

INTERNAL REPORT 85

NUTRIENT BUDGETS IN THE LAKES OF THE CEDAR RIVER WATERSHED

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ABSTRACT

Aquatic mineral measurements and sediment characterization of the Cedar River basin lakes and streams reveals two largely distinct physical and chemical environments. Near the headwaters of the Cedar River Watershed the composition of lakes and streams reflect adjacent rocks but the effects of forest and agricultural practices and of processes occurring downstream very quickly alter the composition to a type largely responsive to the urbanization in the lower reaches of the watershed. The relative ionic composition in the watershed is: $Ca > Mg \geq Na > K$ and $HCO_3 > Cl \geq SO_4$. A 2- to 10-fold increase in concentration is measured with most chemical parameters when comparing upper watershed to lower watershed. The lowest increase is observed with total phosphorus reflecting perhaps identical phosphorus solubility control mechanisms.

Annual nutrient budgets for Lake Sammamish suggest a reduction in sedimented phosphorus since diversion, but little change in the quantity of phosphorus released from anaerobic sediment. Although the sediment phosphorus supply during the summer and fall months is nearly three times higher than the external phosphorus supply its relative contribution to the trophogenic layer phosphorus is a function of lake mixing. An iron precipitation mechanism appears to control the mean winter phosphorus contents of Lake Sammamish. The prevailing anoxic conditions in the lake during late summer and fall bring about large increases in hypolimnetic iron concentrations which upon destratification precipitate phosphorus as an iron (III) hydroxy complex.

Lake sediment characterization indicate differences between lakes with respect to carbon/nitrogen, nitrogen/phosphorus and particle size distribution reflecting drastic variations in the depositional environments and trophic status of the upper and lower watersheds. Higher carbon/nitrogen and nitrogen/phosphorus ratios and coarser sediments are measured in oligotrophic Findley Lake. With the exception of Findley Lake, all sediments appear to have the same composition with respect to Fe, Mn, Ca, Mg, Na, and K contents.

Simulation of sediment phosphorus release at the sediment-water interface in enclosed *in situ* Lake Sammamish sediment-water columns appears to parallel the phosphorus release measured in the lake hypolimnion at the peak of the lake stagnation period. Preliminary studies indicate that it will be possible to relate the nutrient release results from the *in situ* columns to those of laboratory studies, arriving thus at a faster more economically obtained elucidation of the nutrient exchange mechanisms and potentials at lake sediment-water interface.

INTRODUCTION

To facilitate rapid dissemination of scientific results from individual projects of subprojects, the general framework for the collection and interpretation of the data are detailed in this report. The broad outlines of this framework are shown in simplified, schematic form in Figure 1. Briefly the program is intended to: (1) monitor the water quality, identify sources and assess changes; (2) examine the structure and dynamics of the aquatic mineral cycling and budgets; (3) relate observed differences and changes of the aquatic ecosystems to watershed characteristics and activities; (4) develop means for measuring environmental changes; and (5) promote simulation and modeling as tools for environmental characterization and management.

Some of the earliest aquatic studies in the Western Coniferous Forest Biome involved the measurement of nutrient concentrations. Studies of chemical balances and controlling factors were initiated early in the fall of 1970 and focused on Lake Sammamish. In the spring of 1971 the IBP efforts expanded the aquatic program to include Washington, Chester Morse, and Findley Lakes in the inventory and process studies. The Lake Washington study was limited and related to the characterization of sediments and the measurement of parameters other than those monitored by Dr. Edmondson's group under non-IBP funding. The lakes were sampled in the main water bodies, except inflow and outflow streams have been sampled to determine nutrient loading in Lake Sammamish.

Tables 1, 2, and 3 are detailing the aquatic mineral cycling activities by site, year and investigator and indicate the kind of data that has been collected and made available to the data bank. Figures 2, 3, 4, and 5 are also included for identification of sampling sites.

RESULTS

Some of the earliest studies in the Western Coniferous Forest Biome involved the measurement of aquatic mineral concentrations, and the characterization of the lake sediments. Much of the lake nutrient studies in the Cedar River Watershed were concentrated on providing baseline data needed for the biological research. In 1972 and early 1973 studies were initiated emphasizing the interchange between sediments and overlying water and the sedimentation of allochthonous and autochthonous material. At Lake Sammamish, data were gathered for chemical budgets that included both stream and rain water inputs. Current efforts toward developing models of aquatic mineral cycling are concentrated on completing, refining, and testing nutrient cycling as a function of both biological and physicochemical lake processes.

As was indicated in Table 3 the data gathering phase will continue throughout the study to update and expand existing limited data. The work on the comprehensive data collected up to now is not yet complete. Thus, it will

be necessary to confine the presentation of results to a very brief summary of the general trends in chemical element concentrations and to some general remarks on the salient features of individual research projects. Raw data has been entered in the data bank.

Water Column and Stream Studies

The graded sequence in chemical composition of the water from the upper Cedar River basin to Lake Washington that was indicated from preliminary data (Welch and Spyridakis 1972) of 1971 monitoring was further substantiated. A two- to tenfold increase in concentration is observed with most chemical parameters when comparing Findley and Chester Morse Lakes to Lakes Sammamish and Washington. These radical differences in chemical quality of the lake waters in the Cedar River Drainage are readily explainable on the basis of the Watershed's size, type, and prevailing activity. Near the headwaters of the Cedar River Watershed the composition of lakes and streams reflect adjacent rocks but the effects of forest and agricultural practices, and of processes occurring downstream very quickly alter the composition to a type largely responsive to the urbanization in the lower reaches of the watershed. With regard to major cations and anions, the ionic composition in the Cedar River Watershed is: $Ca > Mg > Na > K$ and $HCO_3 > Cl > SO_4$. (values are expressed in meq/liter).

Comparison of nitrogen contents of lower and higher lakes indicates that NO_3-N concentration is easily 10 times higher in Lakes Sammamish and Washington. The smallest variation was observed with phosphorus which was between 2 to 3 times higher in lower watershed (about 20 μg phosphorus/l, mean water concentration) reflecting the low solubility of phosphate compounds and perhaps identical control mechanisms of phosphorus solubility. Stream (inflow, outflow) and rain water nutrient measurements (Moon 1973) made possible the calculation of preliminary inorganic nitrogen and total phosphorus Lake Sammamish budgets (Welch and Spyridakis 1972, Moon 1973). It appears that Lake Sammamish sediments are an important sink for both nitrogen and phosphorus, a characteristic which has not changed appreciably following waste water diversion (1968). Although a deep water column total phosphorus budget in Lake Sammamish indicates a significant release of sediment phosphorus to the overlying water during summer and fall, the relative contribution of internal phosphorus supply (4 $mg/m^2/day$) to the trophogenic layer, when compared to external phosphorus supply (1.5 $mg/m^2/day$) is far from clear. Only a portion of the phosphorus internal supply from the sediment will find its way to the trophogenic layer. Normally most of the sediment-released phosphorus will remain locked in the hypolimnion, and enrichment of the epilimnion, by sediment phosphorus will depend on lake mixing. Thus a more accurate evaluation of the evaluation of the relative importance of sediment phosphorus supply to lake productivity must await a better understanding of the mixing mechanisms.

Winter mean phosphorus content at Lake Sammamish appears to be controlled by iron precipitation. The prevailing anoxic conditions in the lake during late summer and fall bring about large increases in hypolimnetic iron concentrations (Horton 1972), which upon autumn overturn cause rapid disappearance of phosphorus from the water column. Low total iron concentrations in the hypolimnion of Lake Washington likely account for the low removal of phosphorus following autumn overturn and maintenance of higher winter phosphorus concentrations in Lake Washington.

Sediment Characterization

Surface sediments (surface to 10 cm deep) were collected with a Peterson dredge in the four lakes. Surface sediments in Lake Sammamish were sampled more extensively (26 samples from 26 different depths) than those of the other three lakes where only 4-6 samples were collected.

Cursory examination of the sediments prior to analytical determinations revealed striking apparent differences in composition from the upper and lower portions of the Lake Washington Basin. Sediments from the lower basin (Lakes Washington and Sammamish) were generally fine-grained, highly organic (occasionally having an odor of H_2S), and black to brown in color. Oligochaete worms were observed in many samples. Sediments originating in Chester Morse and Findley Lakes, on the other hand, were generally lighter in color, and composed of distinctly coarser materials. These sediments were collected under apparently mildly oxidizing conditions.

Sediment water content values were high and showed few variations from lake to lake. Values were in the 70-80 percent range for most samples. The generally coarser nature of the upper basin lake sediments is not reflected in the moisture content values.

Particle size analysis data for the sediments are shown in Table 4, expressed as a weight percentage of the moisture free sediments. These data indicate drastic differences in the depositional environments of the lakes of the upper and lower basins. A significant discrepancy in size distribution is also noted in the comparison of dispersion methods employed in the particle size distribution analyses. Sediments dispersed ultrasonically appear to be composed of coarser materials than those dispersed using $NaPO_3$. The ultrasonic dispersion method yields perhaps the best results in terms of the actual environmental size distribution of the sediments. Chemical dispersion methods are employed as a matter of course in most size analysis techniques and are best suited for comparisons of data with previous studies. As shown in Table 4, the sediments of the upper basin lakes are noticeably coarser than those of the lower basin lakes. Most of the differences in sediment size distribution among the lakes probably arise from differences in the geologic nature of the materials on the slopes surrounding the lakes. These differences (Vashon glacial till and Alderwood soils around Lakes Sammamish and Washington; tertiary bedrock and rocky soils around Chester Morse and Findley Lakes) in parent materials and soils surrounding the lakes are no doubt enhanced by the generally steeper sloped and harsher climatic conditions of the upper basin. The influence of human activities in the lower reaches of the basin also accounts for some variations in sediment size distribution. Surface sediments from Findley Lake were totally unlike any others examined during the course of this study. Most of the samples were relatively light in color, and had a pulpy, sandy texture. Smear slides of the coarse fraction indicated the presence of a very large amount of diatoms. The siliceous nature of Findley Lake sediments was reflected in the cation exchange capacity (CEC), x-ray and chemical analyses of these sediments.

The CEC of the sediments (Table 4) with the exception of the Findley Lake sediments show little variation among the lakes. Dilution of minerals and

organics of high exchange capacity with silica may be the main reason for the low CEC of the Findley Lake sediments. CEC data indicate a general parallel with soil exchange data in the lower basin, although the exchange capacities of the lake sediments are noticeably higher, due to the relatively large amount of organic matter in the sediments.

X-ray diffraction analyses of the clay (<2 μ) fraction of the surface sediments indicated that most of the detrital minerals (montmorillonite, illite, kaolinite, chlorite, quartz, vermiculite, feldspar, and mixed layer minerals) found commonly in lacustrine sediments were represented in the samples. The data appeared to closely reflect the mineralogical composition of the soils and rocks on the surrounding lake basins. X-ray analyses of the Findley Lake sediments gave inconclusive results as a result of the masking effect of the large amorphous silica present in the samples.

Chemical analyses of lake sediments for Fe, Mn, Ca, Mg, Na, and K are presented in Table 5. With the exception of Findley Lake sediments, all sediments appear to have the same chemical composition. Chester Morse Lake sediments had the greatest content of iron, with Lakes Sammamish and Washington about the same, and Findley Lake generally lower. Lakes Washington and Chester Morse had a higher manganese content than Lakes Sammamish and Findley.

Results of analyses for total carbon, nitrogen, and phosphorus in samples of surface sediments are presented in Table 6. The larger carbon concentrations and the higher carbon/nitrogen ratios in the sediments of Findley and Chester Morse Lakes when compared with those values in the lakes of lower elevation appear to reflect trophic status and are most probably due to differences in allochthonous and autochthonous inputs. In the two oligotrophic lakes, most of the organic carbon in sediments is derived from allochthonous sources which are relatively resistant to mineralization, partially as a result of low nitrogen availability. Autochthonous sources are more significant in the mesotrophic lakes. The phosphorus content of all lake sediments was relatively high, with the highest occurring in Lake Washington. The smaller nitrogen/phosphorus ratios observed in the sediments of Lake Washington are undoubtedly due to the higher sediment phosphorus concentration measured in the lake.

Sediment-Water Nutrient Exchange

Six sediment water columns (in transparent and opaque plastic cylinders) are currently used in Lake Sammamish to simulate nutrient regeneration (phosphorus, nitrogen, carbon) in the sediment-water interface, as a function of measurable environmental and experimental parameters and processes. The columns have been placed at two different depths, 6 m and 10 m, and sampled periodically for nutrient levels and other parameters. The use of two different lake depths and of transparent and opaque columns was undertaken to elucidate the effect of any photosynthetically derived oxygen on the sediment nutrient release. The apparatus design is presented

In Figure 6. It consists of a 3.65-m long, 15.5-cm diameter, plexiglass cylinder, attached perpendicularly to a circular stabilizer base of plastic or stainless steel, 76-cm diameter. The stabilizer base is attached 65 cm above the bottom of the cylinder. Holes were drilled, at regular intervals to the top of the cylinder and serum caps fitted with glass tubing were inserted so that sampling could be carried out from the boat by means of permanently fixed polyethylene tubing connected to the glass tubing of the serum caps. The top 30.4 cm of the column was bored and a plexiglass piston added so that sampling could be made without simultaneous introduction of extraneous water or opening the column to the air. The piston consisted of two circular plexiglass pieces, glued together with a rubber O-ring between them. The total volume of the column was around 57 liters and it had a volume fluctuation capacity of 5 liters. To position the column in the lake was a simple matter. With the piston removed the column was lowered over the edge of the boat and allowed to fall almost freely. The column was inserted in the sediment to a depth of 65 cm. Once in position the piston was fitted, the sampling tubing was attached and the column was ready for operation. The column was sampled at three different depths, 0.9, 1.8, and 2.7 m from the sediment surface. Initially the columns have been allowed to go anaerobic by clamping off the ends of the sampling tubes.

At various intervals samples are removed from the columns by means of a vacuum pump. Samples are collected under vacuum to minimize oxygen contamination. Refilling of the columns is accomplished by supplying nitrogen gas-purged lake surface water at the top of the cylinder under nitrogen gas pressure.

Following long experimentation, preliminary results have been encouraging (Monahan 1973). Figure 7 depicts oxygen depletion and total phosphorus release in one of the *in situ* sediment-water columns as a function of time. For purpose of comparison the results of oxygen depletion and total phosphorus release in laboratory columns and in Lake Sammamish hypolimnion are also included (Horton 1972). It is of interest that the total phosphorus released in the *in situ* column is practically identical to that released in the lake hypolimnion at the peak of the lake stagnation period. The total phosphorus released in the laboratory column is nearly double of that observed in the lake columns and it is most probable due to the higher temperatures observed in the laboratory (20-26°C) as compared to those measured in the lake (6-10°C). Another factor could be that in the laboratory the columns were continuously mixed by means of nitrogen gas delivered 10 cm above the sediment water interface.

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Table 1. Aquatic mineral cycling activities by site and year.

Activity	Lakes and year of study			
	Chester Morse	Findley	Sammamish	Washington
<i>Inputs-Outputs</i>				
Streams ¹	a	b	1970-present	c
Precipitation ²		b	1971	
<i>Lake System</i>				
Water columns ³	1971-present	1971-present	1970-present	d
Sediment ⁴	1971-present	1971-present	1971-present	1971-present
Sediment-water exchange ⁵			1971-present	
Sedimentation (traps) ⁶	1973	1973	1973	1973

¹Parameters measured are flow, temperature, pH, conductance, NO₃-N (+NO₂-N), NH₃-N, soluble (0.45μ millipore) organic N, ortho PO₄-P and Si, total P, Si, and organic N, alkalinity, K, Na, Ca, Mg, Fe, Mn, SO₄ and Cl. Measurements were made at monthly and/or biweekly intervals.

²NO₃-N, total N and P, major cations and anions.

³Parameters measured at monthly or biweekly (summer months) intervals included those listed under (1) above plus DO and light penetration. The water column was sampled at the surface, one meter off the bottom and at regular intermediary depths. In addition, the photic zone was sampled at 1, 15, and 30 percent light penetration depths.

⁴Sediment analysis included particle size fractionation, CEC measurements and clay mineral characterization. In addition, the C, N, P, K, Na, Ca, Mg, Fe, and Mn contents of sediments were measured.

⁵The release of NO₃-N (+NO₂-N), NH₃-N, soluble ortho PO₄-P, organic N, Fe, Mn, total P, N, Fe, and Mn were measured. Other parameters included pH, DO, conductance, alkalinity and Na, K, Ca, and Mg contents.

⁶The weight of sedimented material at various depths of lake water columns at monthly and/or biweekly intervals is measured. Sediment analysis includes determination of C, N, P cellulose/lignin, and metal contents.

a. Stream inflow and outflow water quality data in Chester Morse Lake have been monitored by Q.J. Stober and J. G. Malick.

b. Stream and precipitation (snowpack) inputs have been determined intermittently.

c. The two major contributors to Lake Washington have been monitored by the City of Seattle and USGS.

d. The water column was analyzed intermittently for parameters not measured by Dr. Edmondson (metals).

Table 2. Aquatic physical and chemical data being entered in data bank by name of investigator, year and site (LS = Lake Sammamish, LW = Lake Washington, LF = Lake Findley, LCM = Lake Chester Morse).

Name of investigator	Year	Site	Parameters
Lanich, J. S.	1972 (M.S. Thesis)	LS, LW, LF, LCM	Sediment-particle size distribution and CEC
Bauer, D. H.	1971 (M.S. Thesis)	LS, LW, LF, LCM	Sediment--C and N contents
Horton, M. A.	1972 (M.S. Thesis)	LS, LW, LF, LCM	Sediment--P, K, Na, Ca, Mg, Fe, and Mn, contents. Water column temperature, DO, pH, soluble ortho PO ₄ -P and Fe, total P and Fe
Emery, R. M.	1972 (Ph.D. Thesis)	LS	Water column--NO ₃ -N, NH ₃ -N, organic N, soluble ortho PO ₄ -P, and Si, total P, inorganic C, pH, DO, light penetration
Moon, C. E.	1973 (M.S. Thesis)	LS, inputs and outputs	Rain water--NO ₃ -N and total P. Stream water--NO ₃ -N, soluble PO ₄ -P, total P, temperature, pH, and flow.
Hendrey, G. R.	1973 (Ph.D. Thesis)	LF, LCM	Water column--NO ₃ -N, NH ₃ -N, organic N, soluble ortho PO ₄ -P and Si, total P, inorganic C, metals, pH, DO, temperature, and light penetration
Others	1971-1973	LS, LW, LF, LCM	Stream water--nutrients, metals Water column--metals

Table 3. List of students currently collecting physical and chemical data, by site and parameter (LS = Lake Sammamish, LW = Lake Washington, LF = Lake Findley, LCM = Lake Chester Morse).

Name	Site	Parameter
Barnes, R. S. and P. Birch	LS, LW, LF, LCM	Sediment traps--C, N, P, Si, metals plus cellulose/lignin
Pederson, G. L.	LF, LCM	Water column-- nutrients, pH, temperature, DO, light penetration, and inorganic C
Rock, C. A.	LS, Issaquah Cr.	Water column--nutrients, Fe, pH, temperature, DO, light penetration, and inorganic C. Stream water--total P, Fe, Si, and N (NO ₃ -N, NH ₃ -N, organic N)
Monahan, F. C.	LS	Sediment--water exchange; nutrients, metals, pH, DO, alkalinity and conductance

Table 4. Particle size distribution and cation exchange capacities (CEC) of surface sediments from lakes of Lake Washington drainage.

Lake	CEC ¹ (meq/100g)	Size Distribution Percent					
		NaPO ₃			Ultrasonic		
		Sand	Silt	Clay	Sand	Silt	Clay
Findley	10.9	42.3	34.2	23.5	44.7	31.9	23.4
Chester Morse	25.0	30.2	51.4	17.6	36.9	55.5	7.7
Sammamish	23.9	13.0	60.5	26.9	14.7	71.9	12.7
Washington	20.8	2.3	65.5	33.2	2.4	84.0	13.4

¹Values are in terms of oven-dried (104°C) sediment.

Table 5. Chemical analysis of surface sediments from lakes of Lake Washington drainage¹ (mg/g).

Lake	Fe	Mn	Ca mg/g	Mg	Na	K
Findley	28.2	0.9	7.6	7.8	16.4	2.0
Chester Morse	90.6	2.8	10.7	20.4	27.3	3.9
Sammamish	52.0	1.1	8.1	15.7	21.2	2.9
Washington	59.5	1.7	8.4	17.9	22.6	3.3

¹Values are in terms of oven-dried (104°C) sediment.

Table 6. Average total carbon, nitrogen, and phosphorus contents of surface sediments from Cedar River drainage lakes¹.

Lake	C ² (percent)	N mg/g	P mg/g	C/N	N/P
Findley	8.98	5.55	1.09	16.18	5.14
Chester Morse	6.12	3.71	1.56	16.41	2.37
Sammamish	5.11	4.82	1.32	10.60	3.65
Washington	4.22	3.71	2.13	11.37	1.74

¹Values are in terms of oven-dried (104°C) sediment.

²The sediments from all four lakes contain less than 0.1 percent CO₃-C on an oven-dried basis.

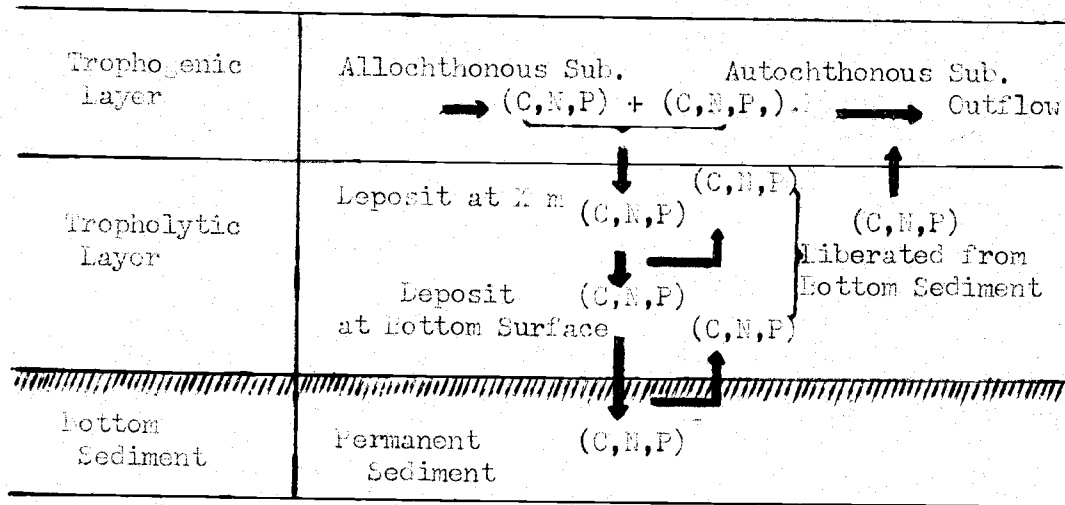


Fig. 1. Aquatic Mineral Cycling

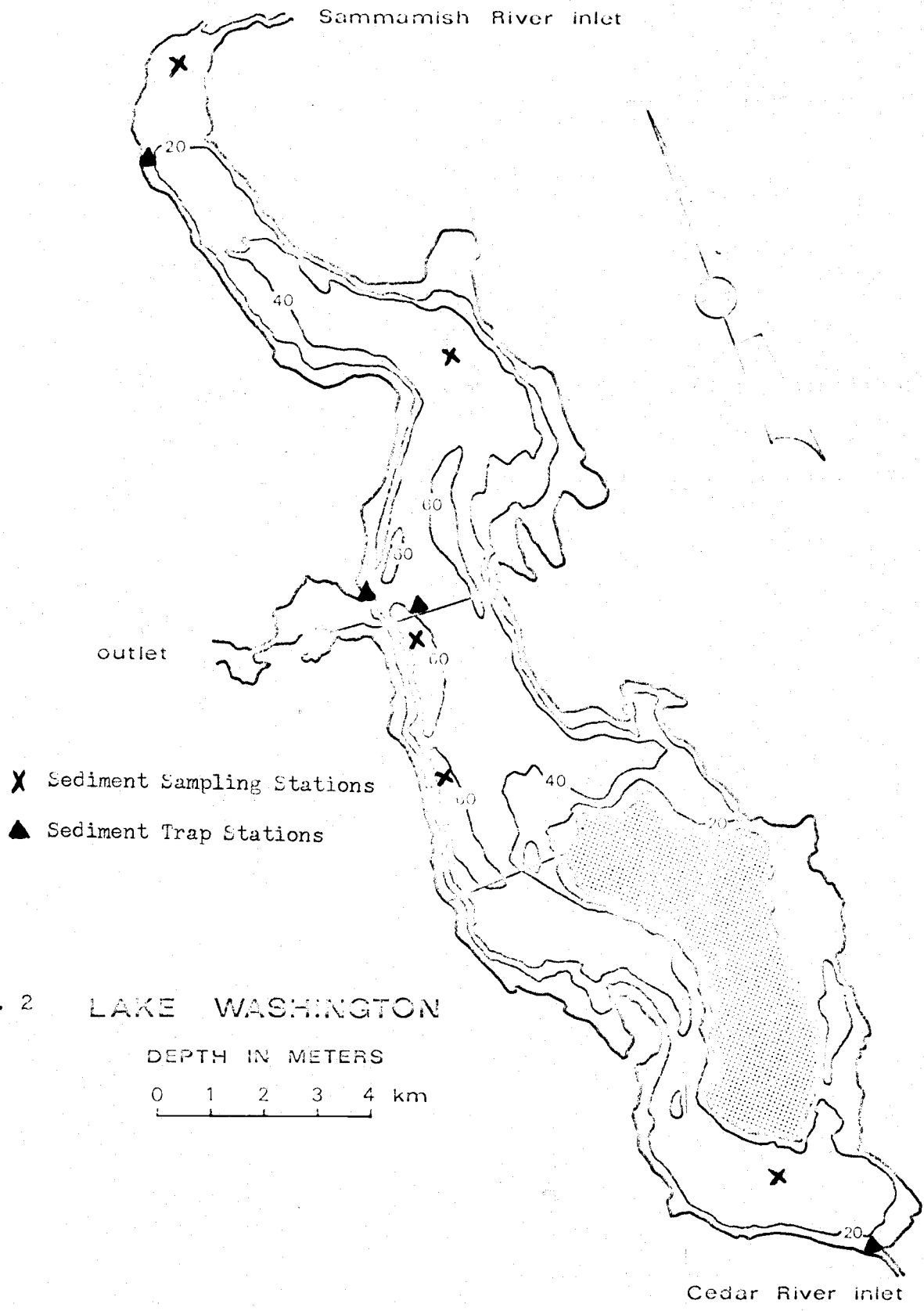
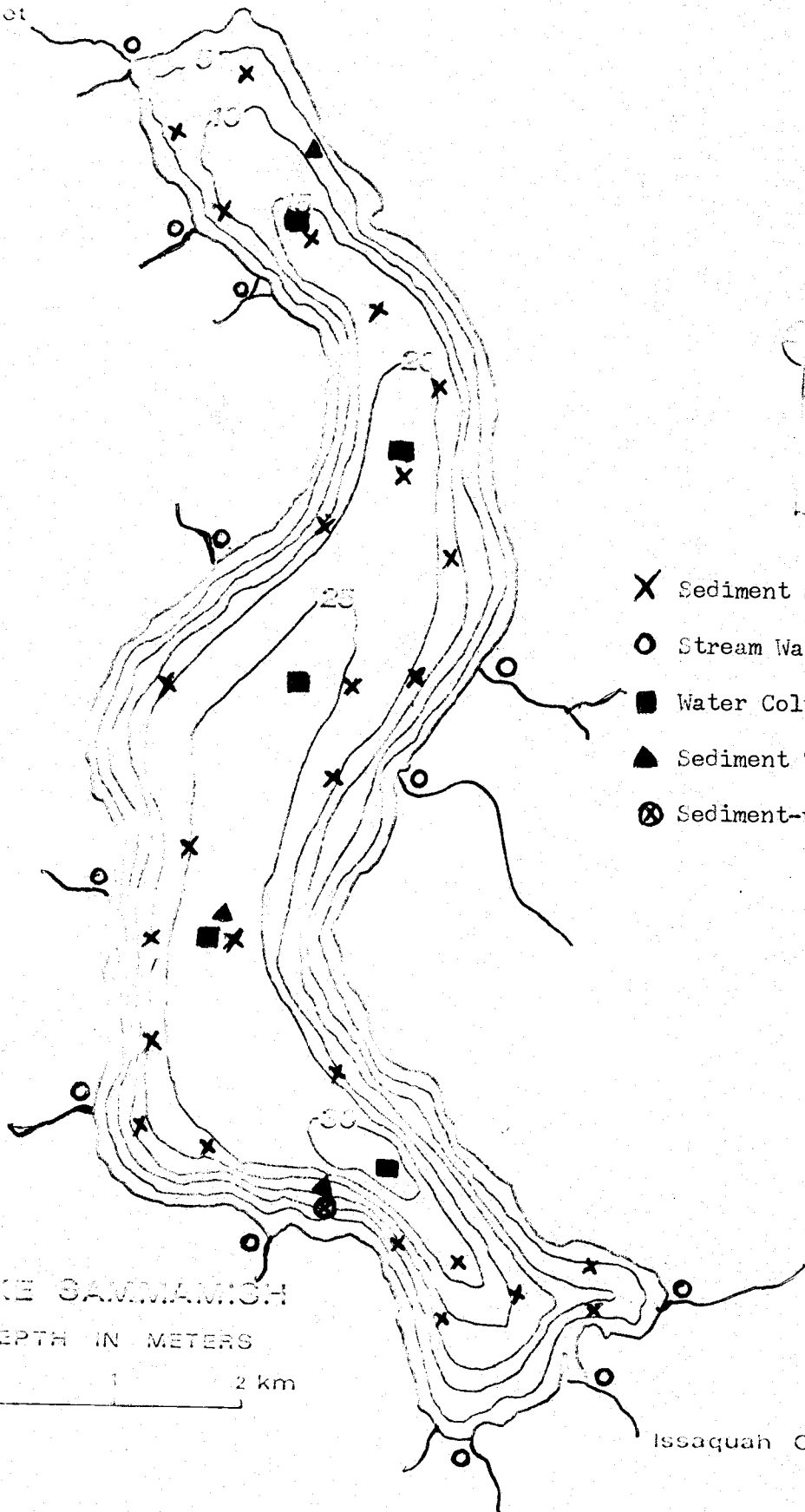


FIG. 2 LAKE WASHINGTON

DEPTH IN METERS

0 1 2 3 4 km

outlet

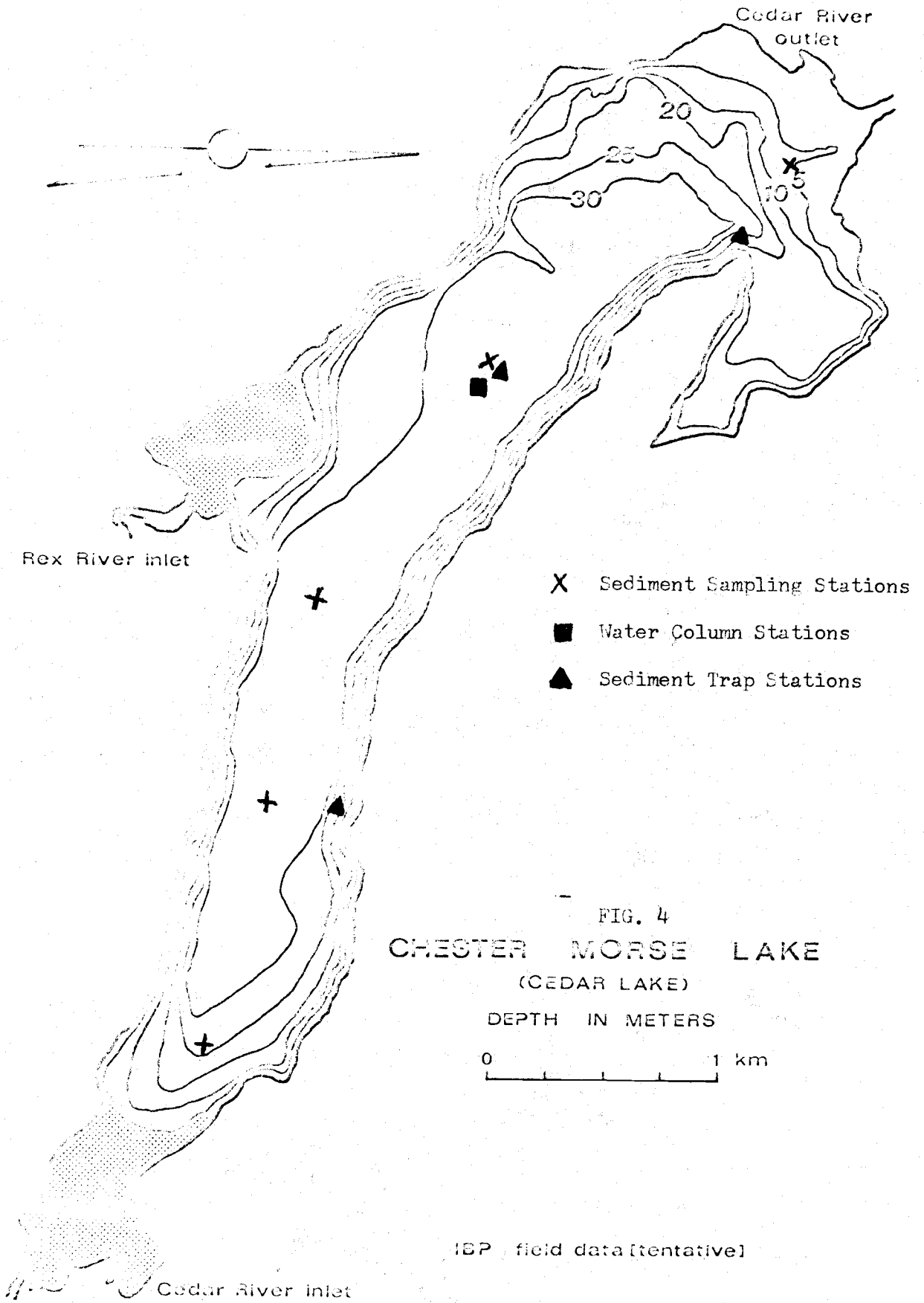


- X Sediment Sampling Stations
- Stream Water Quality Stations
- Water Column Stations
- ▲ Sediment Trap Stations
- ⊗ Sediment-water Column Stations

FIG. 3 LAKE SAWMANICH

DEPTH IN METERS
0 1 2 km

Issaquah Creek



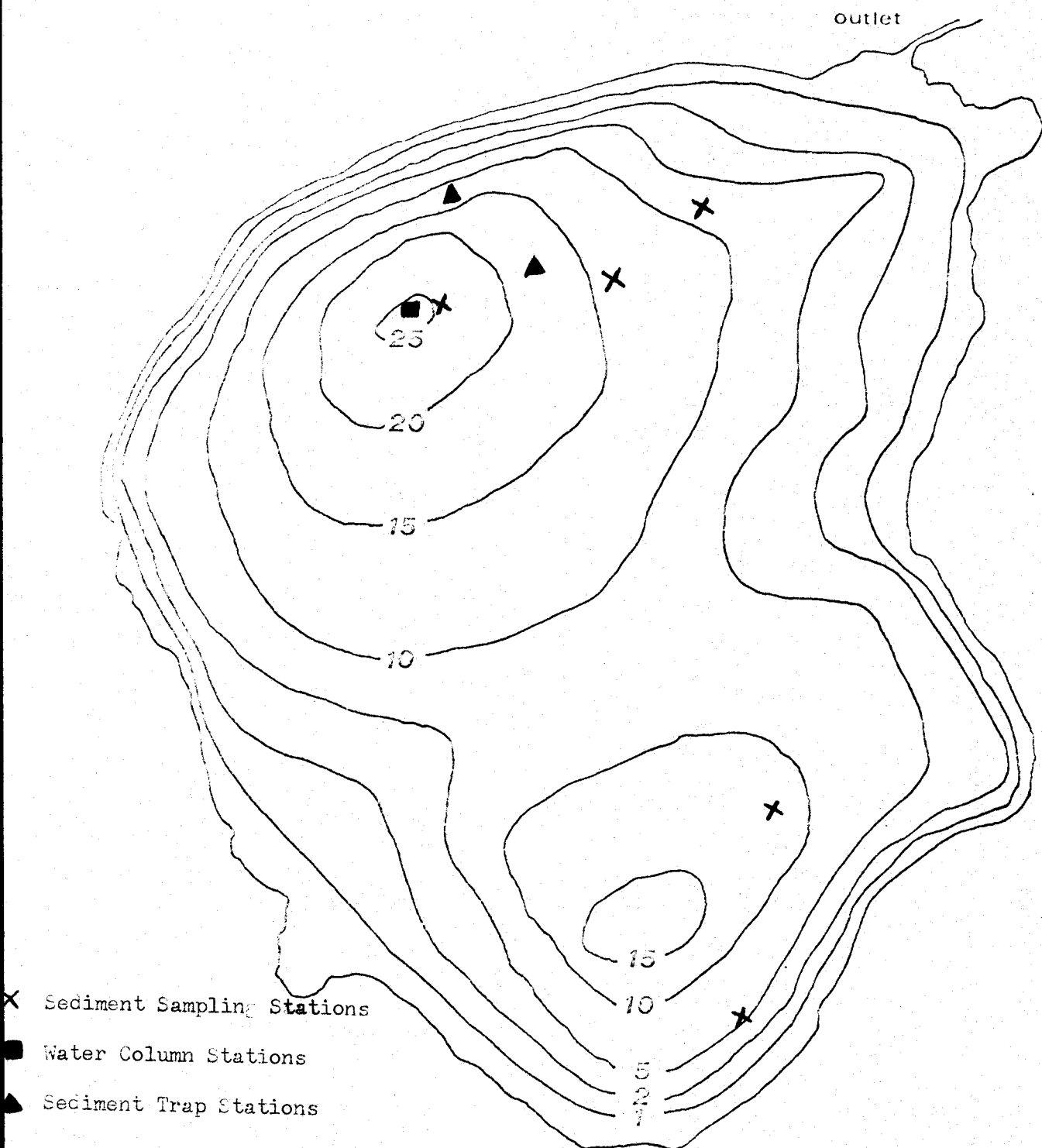


FIG. 5 FINDLEY LAKE

DEPTH IN METERS

0 meters 100

(B.P. field data (tentative))

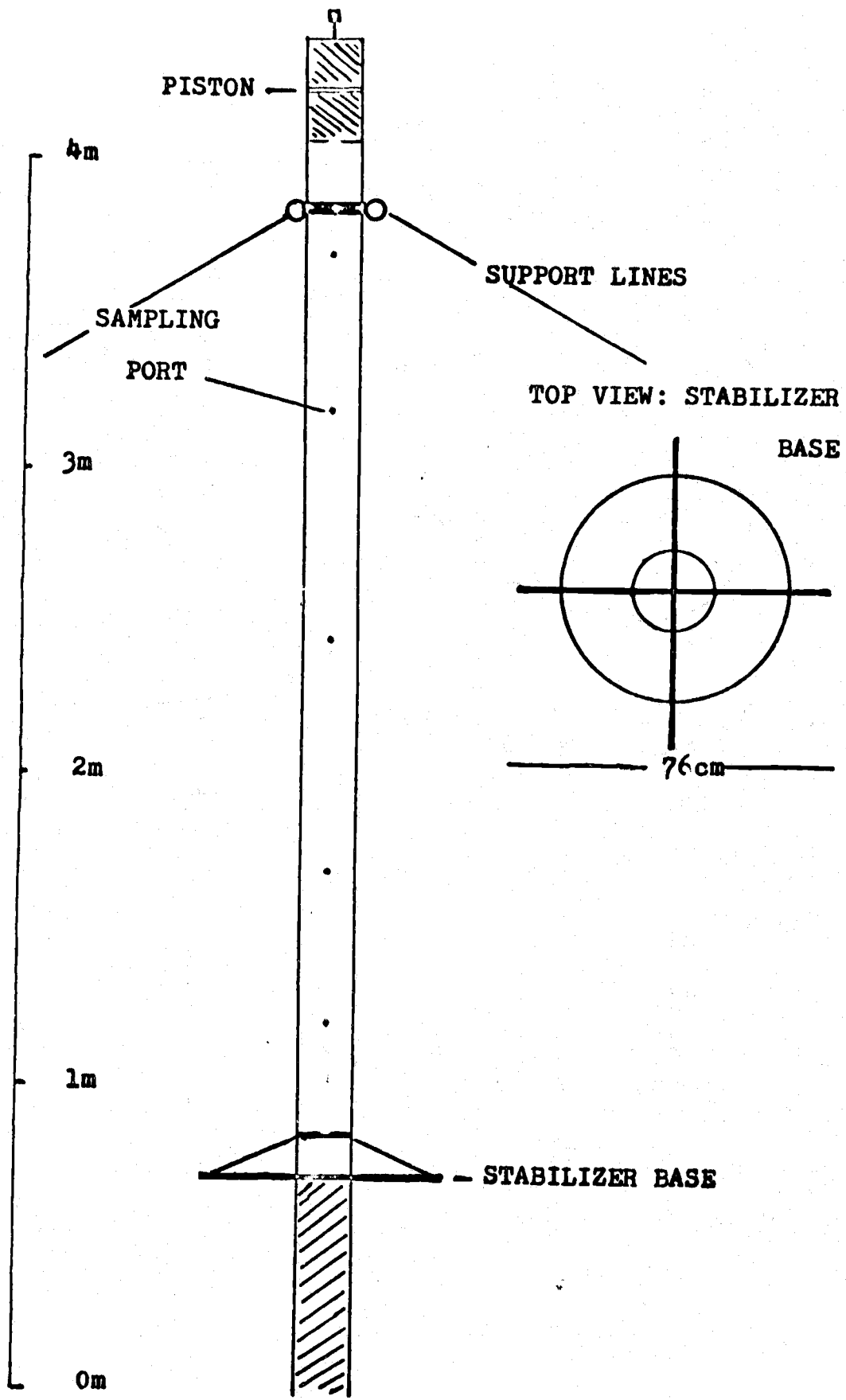


Figure 6 Experimental Apparatus for in situ Sediment-Water Interchange Studies

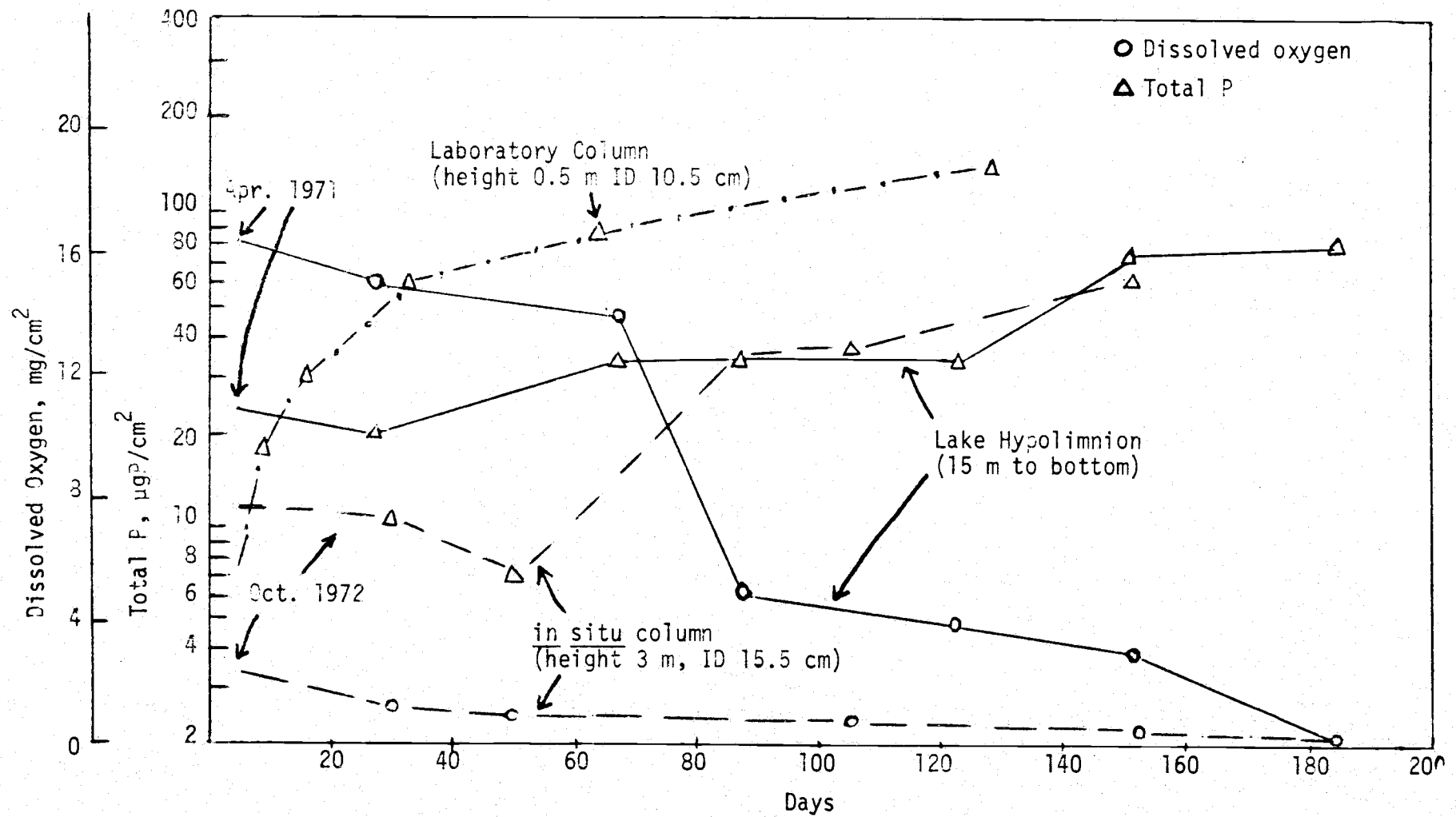


Figure 7 Oxygen and Total P Concentrations in Lake Sammamish Sediment-Water Columns