediments. Iron increases markedly with depth, available phosphorus decreases with depth in the near surface (0-5 cm) layers.

Wood Lake with its low Fe:P ratio seems amenable to an addition of iron to bind surplus phosphorus. A ratio of 10:1 (Fe:P) should provide sufficient additional binding capacity to reduce P by several tonnes in the water column. The most available P fraction (NaOH extractable) is estimated to amount to 1680 kg over the deepest area of the lake (4 km^2). At a ratio of 10:1, by adding 50 tonnes of iron, the potential for binding 5 tonnes of P exists, although some fraction of the iron will be bound in other forms (with sulphur etc.). However, even if only a fraction of the iron is bound with phosphorus, a significant reduction in phosphorus concentration should result. More important, the permanent binding of P in surface sediments holds the possibility of modifying future loading to a significant degree.

TABLE 11

PHOSPHORUS MINERALS IN LAKE SEDIMENTS

Phosphorus/Calcium		
Apatite	$Ca_5(PO_4)_3$ OH	hydroxy form strong binding
Phosphorus/Iron		
Vivianite	$Fe_3(PO_4)_2.8H_2O$	stable in reducing conditions
Strengite	$FePO_4.2H_2O$	
Anapaite	$Ca_3Fe(PO_4)_3$	

Enhancement of iron in Wood Lake sediments is being pursued for a number of reasons related to supply and availability. Stauffer (1981) states that many non-calcareous lakes have a large supply of Fe in the form of organic compounds such as humic acids. Lakes such as the ELA lakes in north-western Ontario have high humic and iron concentrations in their sediments and display little if any phosphorus release from sediments. Wood Lake does not have any appreciable supply of organic iron. Stauffer also notes that supply of iron is low in areas of low inorganic suspended sediment input where sandy or gravelly soils (such as in the Okanagan) cause high infiltration rates. He notes that erosion is an important process for delivering iron to lake sediments. Wood lake has relatively low rainfall, porous soils and low clastic input (and thus likely low iron supply). The situation in Kalamalka Lake where Coldstream Creek delivers large amounts of clastic material to the sediments may provide a partial explanation for the difference in water quality in the two lakes.

Mobility of iron in soils is the second important aspect to consider. Stauffer (1985) states (direct quote): "The chemical mobility of iron is naturally low in temperate calcareous watersheds, particularly those in dryer climates or those characterized by good soil structure and drainage." This is directly applicable to Wood Lake.

Ripl (1986) reported that sediments rich in iron showed sulphate reduction but no P release as long as excessive iron could remove and bind hydrogen sulphide. He felt that the sediments of oligotrophic lakes, even under artificial anaerobic conditions and with high amounts of sulphur, show no P release because excess iron is present.

Stauffer (1981) noted in the work of Einsele (1938) that Einsele's experiments with $iron^{2+}$ oxidized to $iron^{3+}$ with phosphorus at pH 7 resulted in a precipitate with strengite-like composition (Fe:P of 1:1). A more unfavourable reaction of $iron^{2+}$ to $iron^{3+}$ with subsequent contact with phosphorus yielded a higher Fe:P ratio of 6:1. Tessenow (1974) in similar experiments with iron (2) found Fe:P ratios of 1.7:1 (pH 7) to 1.8:1 at pH 8 with an apparent composition of $Fe_2(OH)_3PO_4$.

5.2 SULPHUR

The sulphur content of sediments is important since iron-sulphur reactions can compete with iron-phosphorus reactions. The black colour of Wood Lake sediments is one indication that ferric sulphide is an important component of Wood Lake sediments. Analyses of sulphur in Wood Lake sediments presented in Table 7 give a value of 7.6 mg/g. Analysis done by NWRI (Gray 1986) gives sulphur content as 0.8 to 1.2% S as dry weight (8 to 12 mg/g).

There is a strong coupling of metabolic sulphur, phosphorus, and iron in surface sediments (Ripl 1986). Sulphur content of lake sediments is an important factor which affects iron and consequently phosphorus dynamics. Sediments with high sulphur content and sulphate reduction require iron for formation of pyrite. Iron appears to be preferentially used in sulphur reactions so before iron can react with phosphorus, this demand must be satisfied.

The laboratory experiments to determine effective iron dosage took into account the sulphur:iron binding as well as the phosphorus:iron reactions and were assumed to simulate what would occur in the lake treatment. Details are in section 6.

5.3 SEDIMENTATION RATES

Pinsent and Stockner (1974) present some data from a 75 cm core taken during the Okanagan Basin Study. They note an increase from 3% organic carbon at 75 cm to 10% at about the 5 cm level. A marked increase in organic carbon in surface sediment to 12% has occurred in recent times. Inorganic carbon is very low in the deepest part of the core - 75 to 50 cm level, increases at 20 cm then, except for a peak at about 5 cm, remains at about 5% up to the surface. Pinsent and Stockner estimate the 20 cm level to correspond to 1870 and the beginning of human settlement in the basin. If the sedimentation rate were constant between 1870 and 1970 it would be 2 mm/yr. However, the sedimentation rate would be expected to increase over time and the present sedimentation rate may be 3-5 mm/yr.

6. EXPERIMENTAL RATIONALE AND DESIGN

The goal of improving water quality in Wood Lake requires knowledge of the processes which maintain the high phosphorus concentrations in spite of what appears to be a very low phosphorus loading rate.

An initial interpretation of Wood Lake data was that internal loading of the classical type described by Mortimer (1941, 1942) was occurring; that is, phosphorus is released from sediment when anaerobic conditions allow phosphorus to be released from the iron, to which it is bound under aerobic conditions. One way of preventing phosphorus release in this circumstance is to maintain an aerobic environment by, for instance, aeration of the lake (Nordin, 1980). However, there is now sufficient data both from Wood Lake (Gray and Jasper 1982) and from other lakes that both anaerobic and aerobic phosphorus release may take place. In Wood Lake, there is good evidence that aerobic release is predominant, so aeration would not provide an effective means of reducing phosphorus concentrations in the water column.

Stauffer (1985) put forth the concept that calcareous lakes have some fundamentally different characteristics which set them apart from the general set of north-temperate lakes. He felt that phosphorus was not lost from the water column to be bound more or less permanently, as is the case in many non-calcareous lakes, and that calcareous lakes, as a consequence, have low phosphorus retention coefficients. Phosphorus may interact with calcium, but sediment immobilization of phosphorus may be associated with aluminum, manganese, or particularly iron as discussed earlier.

Information suggests that increases in iron concentration in sediments would be successful in reducing the phosphorus concentration of Wood Lake. Some of this information is discussed in section 5. There have been few attempts at water quality improvement using sediment chemistry alteration. One perceptive application of sediment modification in lake restoration was by Ripl (1976). He used iron as a pretreatment for nitrate oxidation of sediments. There have been a few other recent examples of the use of iron to treat lake sediments. The intent of Ripl's use of iron (ferric chloride, $FeCl_3$) was to remove hydrogen sulphide (H_2S) which interferes with iron-phosphorus binding since iron sulphide compounds are formed more readily than iron phosphorus compounds. The iron would also reduce the amount of available phosphorus in interstitial water which could be exchanged with the water column. A subsequent lime pretreatment raised the pH prior to the oxidation of sediments by calcium nitrate. The treatment was considered to be successful and the procedure was subsequently patented and promoted by Atlas Copco Ltd. as the "Riplox" treatment.

Willenbring _et al_. (1984) used calcium nitrate to oxidize sediments in Long Lake, Minnesota. They determined in that case that iron additions were unnecessary because sediment iron concentrations were sufficiently high to preclude use of additional iron. Cooke _et al_. (1986) state that iron content of sediments of 30-50 mg/g may be adequate so iron addition is not necessary before nitrate treatment. The mean iron concentration reported for 18 samples of Wood Lake sediments taken in winter 1986 is 26.9 mg/g using the Ministry of Environmental Parks Environmental Lab. methods and 13.6 mg/g using the Ministry of Agriculture (Kelowna) soils lab methods. However, available iron and phosphorus and their relative proportions may be more important. There is further discussion of iron analysis in sediments below.

Another use of iron was in White Lough, Northern Ireland where ferric aluminum sulphate was used to reduce internal loading (Foy 1985). There was excellent response (92% reduction of hypolimnetic phosphorus release) in the first year; however, in following years phosphorus release returned to normal levels due to high external inputs of phosphorus.

McQueen _et al_. (1986) used iron additions to oxygenated and anoxic hypolimnia. They found that aerated columns, to which iron had been added, showed very high phosphorus retention and low rates of phosphorus contribution to the water column.

Previous studies of Wood Lake showed low iron in both sediments and water. Jasper and Gray (1982) found that iron in the water was generally less than 0.030 mg/L. The data collected by the Ministry of Environment and Parks regional office shows iron in the water column to be only rarely detectable in Wood Lake.

The work of Mortimer (1941, 1942) showed that phosphorus was bound to iron under aerobic conditions (as insoluble ferric phosphate complexes) but released to the water only under anaerobic conditions (soluble ferrous forms uncoupled from phosphorus). However, there is sufficient evidence now existing that release of phosphorus can take place under aerobic conditions (Kamp-Nielsen 1974, Ryding and Forsberg 1977, Osborne and Phillips 1978, Bostrom et al. 1982). Premazzi and Provini (1985) felt that the classical theory of Einsele and Mortimer of iron-phosphate interaction in a oxic/anoxic context was of limited importance in governing P exchange processes in calcareous lakes. Data collected by Jasper and Gray (1982) give evidence of aerobic sediment release of phosphorus in Wood Lake. Figure 3 shows the amount of phosphorus in Wood Lake over two annual periods. The basic pattern is of highest phosphorus content in winter. There is a decrease in spring, presumably due to phytoplankton uptake and sedimentation. The content is lowest during July-August-September-October when an increase would be expected if anaerobic internal loading were taking place. The increase in phosphorus content takes place in the October through February period when the sediment-water interface would be aerated due to vertical mixing since the lake is generally unstratified in winter.

It would be expected from the relatively small water input to the lake that very little watershed iron (and other minerals) would be supplied to the lake and this may be one reason for the low iron content of Wood Lake. The iron content of the watershed soils is not known and may be another factor. Ellison Lake may also act as a trap for some particulate mineral from the watershed.

6.1 LABORATORY EXPERIMENTS

Although it appears on a theoretical basis that Wood Lake water quality will be improved by adding additional iron to the lake sediments, there are a series of questions both of feasibility of the concept and the environmental consequences which have to be considered before a firm decision can be made to proceed with the project. To obtain additional information related specifically to feasibility of iron additions to Wood Lake, a number of laboratory experiments were run and other investigations made to help answer these questions.

One key question has to do with phosphorus release from sediments. An apparatus consisting of a set of plastic pipes with Wood Lake sediment overlain with water was designed to act as test columns for addition of iron under various treatments. The apparatus is shown in Figure 8 and consists of white PVC water supply pipes with an inside diameter of 67 mm and 23 cm overall length. The bottoms were closed using plastic end-caps glued in place. The columns were filled with 250 mL of lake sediment, and 600 mL of water was carefully added by siphoning through a tygon tube. A set of 12 pipes or columns was built so that different dosages and treatments could be used. Eight of the set of twelve were fitted with 16 gauge hypodermic needles set into the column about 1 cm above the sediment-water interface to allow gas injection. The needles were connected to supply lines from manifolds and fed from a 2.26 m^3 (80 ft^3) nitrogen cylinder or an aquarium air pump. The gas supply systems were intended to keep high oxygen concentration in one set of four columns through which air was being bubbled and low oxygen in a second set of four columns through which nitrogen was being bubbled. Maintaining strict anoxia in experimental columns is very difficult. Holdren and Armstrong (1980), using nitrogen purging (as used here), always had residual oxygen concentrations of 0.8 mg/L or less. Similar results were found in this work. Mortimer (1941, 1942) also reported difficulty in maintaining anoxic conditions in the laboratory. The third set of four columns was simply static treatments. To simulate the low temperature conditions found at the bottom of Wood Lake, the columns were

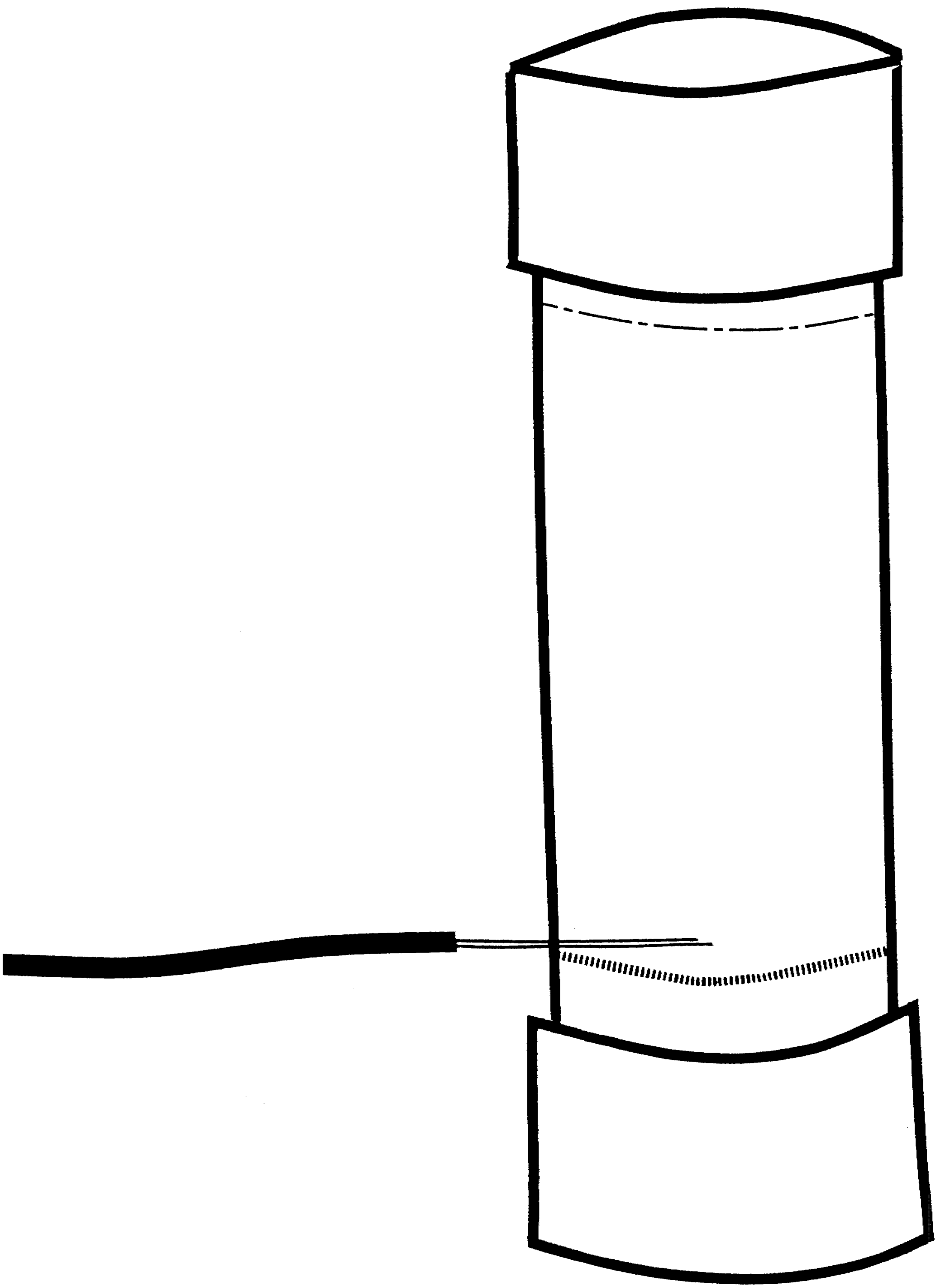

Figure 8 Sediment-water experimental column.

set up in a large refrigerator, maintained at 5°C and in complete darkness. Laboratory experiments such as these have been used by several other investigators as a means of assessing sediment/water interaction (e.g., Bostrom 1984, Premazzi and Provini 1985, Welch et al. 1986).

The first set of experiments was run to determine the concentration of phosphorus in sediment interstitial water and the potential phosphorus available from the sediments. Estimates were made by three methods: 1) squeezing sediment, using compressed air, through a membrane filter (Reeburgh 1967); 2) suspending lake sediment in a dialysis bag in distilled water; and 3) stirring sediment into water, letting the mixture settle, and sampling the supernatant for water chemistry. The results for these three methods are given in Table 12. The results indicate that large amounts of phosphorus are available from the sediments.

The next experiment used the columns described previously to determine more quantitatively the phosphorus release from sediments, first using distilled water overlying the sediments and second using Wood Lake water. Combined with this aspect were investigations of the effects of high or low oxygen and the additions of iron in the form of spent pickling liquor (see section 7.1). The first experiment with distilled water gave several interesting results (Table 13).

It showed that in distilled water the phosphorus concentration rose in all columns, but particularly in columns which did not receive any iron addition. The concentrations in the aerated, low oxygen, and static columns after short-term incubations (2 weeks) at 3-4°C were 54, 87 and 326 µg/L total phosphorus respectively, with no iron addition. The highest concentration is equivalent to a release rate of 4.1 $mg/m^2/d$. It is interesting to note that using Figure 3, a release rate for the lake is calculated to be 5.4 $mg/m^2/d$. This value is based on an increase of 2.8 tonnes of phosphorus from 5.6 km^2 (area below 20 m) over a period of 92 days (15 October to 15 January), assuming that the lake concentration increase is due to internal rather than external loading. The external loading during this period would

TABLE 12

SEDIMENT INTERSTITIAL WATER ESTIMATES

Concentrations in mg/L except as noted

A. Squeeze method (Reeburgh 1967)

orthophosphorus	1.13	conductance	672 μS/cm
total dissolved P	1.24	pH	7.1
total phosphorus	2.88	alkalinity	356
		sulphate	2.7
		TOC	8.4
		TKN	19.0
		NH_3-N	106
		NO_3-N	<0.02

B. Dialysis bag

	1:5 sediment:water		2:5 sediment:water	
	unfiltered	filtered	unfiltered	filtered (x of 2)
orthophosphorus	<0.003	<0.003	0.005	0.010
total dissolved P	0.049	0.036	0.114	0.126
total P	0.542	0.426	1.140	0.844

filtration was done on some samples since a fine suspended material was present on the walls and bottom of the containers.

C. Slurry method (1:5 sediment to water, settled for 2 weeks)

ortho phosphorus	0.490
total dissolved P	0.550
total phosphorus	1.320

TABLE 13

RESULTS OF SEDIMENT-WATER COLUMN EXPERIMENT USING WOOD LAKE SEDIMENT AND DISTILLED WATER AFTER TWO WEEK INCUBATION AT 4°C

Experiment #1:

Column #	Treatment	Dosage*	Ortho P	TDP	TP
1	aerated	none	<3	14	54
2	aerated	36 mL/m^2	5	8	19
3	aerated	72 mL/m^2	7	7	9
4	aerated	360 mL/m^2	9	9	9
5	static	none	199	221	326
6	static	36 mL/m^2	4	10	13
7	static	72 mL/m^2	<3	7	12
8	static	360 mL/m^2	11	13	36
9	nitrogenated	none	<3	11	87
10	nitrogenated	36 mL/m^2	<3	14	79
11	nitrogenated	72 mL/m^2	4	13	53
12	nitrogenated	360 mL/m^2	14	17	20

phosphorus concentrations in µg/L

* pickling liquor

be expected to be low. From the mass balance data of Gray and Jasper (1986) it should be noted that the release rates vary considerably through the year. A peak in July gives release rates of up to 10 $mg/m^2/d$ and in September-October rates are reduced.

Other results included very low phosphorus in columns which were aerated and in which iron was added, reflecting the findings of McQueen et al. (1986). Also, consistently lower rates of phosphorus release with iron added. Even with low oxygen (nitrogen purged) columns, iron reduced phosphorus-release rates from the sediment.

The second and third experiments were run in a similar way, except that Wood Lake water was used rather than distilled water. The results (Table 14) are similar to the previous experiment; however, the end concentrations were variable with the second experiment having generally lower concentrations than the third experiment. The starting phosphorus concentrations for lake water experiments were higher (generally 75-90 µg/L) than the distilled water experiments. The third experiment was run using identical conditions to the second for replication purposes. What can be concluded from these experiments is that (a) the columns which received iron additions had much lower phosphorus concentrations than the columns which did not receive iron; (b) columns which were actively aerated or were not aerated but maintained high oxygen had low phosphorus concentrations with iron additions; (c) columns which had low oxygen concentrations maintained by bubbling nitrogen through them had higher phosphorus concentrations than equivalent high oxygen columns but significantly lower than columns without iron additions; (d) highest phosphorus release rates occurred, not as might be expected with low oxygen but in the static columns - this occurred consistently through these three experiments; (e) the dosage rates of iron appeared to have little effect on resulting phosphorus concentrations.

Two factors which can have an effect on phosphorus release rates are oxygen tension and pH. Oxygen was controlled by either aerating to ensure consistently high concentrations or using bubbled nitrogen to maintain low

TABLE 14
RESULTS OF SEDIMENT-WATER COLUMN EXPERIMENTS USING WOOD LAKE SEDIMENT AND WATER AFTER TWO WEEK INCUBATION AT 4°C

Experiment #2:

Column #	Treatment	Dosage*	Ortho P	TDP	TP
1	aerated	36 mL/m²	<3	5	15
2	aerated	none	<3	11	62
3	aerated	72 mL/m²	<3	4	16
4	aerated	360 mL/m²	6	10	16
5	static	36 mL/m²	<3	4	11
6	static	none	155	168	222
7	static	72 mL/m²	6	8	20
8	static	360 mL/m²	10	10	13
9	nitrogenated	36 mL/m²	<3	17	39
10	nitrogenated	none	<3	32	91
11	nitrogenated	72 mL/m²	<3	16	88
12	nitrogenated	360 mL/m²	10	12	28

Experiment #3:

Column #	Treatment	Dosage*	Ortho P	TDP	TP
1	aerated	none	19	31	81
2	aerated	36 mL/m²	3	5	15
3	aerated	72 mL/m²	3	5	8
4	aerated	360 mL/m²	7	10	11
5	static	none	362	374	570
6	static	36 mL/m²	7	8	11
7	static	72 mL/m²	3	7	10
8	static	360 mL/m²	9	9	20
9	nitrogenated	none	<3	43	190
10	nitrogenated	36 mL/m²	3	27	61
11	nitrogenated	72 mL/m²	4	21	52
12	nitrogenated	360 mL/m²	9	11	13

phosphorus concentrations in µg/L

* pickling liquor

concentrations. The static columns were expected to be intermediate. Results from monitoring typical experiments are shown in Table 15. The data show that, in general, three separate oxygen regimes were maintained. The pH in each column appears to be related to the dosage with only a minor depression at the two lesser pickling liquor application rates (36 and 72 mL/m^2) but a substantial depression when the heaviest dosage was used (360 mL/m^2). The latter is out of all practical consideration since the treatment would require vast amounts of iron. The range of dosage rates used was designed to determine minimum effective dosage.

Two additional experiments were run to determine changes in iron in the water column after pickling liquor additions. There was insufficient volume in the columns to sample phosphorus and iron simultaneously. It was intended to determine, if possible, how much iron would be sufficient to precipitate phosphorus, and active iron and iron to phosphorus ratios. Dosage of pickling liquor was the same as in previous experiments. The columns were sampled after one and two weeks and the results after two weeks are shown in Table 16. The results show surplus amounts of iron at the two higher dosage rates (72 and 360 mL/m^2) with all treatments. With static or aerated columns the lowest dosage rate was sufficient. This may not be the case with the nitrogenated columns since iron was reduced to 0.10 and 0.21 mg/L dissolved and total iron respectively. This may or may not represent surplus available iron.

The next experiment was run since the results from the previous experiments seemed to show that all the levels of iron dosage appeared to be sufficient to reduce the release of phosphorus from the sediment. What was to be tested was whether lower dosages might suffice since one of the inherent difficulties of the project was the handling of the large volumes of pickling liquor required. The dosages used were the original dosage rate (36 mL/m^2), and 2/3 and 1/3 of this. The three oxygen treatments were again used. The results are given in Table 17. The lowest addition rate (12 mL/m^2) is clearly not effective. The 24 mL/m^2 rate appears to be acceptable in the aerated or static columns but far less effective in the

TABLE 15

OXYGEN CONCENTRATION AND pH IN EXPERIMENTAL COLUMNS

Column #		Expt. #1		Expt. #2 (at start)		Expt. #2 (at end)	
		D.O.	pH	D.O.	pH	D.O.	pH
1	aerated	12.2	8.4	12.2	-	>10.0	7.5
2	aerated	12.2	7.9	12.4	-	9.6	7.6
3	aerated	12.3	5.8	11.4	-	>10.0	7.3
4	aerated	11.2	4.4	11.1	-	6.1	4.8
5	static	10.8	7.4	8.4	-	6.7	7.0
6	static	9.5	5.6	10.0	-	9.0	7.7
7	static	9.7	4.9	7.8	-	6.5	6.3
8	static	9.4	3.2	6.1	-	4.0	5.2
9	nitrogen	1.3	7.3	1.0	-	<1.0	7.0
10	nitrogen	1.1	6.9	<1.0	-	2.2	7.0
11	nitrogen	1.5	6.6	<1.0	-	1.5	6.7
12	nitrogen	1.2	6.2	<1.0	-	1.3	5.9

D.O. in mg/L

TABLE 16

IRON CONCENTRATIONS IN SEDIMENT-WATER COLUMNS (mg/L)

Experiment #4:

Column #	Treatment	Dosage	dissolved Fe	Total Fe
1	aerated	72 mL/m^2	29.0	29.2
2	aerated	36 mL/m^2	0.41	0.04
3	aerated	none	0.036	0.99
4	aerated	360 mL/m^2	386.0	395.0
5	static	72 mL/m^2	15.4	14.3
6	static	36 mL/m^2	0.28	0.12
7	static	none	0.06	1.23
8	static	360 mL/m^2	463.0	462
9	nitrogenated	72 mL/m^2	15.0	13.4
10	nitrogenated	36 mL/m^2	0.10	0.21
11	nitrogenated	none	0.05	2.15
12	nitrogenated	360 mL/m^2	266.0	279.0

TABLE 17

EXPERIMENT #5. PHOSPHORUS CONCENTRATIONS IN SEDIMENT-WATER COLUMNS (μg/L) (low dosages)

Column #	Treatment	Dosage	Ortho P	TDP	TP
1	aerated	36 mL/m^2	<3	8	29
2	aerated	none	40	54	140
3	aerated	24 mL/m^2	<3	8	27
4	aerated	12 mL/m^2	3	10	52
5	static	36 mL/m^2	<3	7	67
6	static	none	200	214	438
7	static	24 mL/m^2	<3	10	22
8	static	12 mL/m^2	3	11	90
9	nitrogenated	36 mL/m^2	3	8	48
10	nitrogenated	none	314	330	490
11	nitrogenated	24 mL/m^2	13	21	138
12	nitrogenated	12 mL/m^2	37	45	200

nitrogenated column. From this data, it might be concluded that the original dosage rate (36 mL/m^2) appears to be the most appropriate although 24 mL/m^2 may be as effective at high oxygen conditions.

There are a variety of limitations to this type of investigation. Because it is, by necessity, artificial in many of aspects, and based on a number of assumptions, there is some hesitation in applying these results directly to Wood Lake. The use of small containers and mixed sediment columns are two factors which may give results somewhat different than a full scale lake treatment. It is therefore useful to consider in-lake experiments to further evaluate the iron addition proposal.

It is proposed to undertake, in September 1987, a set of field experiments that would provide additional information on the practicality of the project. The experiments would check the conclusions drawn from the literature evaluations and the laboratory experiments given in the draft report and provide an opportunity to inform the public about the project.

There are a number of ways to evaluate the addition of pickling liquor to sediments. A treatment of a smaller lake or a portion of a lake with similar water and sediment chemistry was suggested and considered (Ellison Lake or Frisken Lake). This method has the disadvantage of still requiring extrapolation from these results to Wood Lake and may require another trial in Wood Lake itself to be sure that the results are similar.

Several reviewers of the draft version of this report suggested that experiments be done with isolated water columns ("limnocorrals") to simulate the effect of the treatment. This has been done in many other lakes but there are difficulties in using this exact approach in Wood Lake. Typical limnocorrals (at least two would be required) would be difficult and expensive to fabricate, establish, and maintain in 30 m of water in a lake the size of Wood Lake with its winds and currents (and possibly ice) over the fall and winter period. The cost in materials and manpower would probably exceed the budget allocated for the whole lake treatment.

It is proposed that a test area of 5 ha of Wood Lake be treated with pickling liquor in the same manner planned for the full treatment (dispersal at 20 m depth). This is slightly more than 1% of the full treatment (0.5% of the lake surface area). At the treatment area a 6 X 6 X 3 m open-topped "limnocorral" enclosure would be placed on the bottom. A second enclosure would be located away from the treatment area to serve as a control (Figure 9) gives a 2 x 2 factor design to test both treatment and enclosure effects. The purpose of the treatment enclosure is to better simulate a whole lake treatment. Because only an area of the lake is being treated in this experiment the water column and sediment treatment will be diluted by horizontal water movements in the hypolimnion. By using the enclosures the dilution will be substantially slowed. The control enclosure serves to duplicate the enclosure environment without the added iron. Because the pickling liquor has a high chloride content, dilution rates can be monitored for the treatment enclosure.

This particular design allows the following questions regarding water chemistry and sediment to be evaluated: the changes in concentration of trace metals in the water column immediately after treatment (copper, zinc, lead etc.), the changes in metals in the surface sediments; changes in interstitial phosphorus concentrations before and after treatment and inside and outside the treatment area; differences in phosphorus concentration within 3 m of the bottom after treatment; differences in near bottom phosphorus inside and outside the treated enclosure and inside and outside the untreated enclosure, particularly over the months following treatment; evaluation of the movement of pickling liquor into the epilimnion, and several other questions which would contribute to an evaluation of whether or not the whole lake treatment will be successful in reducing phosphorus movement from the sediments.

A second area of concern expressed in the reviews of the proposal was effects on fish. By using hydroacoustic transects of areas inside and outside the treatment area, an evaluation of the density of fish in treated versus untreated areas will be done on the assumption that fish will avoid the area if pickling liquor moves out of the hypolimnion. This will also provide some data on depth distribution of fish in late September when the full treatment would be done.

Zooplankton samples will be taken to determine if there is a change in their vertical distribution or if there are changed numbers of zooplankton in the treatment area as compared to the control area.

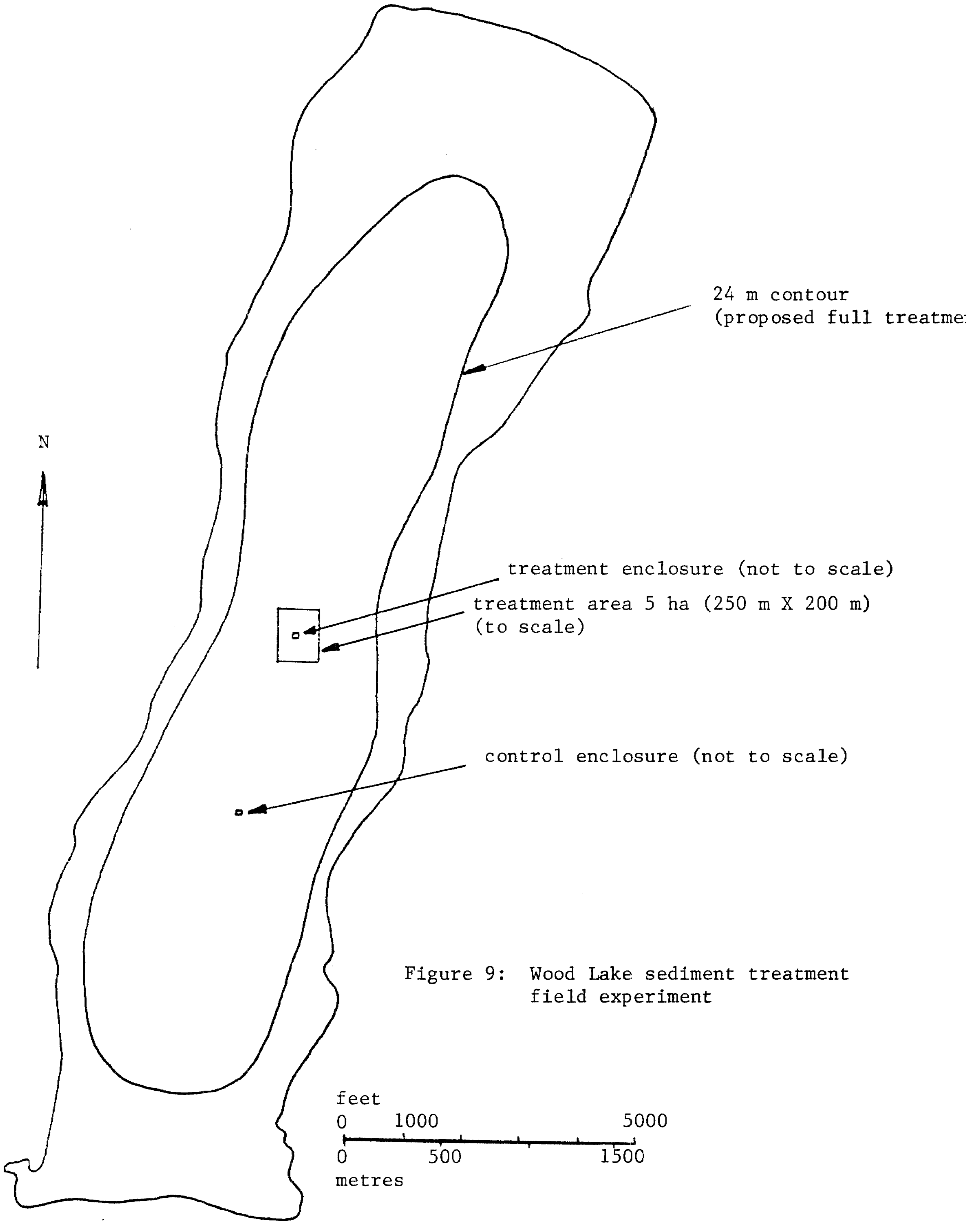

Figure 9: Wood Lake sediment treatment field experiment

7. PROPOSED WHOLE LAKE TREATMENT

7.1 PICKLING LIQUOR

In considering the feasibility of the concept of enhancing the iron concentration of Wood Lake, one of the constraining factors was the cost of the project. Although bulk ferric chloride would be the best form of iron to use, the size of Wood Lake and the consequent cost of ferric chloride in the amounts needed (preliminary estimates were 50 tonnes at $6000/tonne) made this possibility impractical. The possibility of utilizing a free source of iron made the idea economically feasible since steel plants produce, as a waste product (pickling liquor), a material which appeared to be suitable. Steel plants use acid to clean steel products such as wire, nails, castings or stampings prior to fabrication, assembly, plating, painting or marketing. Acid baths clean any rust, scale or grease from these steel products. After a certain amount of material is cleaned, the acid becomes exhausted. The spent pickling liquor is essentially exhausted acid saturated with iron. Different companies use different acids - sulphuric or hydrochloric; however, the latter is preferred since adding additional sulphate to lakes is generally undesirable. The reduced sulphur has a strong affinity for iron (forming pyrite) and leaves less iron to bind with phosphorus. Tree Island Steel in the Vancouver area (Queensborough, New Westminster) uses hydrochloric acid-based pickling liquor and seemed to be the most suitable source. In the early operation of the plant the pickling liquor was disposed of in exfiltration ponds adjacent to the plant (and the Fraser River). Spent pickling liquor is now used in three sewage treatment plants (Penticton, Merritt, Whistler) as part of a phosphorus removal step. The remaining output from Tree Island Steel is taken by Brenda Mines of Peachland apparently for use in their mining operation. Brenda Mines needs only a portion of the Tree Island spent pickling liquor but takes the entire output to guarantee a continued supply.

There has been no experimental use of pickling liquor in lake restoration. An unintentional treatment has been noted for Hamilton harbour by Murphy (1987). The harbour (largely isolated from Lake Ontario) has received many different wastes over several decades including sewage which has caused the harbour to become eutrophic. The harbour also received pickling liquor from several steel mills. The discharge of pickling liquor ended about ten years ago; however, no release of phosphorus from bottom sediments occurs although the organic loading is very high and the sediments are anoxic. Murphy indicated that this observation supported the hypothesis that addition of iron should suppress phosphorus release from lake sediments.

The use of pickling liquor in Wood Lake is an unorthodox proposal. Since the pickling liquor may possibly contain toxic constituents, a variety of investigations were carried out to determine if the proposed sediment treatment might harm the biota, water chemistry or sediments of Wood Lake. The low pH of the pickling liquor was a primary concern. The effects on Wood Lake water were investigated and it was concluded that the high alkalinity and buffering capacity ensure that no pH shift would occur.

The pickling liquor was analysed for a wide range of constituents and the results are tabulated as Table 18. There are a number of factors to consider on the basis of these analyses. The density of the pickling liquor (approx. 1.3), reflected in the conductance and chloride, is not likely to be a major cause of environmental concern (toxicity of chloride and dissolved salts are very low) and will be a benefit in an application of pickling liquor to the sediment since the high density would ensure high sinking rates of this liquid. The chemical oxygen demand is high; however, with the application rates considered (30-40 mL/m^2) the oxygen demand on an areal basis would be 85 mg/m^2, or in a 5-metre water column (5 m^3) an additional instantaneous oxygen demand of 0.0017 mg/L. This is insignificant in comparison to the normal oxygen demand of the lake (0.054 mg/L/d) - the equivalent of 1/3 of 1 day's oxygen demand. Oil and grease in the sample is of apparent concern but, considering the dosage rate, the effect is expected to be unmeasurable since the dilution in the hypolimnion is high (100 000:1). The result reported as oil and grease is not "oil and grease" in the conventional sense but is an analytical term representing all substances which are solvent extractable.

TABLE 18

CHEMICAL ANALYSIS OF TREE ISLAND STEEL PICKLING LIQUOR

	total	dissolved
cadmium	1.25 mg/L	1.25 mg/L
chromium	67.0 mg/L	67.0 mg/L
copper	384.0 mg/L	384.0 mg/L
iron	90 000 mg/L	90 000 mg/L
magnesium	9.0 mg/L	9.0 mg/L
manganese	880 mg/L	880 mg/L
molybdenum	8.0 mg/L	7.8 mg/L
nickel	70.0 mg/L	70 mg/L
lead	28.5 mg/L	28.5 mg/L
zinc	64.0 mg/L	64.0 mg/L
mercury	0.01 mg/L	-
nitrate nitrogen	<0.02 mg/L	
nitrogen organic	<0.01 mg/L	
nitrogen total	<0.02 mg/L	
phosphorus ortho	40.8 mg/L	
phosphorus total	interference	
total inorganic carbon	9.0 mg/L	
total organic carbon	178.0 mg/L	
nitrogen ammonia	interference	
nitrogen nitrite	interference	
sodium	376.0 mg/L	
chloride	280 000 mg/L	
colour (TAC)	>10 000	
C.O.D.	3 380 mg/L	
non-filterable res (suspended sed)	191 mg/L	
specific conductance	>100 000 µS/cm	
oil and grease	1 680.0 mg/L	
pH	<1	

The other undesirable effect could be caused by increases in metal concentrations in the sediment. This effect was evaluated by estimating the increase in metals which would occur in the surface sediments (top 1 cm) by the addition of the pickling liquor. The estimates (Table 19a) show that only copper would be increased significantly in surface sediments. Wood Lake has a relatively low natural copper concentration in the sediments (see Table 7 - 21.4 µg/g). The mean concentration of lakes in B.C. is 45.3 µg/g so a 20% increase in copper in Wood Lake sediments (i.e., to 25.7) would result in a sediment concentration which was still far less than the majority of B.C. lakes. Table 19b shows projected increases in the lake volume below 16 m assuming that all the metals were mixed homogeneously in the hypolimnion and a second example showing increases in concentration if mixed into the entire lake.

Additional analysis of the effluent was done by gas chromatography-mass spectrometry (GC/MS) to determine if unexpected or unusual organic compounds were present in the pickling liquor. Two compounds are added in the steel plant pickling liquor process. Rodine XL-1090 is an organic additive which is added to the liquor tanks and binds to the steel products to prevent further action by the acid. It is added to the tanks at 0.2% (2 L/1000 L). The second additive is Chemclean Conox NF, a blend of surfactants designed to reduce fumes in the rinsing tanks. It is added at a ratio of one litre per 13 500 litres of pickling liquor.

The GC/MS analysis showed low concentrations (less than 1 ppm) of some 16-18 carbon fatty acids (hexadecanoic acid and heptadecanoic acid, 16 methyl) and a phthalate tentatively identified as di-ethyl hexyl. The analysis showed no evidence of solvents, petroleum products or pesticides. No other compounds were extractable at neutral pH or alkaline pH.

The fatty acids are probably present as components of the surfactant additive noted above. The toxicity of these compounds are apparently low with the toxicity of hexadecanoic acid (palmitic acid) given as 11 mg/L for goldfish.

TABLE 19a
CALCULATED INCREASES IN METALS IN WOOD LAKE SEDIMENTS

A. Metals in pickling liquor	Concentration	Amount in 450 m^3
chromium	67 mg/L	30.2 kg
copper	384 mg/L	172.8 kg
lead	28.5 mg/L	12.6 kg
mercury	0.01 mg/L	0.005 kg
zinc	64 mg/L	28.8 kg

B. Metals in Wood Lake sediments	Concentration	Amount in top 1 cm in area of 400 ha
chromium	42.3 μg/g DW	1 692 kg
copper	21.8	856 kg
lead	42.5	1 688
mercury	0.05	0.2
zinc	68.3	2 732

C. Increase of metals (in %) due to treatment

chromium	1.8% (30.2 kg in 1692 kg)
copper	20.2%
lead	0.7%
mercury	2.5%
zinc	1.1%

TABLE 19b
CALCULATED INCREASES IN METALS IN THE WATER COLUMN*

A. Hypolimnion (volume below 16 m, 56.1 x $10^6 m^3$), pickling liquor application 35 mL/m^2

chromium	0.5 μg/L
copper	3.1 μg/L
lead	0.2 μg/L
mercury	0.00009 μg/L
zinc	0.5 μg/L

B. Whole lake (volume 199.5 x $10^6 m^3$)

chromium	0.14 μg/L
copper	0.87 μg/L
lead	0.06 μg/L
mercury	0.00002 μg/L
zinc	0.14 μg/L

*Assuming homogeneous dispersal without precipitation loss

The phthalate which was found is one of a large group of chemicals used in plastics and is likely to have been a piece of plastic strapping or packaging or coated cable accidentally included with the steel products being cleaned in the particular pickling liquor batch. The toxicity of phthalates to aquatic life are quite low. Environment Canada (1983) gives LC_{50} concentrations for diethylphthalate (DEP) to Daphnia as 52.1 mg/L to bluegill (Lepomis) as 98.2 mg/L. The toxicity (96 hr LC_{50}) of di- (2 ethylhexyl) phthalate (DEHP) is given as 11.1 mg/L for Daphnia, >32.0 for Gammarus 540 mg/L for rainbow trout and >77.0 mg/L for bluegill. Considering the high dilution which will occur, the possibility of toxicity to aquatic life from the organic components of the pickling liquor appears to be unlikely.

Bioassays were done with rainbow trout and Daphnia. Both methods showed that the pickling liquor was toxic in relatively low dilutions. Rainbow trout (in Vancouver City water) showed a 96 h LC50 of 12 mg/L. In Wood Lake water the value was 250 mg/L. Daphnia magna showed 100% toxicity at the lowest dilution used (0.1% = 1000 parts per million) in both standard Vancouver water and Wood Lake water. The toxicity has marginal relevance since the pickling liquor will be added in such a way as to be separated from the lake biota. However, it shows that detailed testing should be done to confirm that the pickling liquor will not move into the surface and mid-water areas where fish and zooplankton might be present.

It is intended to spread the liquor onto the deep sediments (>24 m) from a boat, using a hose and diffuser with an outlet at 20 m, during August and September. This is the period of maximum thermal stratification so little vertical movement of water will occur and 20 m is well below the oxic zone where biota (zooplankton and fish) are present. Both these groups of animals avoid the low oxygen area below 15 m. The other group of organisms which could be affected is benthos. Wood Lake benthos was surveyed during the Okanagan Basin Study by Saether and McLean (1972). They described the bottom as virtually without invertebrate life and were surprised by the astonishing change from the 1930's description of Rawson. More recent sampling (1986) confirmed the lack of any important benthic community. The treatment would likely have little effect on the biotic system of the lake even if the remnants of the benthos were adversely affected. If the project proves to be successful, a lower phosphorus concentration will cause less oxygen demand. This will encourage recolonization of deep sediments by benthos as well as the use of deeper, cooler lake strata in the summer by salmonids.

With a reduction in phosphorus loading there should be a response in the following year with regard to algal production and oxygen depletion.

The lake will require periodic re-treatments. It is estimated that the addition of iron would have to be redone at 5 to 10-year intervals a few times until a reservoir of iron is established in the sediments. However, as noted above, the benefits should greatly outweigh the costs.

One aspect of the full scale project was an evaluation of the vertical movement of iron into the surface waters, i.e., the possibility of movement of iron by diffusion from the hypolimnion to the surface waters because of the concentration gradient created by the treatment. There are a number of considerations which need to be made in evaluating this possibility. The following was the rationale used in regards to potential diffusion of materials in the lake.

The most important factor is the relatively low concentration of iron to be used in the treatment. The expected application rate (36 mL/m^2 pickling liquor - about 10% iron) would result in a concentration of less than 1 mg/L if no precipitation occurred and if the iron were homogeneously mixed into the deep hypolimnion (depth greater than 20 m). In the lab column experiments there was considerable precipitation and the same would be expected to happen in the lake environment. Because of the affinity of iron for phosphorus in the sediment and water column, the water-column concentration will be reduced significantly and rapidly. Even if the highest possible concentration (no iron precipitation) is considered, the rate of vertical movement will be very slow because of the thermal barrier represented by the lake stratification. Preliminary calculations of flux due to eddy diffusion (which is a more important transfer mechanism than molecular diffusion) seems to indicate there would be little if any movement above 15 m because of the thermocline, even with higher concentration gradients than were noted above. The observational data for Wood Lake (and other well stratified lakes) bear this out. Even with gradients of several mg/L of dissolved materials such as oxygen, silica, calcium or a variety of other dissolved constituents, there is little vertical movement as a result of concentration gradients and considerable difference is maintained between epilimnion and hypolimnion. The thermal stratification of the lake is a substantial barrier to movement of dissolved materials and combined with the low concentration gradients leads to the conclusion that there can be no significant amounts of iron transferred to surface waters in the period when the project is done (August and September).

7.2 LOGISTICAL ASPECTS

The logistics of the proposed project are a major problem and some effort will be required to bring the project to an operational phase. Using the estimates derived from the experiments, approximately 450 m^3 of pickling liquor will need to be transported from Vancouver to Wood Lake. It is possible to use rail transport or truck transport or a combination of the two. The difficulty with rail transport is obtaining acid-resistant tank cars. Inquiries to this time have indicated that rail cars - owned by companies such as Procor - are difficult to obtain since most are on long-term lease to customers. Short-term lease (3 to 6 month lease) of acid-resistant cars is very difficult to obtain and at present this method does not appear to be likely for transportation of the entire amount of pickling liquor. The use of a single tank car as a storage tank on the siding at Oyama adjacent to the lake is an arrangement with a number of benefits (flexibility, security, large available supply, and direct access).

An alternative method of transportation is by truck. Brenda Mines presently receives its pickling liquor from Tree Island Steel by tanker truck. The cost, in comparison to rail freight, is lower; however, the problem of storage at the site is more difficult. At least one tank truck would need to be left at the site so that distribution on the lake would be feasible. The next tractor-trailer unit could deliver a full tank and return to Vancouver with the empty tank. This type of arrangement (in contrast with using a rail tank car) for storage would require tighter scheduling. There would be less latitude for mechanical breakdown of the boat or for staffing problems.

The pickling liquor would be available from the plant at a rate of approximately 45 m^3/week. This rate determines the length of time the treatment would take (8-10 weeks) and the amount of iron solution applied each week (45 m^3/week).

It is proposed that a boat with a fitted tank (2 m^3), flowmeter, and pump would discharge the iron solution through a hose and diffuser at a depth of 20 m. The area of the lake to be covered is the bottom below the 24 m contour (an area of 430 ha). The iron would be dispersed on crosswise transects approximately 1000 m long and 10 m apart - about 500 transects in total. Each transect would disperse 1 m^3 which, at a boat speed of 5 km/h, would require a flow of 83 L/min (18 gal/min). One boat-tank-load (2 m^3) would probably take one hour with transit and loading time, so 6 trips per day using 12 m^3/day of liquor can be expected. This scheme would require approximately 4 days to disperse an incoming supply of 45 m^3/week. The work is proposed to be done in late August, September, and early October at the time of maximum thermal stratification. This is advantageous since the deep waters of Wood Lake are high in phosphorus and some binding of water-column phosphorus is likely. If this phosphorus is permanently bound in the sediment it would be eliminated from the phosphorus cycle. Carrying out the project at this time also ensures maximum separation between biota in the surface water and the iron solution, thus avoiding any potential toxicity. This period also appears to be the optimal time since surface sediment phosphorus content is highest. At this period the iron is held in the hypolimnion so maximum efficiency of phosphorus binding from the water column and in the sediments should be achieved.

REFERENCES

Alexander, D.G. 1982. Summary of nitrogen and phosphorus loadings to the Okanagan main valley lakes from cultural and natural sources. Okanagan Basin Implementation Working Report. Penticton, B.C. 22 p.

Allan, R.J. and J.D.H. Williams. 1978. Trophic status related to sediment chemistry of Canadian prairie lakes. J. Environ. Qual. 7:99-106.

Avnimelech, Y. 1980. Calcium-carbonate-phosphate surface complex in calcareous systems. Nature 288: 255-257.

Baccini, P. 1985. Phosphate interactions at the sediment-water interface. P.159-205 in Stumm, W. Chemical Processes in Lakes. Wiley and Sons.

Bostrom, B. 1984. Potential mobility of phosphorus in different types of lake sediment. Int. Revue ges. Hydrobiol. 69:457-474.

Bostrom, B., M. Jansson and C. Forsberg. 1982. Phosphorus release from the sediments. Arch. Hydrobiol. Beih. Ergebn. Limnol. 18:5-59.

Brock, T.D. 1985. A eutrophic Lake: Lake Mendota Wisconsin. Springer-Verlag. New York. 308 p.

Bryan, J.E. 1986. Personal communication. Head, environmental section, Waste Management Branch, Okanagan sub-region, Penticton, B. C.

B.C. Research. 1976. Evaluation of alum treatment as a method to upgrade Wood Lake water quality. Vancouver. 32 p.

Canfield, D.E. and R.W. Bachmann. 1981. Prediction of total phosphorus concentrations, chlorophyll a, and Secchi depths in natural and artificial lakes. Can. J. Fish. Aquat. Sci. 38:414-423.

Clemens, W.A., D.S. Rawson and J.L. McHugh. 1939. A biological survey of Okanagan Lake B.C. Fish Research Board Canada Bulletin 56, 70 p.

Cooke, G.D., E.B. Welch, S.A. Peterson and P.R. Newroth. 1986. Lake and Reservoir Restoration. Butterworth Publishers. 392 p.

Environment Canada. 1983. Guidelines for surface water quality. Vol. 2. Organic chemical substances. Phthalic Acid Esters. Inland Waters Directorate, Water Quality Branch. Ottawa. 23 p.

Foy, R.H. 1985. Phosphorus inactivation in a eutrophic lake by the direct addition of ferric aluminum sulphate: impact on iron and phosphorus. Freshwater Biology 15:613-629.

Gray, C.B.J. 1986. Personal Communication. Unpublished Data. Letter of 27 April 1986.

Gray, C.B.J. and S. Jasper. 1982. Limnological trends in Wood Lake, B.C. (1971-1981) with some implications for lake management. Inland Waters Directorate, N.W.R.I. West Vancouver. 22 p.

Gray, C.B.J. and R.A. Kirkland. 1982. Nutrient composition and bioavailability in major tributaries and interconnecting rivers in the Okanagan basin National Water Research Institute, Inland Waters Directorate, Pacific and Yukon Region, West Vancouver, B.C. 51 p. + appendices.

Gray, C.B.J. and S. Jasper. 1986 MS. Components of nutrient supply and their utilization by phytoplankton in Wood Lake B.C. Unpublished Manuscript. National Water Research Institute, West Vancouver, B. C.

Gray, C.B.J. and R.A. Kirkland. 1986. Suspended sediment phosphorus composition in tributaries of the Okanagan Lakes, B.C. Water Research 20:1193-1196.

Jasper, S. and C.B.J. Gray. 1982. The chemical and microbiological limnology of Wood Lake, B.C., 1980. National Water Research Institute, Inland Waters Directorate, Pacific and Yukon Region, West Vancouver, B.C. 107 p.

Jensen, E.V. 1981. Results of the continuing water quality monitoring program on Okanagan Lakes for years 1979-1980. Canada-British Columbia Okanagan Basin Agreement. Penticton. 73 p.

Kamp-Nielsen, L. 1974. Mud-water exchange of phosphate and other ions in undisturbed sediment cores and factors affecting the exchange rates. Arch. Hydrobiol. 73:218-237.

Lijklema, L. 1977. The role of iron in the exchange of phosphate between water and sediments. In Interactions Between Sediments and Fresh Water. ed. by H.L. Golterman. Junk - The Hague.

Lofgren, S. and S.O. Ryding. 1985. Apatite solubility and microbial activities as regulators of internal loading in shallow eutrophic lakes. Verh. Internat. Verein. Limnol. 22:3329-3334.

Manning, P.G. 1977. Mossbauer spectral studies of ferric phosphate interactions in sediments underlying oxic lake waters. Can. Miner. 15:522-426.

McNeill, R. 1983. Lake water quality and beach use in the Okanagan Basin, British Columbia. p.73-76 in: Lake Restoration Protection and Management. EPA 440/5-83-001.

McQueen, D.J., D.R.S. Lean and M.N. Charlton. 1986. The effects of hypolimnetic aeration on iron-phosphorus interactions. Water Research 20: 1129 - 1135.

Ministry of Environment. 1985. Phosphorus in the Okanagan Valley Lakes: Sources, Water Quality Objectives and Control Possibilities. Water Management Branch, Waste Management Branch, Ministry of Environment. Province of British Columbia, Victoria, 103 p.

Mortimer, C.H. 1941, 1942. The exchange of dissolved substances between mud and water in lakes. J. Ecol. 29:280-329 and 30:147-201.

Murphy, T.P. 1987. Letter of 19 March 1987 conveying review of draft report on Wood Lake iron treatment. Canada Centre for Inland Waters, Burlington, Ontario.

Murphy, T.P., C.J. Hall, K.I. Ashley, A. Murdoch, M. Mawhinney and H.J. Fricker. 1985. In-Lake precipitation of phosphorus by lime treatment. Environment Canada. NWRI contribution Series 85-167. 41 p+ appx.

Murphy, T.P., K.J. Hall and I. Yesaki. 1983. Coprecipitation of phosphate with calcite in a naturally eutrophic lake. Limnol. Oceanogr. 28: 58-69.

Nordin, R.N. 1980. Strategies for maintaining water quality in two British Columbia Lakes. Can. Water Resources Journal 5:90-101.

Nordin, R.N. 1985. Water quality criteria for nutrients and algae. Summary (7 p). Technical Appendix (104 p.) Water Management Branch, B.C. Ministry of Environment. Victoria.

Osborne, P.L. and G.L. Phillips. 1978. Evidence for nutrient release from sediments of two shallow and productive lakes. Verh. int. Verein. Limnol. 20:654-658.

Otsuki, A. and R.G. Wetzel. 1972. Coprecipitation of phosphate with carbonates in a marl lake. Limnol. Ocenogr. 17:763-767.

Pinsent, M.E. and J.G. Stockner. 1974. Limnology of the major lakes in the Okanagan Basin. Technical Supplement V. Canada-British Columbia Okanagan Basin Agreement. 261 p.

Premazzi, G. and A. Provini. 1985. Internal phosphorus loading in lakes:a different approach to its evaluation. Hydrobiologia 120: 23-33.

Reckhow, K.H. and J.T. Simpson. 1980. A procedure using modeling and error analysis for the prediction of lake phosphorus concentration from land use information. Can. J. Fish. Aquat. Sci. 37:1439-1448.

Reeburgh, W.S. 1967. An improved interstitial water sampler. Limnol. Oceanogr. 12:163-165.

Ripl, W. 1976. Biochemical oxidation of polluted lake sediment with nitrate - a new restoration method. Ambio 5:132-135.

Ripl, W. 1986. Internal phosphorus recycling mechanisms in shallow lakes p.138-142 in Redfield, G., J.F. Taggart and L.M. Moore. Lake and Reservoir Management Vol. II. Proc. 5th Annual Conf. Int. Symp. N. Arm Lake Manage. Soc. Nov. 1985.

Ryding, S.O. and C. Forsberg. 1977. Sediments as nutrient source in shallow polluted lakes. P. 227-294. in: Interactions between sediments and fresh water, edited by H.L. Golterman. Junk. The Hague.

Saether, O.A. and M.P. McLean. 1972. A survey of the bottom fauna in Wood, Kalamalka and Skaha lakes in the Okanagan Valley, British Columbia. Fish. Res. Board Can. Tech. Report No. 342. 20 p.

Shukla, S.S., J.K. Syers, J.D.H. Williams, D.E. Armstrong and R.F. Harris. 1971. Sorption of inorganic phosphate by lake sediments. Soil Sci. Soc. Amer. Proc. 35: 244-249.

Stauffer, R.E. 1981. Sampling strategies for estimating the magnitude and importance of internal phosphorus supplies in lakes. U.S. Environmental Protection Agency, Corvallis, Oregon. EPA-600/3-81-015.

Stauffer, R.E. 1985. Relationships between phosphorus loading and trophic state in calcareous lakes of southeast Wisconsin. Limnol. Oceanogr. 30:123-145.

Stauffer, R.E. 1986. Linkage between the phosphorus and silica cycles in Lake Mendota, Wisconsin. Water Research 20:597-609.

Stein, J.R., and T.L. Coulthard. 1971. A report on the Okanagan water investigation. Univ. Br. Col. Prepared for Water Invest. Br., Br. Col. Water Resour. Serv. Parliament Buildings, Victoria, B. C.

Stumm, W. and J.J. Morgan. 1970. Aquatic chemistry. Wiley-Interscience. 583 p.

Tessenow, U. 1974. Solution, diffusion and sorption in the upper layer of lake sediments. IV. Reaction mechanisms and equilibria in the system iron - manganese - phosphate with regard to the accumulation of vivianite in Lake Ursee. Arch. Hydrobiol. Suppl. 47: 1-79.

Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. 1st. Ital. Idrobiol. 33:54-83.

Water Investigations Branch. 1974. Kalamalka-Wood Lake Basin Water Resource Management Study. British Columbia Water Resources Service, Dept. of Lands, Forests and Water Resources, Victoria, B. C. 208 p.

Welch, E.B., D.E. Spyridakis, J.I. Shuster and R.R. Horner. 1986. Declining lake sediment phosphorus release and oxygen deficit following wastewater diversion. J. Wat. Poll. Contr. Fed. 58-92-96.

White, W.S. and R.G. Wetzel. 1975. Nitrogen, phosphorus, particulate and colloidal carbon content of sedimenting seston of a hard-water lake. Int. Ver. Theor. Angew. Limnol. Verh. 19:330-339.

Wiegand, R.C. 1984. Data report on the physical limnology of Wood Lake, British Columbia: observations of temperature, conductivity, turbidity and chlorophyll _a_, June-October 1981. National Water Research Institute, Inland Waters Directorate, Environment Canada. West Vancouver.

Wiegand, R.C. and V. Chamberlain. 1987. Internal waves of the second vertical mode in a stratified lake. Limnol. Oceanogr. 32:29-42.

Willenbring, P.R., M.S. Miller and W.D. Weidenbacher. 1984. Reducing sediment phosphorus release rates in Long Lake through the use of calcium nitrate. In: Lake and Reservoir Management. P. 118-121. EPA 440/5-84-001.

Williams, J.D.H., J.K. Syers, S.S. Shukla amd R.F. Harris and D.E. Armstrong. 1971. Levels of inorganic and total phosphorus in lake sediments as related to other sediment parameters. Environmental Science and Technology 5: 113-1120.