

LAKE SEDIMENTS

Characterization of Lake Sediments and Evaluation of Sediment-Water
Nutrient Interchange Mechanisms in the Upper Klamath Lake System

by

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CHARACTERIZATION OF LAKE SEDIMENTS AND EVALUATION OF SEDIMENT-WATER
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Abstract. The characteristics of the bottom sediments of the eutrophic Upper Klamath and Agency Lakes are described and their possible contribution in supplying algal nutrients is discussed.

The thickness of the bottom sediments over consolidated deposits varied between 14 and 32 meters below the lake surface at the time of measurement. Carbon-14 dating indicated an age of about 4200 years at the 90-cm level.

The C, N, P, Fe, Al, Mn and interstitial water composition of ten 150-cm cores indicated appreciable variability from core to core in concentration change of elements and nutrients with depth in the sediment.

The net effect of biological, chemical, and physical processes which take place at the sediment water interface was examined by the determination of soluble nutrients in the sediment interstitial water. High concentrations of orthophosphate, ammonia, and total Kjeldahl nitrogen occurred in some of the interstitial water.

Nutrients were released when Oscillatoria princeps and attached sediment rose to the surface of the lake. (Key words: Bottom sediments; cores; C¹⁴ dating; interstitial water; nutrient interchange; Oscillatoria princeps; Upper Klamath Lake.)

INTRODUCTION

Lake bottom sediments have been recognized as nutrient sources or traps which may either release or remove algal nutrients depending upon the biological, chemical, or physical processes occurring in the ecosystem.

In order to devise methods for the reduction of algal growth in lakes, the National Eutrophication Research Program of the Water Quality Office, Environmental Protection Agency has conducted research to learn what occurs at the sediment-water interface in various lake systems relative to the uptake and release of nutrients.

The intense growth of algae appearing for about eight months each year in the highly eutrophic Upper Klamath and Agency Lakes in Oregon has been attributed in part to release of nutrients from the bottom sediments to the overlying water. An investigation was initiated in 1966 to evaluate the influence of the lake sediments on algal growth and to determine the conditions under which nutrient release or uptake might occur. From limnological information it was hoped that appropriate laboratory and field tests could be designed to yield quantitative data on the nutrient release or uptake by sediments.

Although several types of tests have been proposed in the literature, application of the results to natural systems has not been demonstrated. Nutrient concentrations in sediments have often been expressed in terms of total phosphorus, nitrogen, and carbon, but it is the availability of the different nutrient compounds of these elements under the varying ecological conditions of the lake system that must be measured. The trend has been to apply soil and biochemical test procedures to evaluate

lake bottom sediments for nutrient "availability." These laboratory tests may be applicable in calculations of rate of recovery of a lake following restoration measures, but they will require future evaluation (Kemp and Mudrochora, 1970; Williams, Syers, Harris and Armstrong, 1970).

In an effort to determine nutrient availability in sediments and to evaluate the overall effect of the biological, chemical, and physical processes taking place at the sediment-water interface, as well as in the underlying sediment, it was decided to determine the concentration of the soluble nutrients in the interstitial water from Upper Klamath and Agency Lake sediments. If appreciable concentrations of soluble nutrients were present, it is likely that they would be transferred to the overlying water by currents caused by wind, fish, and boats; eddy and molecular diffusion; mixing by benthic organisms; gas evolution from the sediments; algal growth on the sediments; etc. Harriss (1967) has stated, "The composition of interstitial waters from river and lake sediments is controlled by a complex interaction of the ground water recharge system, mineralogical dissolution and precipitation reactions, biological activity, and the degree of physical interaction between the sediment and overlying water." He studied the soluble silica and chloride concentration in interstitial water from freshwater sediments and found that chloride concentration changes were useful for studying diffusional processes in sediments. Several investigators have measured soluble constituents in interstitial water for the purpose of studying mineral-water equilibria and mineral transformations. (Sutherland, Kramer, Nichols and Kurtz, 1966). Gorham (1961) suggests that ions would

diffuse from the interstitial water to the overlying water particularly during stormy periods. Sullivan (1967) has shown that orthophosphate increases in the sediment interstitial water from Lake Bloomington during stratification with a decrease following turnover.

Since it has been proposed that excessively eutrophic lakes may be restored in some cases by dredging to remove the top layer of nutrient-rich sediment, it is of interest to evaluate nutrient concentrations and availability in sediments at various levels below the sediment surface. The effect of dredging upon water quality in lakes has not been carefully studied, nor has the effect of dredging been predicted from examination of the available nutrients in sediment cores. After dredging, it is quite possible that the new sediment surface could release more nutrients to the water than the original surface. If so, dredging would not be beneficial except to increase the storage capacity of the lake and possibly to keep the water slightly cooler. On the other hand, a layer might be reached below the sediment surface which is either nonadsorptive or perhaps adsorptive to phosphate or other nutrients, so that dredging could be applied as a lake restoration method.

It is the purpose of this paper to report the results of studies on sediments and sediment-water nutrient interchange processes in the Upper Klamath Lake system. To accomplish the objectives described the sediments were evaluated for physical properties (particle size, depth of recent sediments, stratification, deposition rate), chemical composition, mineralogical composition, bacteriological characteristics, and nutrient content of sediment interstitial water at the surface and at depths in

cores down to about 150 cm. The results of a survey of the benthos in the sediment throughout the lake system has been described by Hazel (1969). A group headed by Dr. R. Y. Morita, Oregon State University has studied concurrently the influence of bacterial activity upon the eutrophication process in Upper Klamath Lake and will report the results elsewhere.

DESCRIPTION OF LAKE SYSTEM AND WATERSHED

Upper Klamath and Agency Lakes are located in the structural valley, the Klamath Graben, in Southern Oregon east of the Cascade Mountains (Figs 1, 2). The lake system, which covers an area in excess of 120 square miles (31,000 ha), is one of the largest in the Western United States. Water level is regulated by a dam constructed in 1917. The surface elevation is maintained between 4,136 feet (1261 m) and 4,143 feet (1264 m) resulting in a mean depth of the lake of 8 feet (2.44 m). The watershed occupies an area of about 3,800 square miles (985,000 ha), much of which is located in mountainous volcanic areas or rolling regions covered with volcanic pumice deposits derived from formation of the Crater Lake Caldera. Most drainage entering Upper Klamath Lake is either from Agency Lake or through the Williamson River. Agency Lake receives the drainage from the mountainous northwest area of the watershed by Wood River, its major tributary. The Williamson-Sprague River system, the largest tributary in the watershed, drains the eastern and northeastern areas of the watershed. It enters the northeast end of Upper Klamath Lake. Upper Klamath Lake discharges into

the Klamath River which eventually enters the Pacific Ocean in Northern California.

The lake is used extensively by waterfowl during the fall and spring migrations in the Pacific Flyway. A fair-sized population of ducks and geese is native to the immediate area, but the largest numbers are represented by the transient populations. Rainbow trout (Salmo gairdneri) are common in the lake in early spring but later migrate into the incoming tributaries and spring areas. Two genera of Cyprinidae, Blue chub (Gila bicolor) and Tui chub (Siphateles bicolor), constitute 90% of the total fish population (Bond, Hazel, and Vincent, 1968).

The elevation of the watershed varies generally from approximately 4,200 feet (1281 m) to 8,000 feet (2440 m) with some of the higher peaks reaching elevations greater than 9,000 feet (2745 m). The Cascade Mountains border the watershed to the west and create a rain shadow over much of the area. Precipitation varies with location in the watershed; the sheltered, lower elevations receive 10-30 inches (25-76 cm) annually and the higher regions 60 inches (152 cm). Most precipitation occurs between October and March. In the city of Klamath Falls at the south end of the lake, the sun shines approximately 90% of the time in July and 33% of the time in January, the wettest part of the year.

Vegetation varies, the mountainous regions having forests of Douglas-fir, ponderosa pine, lodgepole pine and true firs. The distribution of forests depends upon climatic conditions and geographic

location. Large areas are occupied by grass-shrub communities which are most commonly found in the open flatland associated with large pumice deposits. Marshes are extensive in parts of the watershed. The Sycan and Klamath marshes cover the basins of former Pleistocene Lakes and extensive marsh areas surround much of the present Upper Klamath and Agency Lakes. Since World War I large sections of marsh have been reclaimed for agricultural utilization. The flora associated with the marsh area is a typical sedge-reed community.

CHARACTERIZATION OF SEDIMENTS IN UPPER KLAMATH AND AGENCY LAKES

To attain the objectives outlined in the introduction, it was necessary to examine the surface and underlying sediments throughout the lakes and to determine the lake conditions to which the sediments were subjected. The limnology of the lake system has been reported (Gahler, 1969). The pH of the water varied from 7 to greater than 10, temperature from 0° to 26°C, and dissolved oxygen from less than 1 to about 16 mg per liter.

Physical Nature

The bottom sediments from Agency Lake are darker and much firmer than those in Upper Klamath Lake. In fact, it is impossible to obtain a core longer than 1.7 m with a modified Livingstone (1967) piston-type corer with a plastic film liner. Upper Klamath sediments are much more ooze-like, especially in the bays. In Howard Bay (09d in Fig 1) it is possible to push a 10 x 10 cm square end post by hand down into the mud 4 to 5 m.

The sediments at sites 09d, V7d, and Y1b are composed of diatoms, organic matter, and mineralogical components consisting of feldspar, chlorite, vermiculite, and mica (Wildung, Blaylock, Routson, and Gahler; 1970).

The water content of the sediments throughout the entire system is high, from 88 to 92% at the water interface and from 80 to 88% four feet (1.2 m) below the interface. At locations V19b and Y1b the water content decreases to 55-65% at four feet. A layer of pumice-like material occurs at this level at both locations. Since the sediments contain so much water, the density is low, 1.09 g/cc for Agency Lake and 1.04 g/cc for Upper Klamath Lake (Howard Bay) surface sediment.

Based on particle size distribution, the two sediments from Upper Klamath Lake are characterized as silty clay, as shown by the data in Table 1 (Volk, 1968). The cation exchange capacity is in the range of 30 to 55 meq/100 g.

The temperature of the sediment exhibits considerable seasonal variation. In winter, the surface of the sediment is near 0°C, depending upon the location, and as high as 22°C in the summer in the middle of the lake.

The pH of sediment surface grab samples throughout the lakes at different times of the year varies from 6.1 to 7.8. Measurements of pH were generally made by insertion of the electrodes directly into the fresh sediment in the field.

The sediments are mildly reducing in nature, the E_h varying from -0.1 to +0.3 volt. The odor of hydrogen sulfide was thought to

be detected only once or twice in the sediments. Undisturbed sediment surface samples taken with a Jenkins corer do not reveal the usual light brown oxidized surface and reduced black layer below the surface as often described in the literature.

Thickness of Recent Sediments

The thickness of the very soft, fine-grained bottom sediments overlying the geologically older deposits in the lakes was surveyed in June 1968 by S. D. Schwarz of Geo Recon Inc. for the National Eutrophication Research Program. A 8.5 KHz, 1500 watt high energy recording sonar system and a 100 cycle, 16 joule Pulser system were used simultaneously for this measurement. The first horizon that has significant continuity occurs at a depth of 48 feet (14.6 m) to 107 feet (32.6 m) below the lake surface and is believed to represent the approximate base of recent, unconsolidated lake deposits. The depth in feet of this horizon is marked along the traverse lines of Figure 3. Several shallower reflecting horizons are discontinuous and are believed to represent geologic structure within the recent lacustrine deposits. Older alluvial deposits are believed to be the principal deposits underlying the areas of dotted traverse lines on Figure 3; the numbers indicate the depth in feet of overlying material referenced to the lake surface in June 1968. At the time of the survey the lake depth averaged 7 feet (2.1 m) to 8 feet (2.4 m) with occasional localized holes to 37 feet (11.3 m).

Core samples taken with a modified Livingstone corer indicate that there is very little difference in the sediment at the surface and at

the 1.5 meter level below the interface. The layer found at about 100 cm at locations Y1b and V19b represents the only stratification observed in all the cores taken in Upper Klamath Lake except at V19b where some changes in color and texture were noted.

Rate of Deposition

The most common methods for obtaining information on deposition and eutrophication rates are by paleolimnological techniques or by carbon-14 dating. Ideally, both methods should be utilized simultaneously, but this was not possible. Three cores were taken with a 2-inch modified Livingstone piston-type corer lined with mylar film at sites R19b, V7d, and Y1b. Sections were removed at points ± 5 cm both sides of the 15, 30, 60 and 90-cm depths of the core. These samples were dated by the Radioisotopes and Radiations Laboratory at Washington State University. The results are shown in Table 3.

The age of the sediment south of Buck Island (location V7d) in the Upper Klamath Lake at a core depth of 90 cm is about 4110 years. At the outlet of the lake (Y1b) it took 3000 years to deposit a 15-cm layer of sediment between the 60 and 90-cm level, but only about 100 years to deposit the layer at 30 to 60 cm. The overall rate of sediment deposition, using the dates at the 30-cm and 90-cm levels at site Y1b averages about 0.22 mm per year. The deposition rate is about the same at the Buck Island location.

No simple explanation can be given for the dating data at coring location R19d where the sediment at 60 cm is shown to be significantly older than that at 90 cm. Chatters (1968) states that there have been

cases where movements of earth structures move material of an older age over the more recent material.

Chemical Composition

Total phosphorus varied in surface sediment samples from 0.022 to 0.12% on a dry weight basis or about 0.002 to 0.01% on a wet weight basis (representative data are shown in Tables 4 and 5). The wet weight values more clearly represent the actual phosphorus concentration at the sediment-water interface. A separate study of different phosphorus compounds in the sediments throughout 1969 and 1970 was made by Battelle-Northwest under contract to FWPCA (Wildung, et al., 1970). Analyses of Ekman dredge samples taken from May 1969 to July 1970 showed that the total, inorganic, and organic phosphorus concentrations changed throughout the year at locations 09d, V7d, Y1b and L33d. The organic phosphorus fraction in the Upper Klamath Lake sediments ranges from 44 to 70% of the total phosphorus concentration whereas that at the Agency Lake location varied from 29 to 54%. A decrease in total and inorganic phosphorus which occurred during 1969 from May to August corresponded to a heavy bloom of Aphanizomenon flos-aquae; a decrease in April 1970 coincided with an extensive increase in diatom numbers (Gahler, 1969), suggesting an equilibrium shift as nutrients were used.

The total phosphorus content in surface sediment did not increase appreciably with depth of water. Samples taken along transects across areas where deeper holes occur in the lake near Bare Island (022) showed no significant increase in phosphorus; 0.072% P at 3 m to 0.075% P at

8 m along a transect northward of the island and 0.062% P at 4 m to 0.073% at 15 m along a transect south of the island.

The total carbon content varied from 3.7 to 10% (dry basis), with the highest values in Agency Lake and Howard Bay area of Upper Klamath Lake. Nitrogen content was 0.46 to 1.3%. The carbon and nitrogen in the sediment increased to a level of 16.6% and 1.6%, respectively, in a sample taken from a Wocus marsh area in the northern part of Howard Bay.

No carbonate occurred in the surface sediments indicating that all carbon was present as organic matter. The approximate percent organic matter can be obtained by multiplying the total carbon value by the factor, 1.7. The C/N ratios (7 to 10:1) are indicative of stabilized organic matter and absence of polluttional effects. Calcium varied from 0.47 to 0.60% in the three core samples tested.

The total P, C, N, Fe, Al, Mn, and Mg varied appreciably in ten cores taken in several locations in Upper Klamath Lake. Phosphorus decreased with depth in the core at some sites and increased at others. Carbon, in general, decreased, but at locations Y1b and V7d the carbon increased significantly below the 90-cm level. At Y1b both carbon and nitrogen decreased to a very low level at the 120-150 cm level. There was good correlation between carbon, nitrogen and phosphorus at all levels (correlation coefficient >0.7), but poor correlation between iron and phosphorus ($R < .5$). Manganese was less than 0.01% at the surface and remained nearly constant with depth in some cores, but it increased directly with the increase in aluminum and iron concentration in others.

Good correlation existed between concentrations of aluminum and iron, and aluminum and manganese ($R > 0.7$) except for the core samples from location V19b at the 120 to 150-cm and 150 to 160-cm level. These two samples had similar chemical composition but differed from the others in that nitrogen and carbon were lower yet P, Al, Mg, and Mn were much higher.

Soluble Nutrients in Interstitial Waters from Upper Klamath Lake Sediments

The presence of soluble nutrients was tested in Upper Klamath Lake sediments by centrifuging samples at 13,000 rpm for 15 minutes in 250-ml polycarbonate bottles in a refrigerated centrifuge (4°C) and the supernatant water filtered through a 0.45 micron membrane filter. The interstitial water contained surprisingly high concentrations of soluble phosphorus and ammonia; from 0.02 to 10.5 mg P/l and 1.3 to 86 mg N/l in Ekman dredge sediment samples (Table 5). Filtration through a 0.22 micron filter yielded identical results for phosphorus as compared with filtration through a 0.45 micron membrane. In addition, the interstitial water contained high concentrations of dissolved silicon, total carbon, and occasionally soluble non-volatile organic carbon compounds. A comparison of the nutrients measured in the interstitial water of the sediment and the lake water directly overlying the sediment showed that there was a good supply of soluble nutrients available in the sediment and that mixing or diffusion would permit these to pass into the lake water (Table 6).

To further determine the nature of the sediments and the concentrations of the soluble nutrients with depth, cores were taken throughout the lake.

The orthophosphate and total soluble phosphorus concentration of the interstitial water in 30-cm sections of cores increased to approximately 60-90 cm in about half of the cores and then decreased with depth (Table 6). The sediments at Howard Bay (09d), Pelican Marina (Y1b), and at S18d, however, showed a continual increase in the soluble phosphorus compounds with depth. Cores from three locations, V9d, P12b, and Q11a, indicated a gradual decrease in soluble P with depth of sediment. The concentrations of soluble phosphorus in the interstitial water did not bear any relationship to the values for total phosphorus calculated on the dry weight basis.

Ammonia and total Kjeldahl nitrogen in the core increased with depth in nearly all cases. There usually was very little nitrite or nitrate detected although up to 0.1 mg N/l of nitrate was found at V7d.

Soluble silica decreased with depth in Upper Klamath Lake sediments but increased in Agency Lake. The calcium and total hardness were less in the interstitial water than in the overlying water with the exception of Howard Bay (09d). In general, both increased in the interstitial water with depth in the core. Total carbon and alkalinity also increased with depth.

Variations in the soluble nutrient concentrations in the interstitial water from Ekman dredge samples were observed. In Howard Bay (09d) a large decrease in phosphorus from 7.1 mg to 0.32 mg P/l occurred between April 2 and June 3, 1969 (Table 5 and Fig 4). At the same time ammonia decreased from 64 to 2.3 mg N/l, total Kjeldahl nitrogen from 66 to 3.9 mg N/l, and conductivity from about 940 to 190 micromhos/cm.

Soluble silica and alkalinity also decreased. The same general pattern was observed in June 1968. In both 1968 and 1969, the concentrations of the soluble constituents increased in the late summer and autumn.

In 1970, the data did not show a great decrease in phosphorus although the ammonia and total Kjeldahl nitrogen did decrease. The same effects are noted, but not so dramatically, at the Pelican Marina (Y1b).

These variations were first thought to result from wave or current action on the sediment or from the utilization of nutrients by the developing bloom of Aphanizomenon flos-aquae. The small change in 1970 is attributed to the fact that A. flos-aquae did not develop at the usual time or intensity in May or June, but appeared instead in August. A well developed growth of Oscillatoria princeps formed over the bottom and Gloeotrichia was predominant over much of the lake in August. However, a core taken August 5, 1969, at Howard Bay (09d) appeared to have very little soluble nutrient down to 1.2 meters as compared with the previous late autumn (Table 6).

Correlation coefficients of seasonal changes in inorganic phosphorus, total soluble phosphorus, and conductivity of the interstitial water were greater than 0.9 at all the sampling locations (09d, V7d, Y1b, L33d). These three factors had a correlation coefficient (R) of about 0.6 with organic phosphorus in the sediment.

It is interesting to note that during the year the interstitial water contained less than 0.2 mg Fe/l and undetectable concentrations of manganese. Sulfate and chloride concentrations were less than 10 mg/l; sodium varied from 10 to 20 mg/l and potassium from 3 to 8 mg/l.

Nutrient Release Mechanisms in the Upper Klamath Lake System

To determine whether nutrient interchange could be observed in the field by biological, chemical, or physical measurements, it was necessary to observe several parameters in the lakes. Water quality measurements for about 25 different factors were made regularly between July 1967 and March 1969 and irregularly during 1970.

Sediment-water nutrient interchange occurred in June and September 1968 and in August 1970 through an interesting and effective mechanism. Oscillatoria princeps, which grew on the sediment, produced and collected sufficient gas to cause it to be lifted to the lake surface. As the algae rose, it brought with it attached sediment in pieces 30 cm or more in length and from 15 to 30 cm thick. Such clumps were found floating throughout the lake system in June 1968, in the northern area of the lake in August 1970, and throughout Howard Bay in September 1968. The floating O. princeps in various stages of decomposition, fragments of sediment, and small dead fish 4 to 8 cm long (Blue chub) caused a very disagreeable odor in Howard Bay in September 1968. When the floating sediment broke apart, the soluble nutrient in the interstitial water was dispersed as evidenced by the increase in nutrients in the water. Between August and September, the average concentrations of nutrients in the surface and bottom water in Howard Bay increased as follows: from 0.4 to 1.1 mg total phosphorus/l, from 0.15 to 1.2 mg ammonia nitrogen/l, and from 5.2 to 8 mg total Kjeldahl nitrogen/l. The conductivity increased from 125 to 190

micromhos/cm and the dissolved oxygen decreased from 6 to 3 mg/l. The orthophosphate concentration at the time of the floating O. princeps was only 0.02 mg P/l. This is attributed to the intense, healthy growth of other species of algae evident in the water. The water in the main portion of the lake (locations Y1b and V7d) where a A. flos-aquae algal bloom was occurring, but where O. princeps was undetected on the lake surface, contained levels of 0.25 mg total P/l, <0.1 mg ammonia N/l, 5.5 mg total Kjeldahl N/l, 7.5 mg O/l, and a conductivity of 122 micromhos/cm (average of surface and bottom water at sampling sites Y1b and V7d).

Thus it appears evident that some of the nutrients in the Howard Bay lake water came from the sediment interstitial water when the sediment was lifted by the O. princeps. The interstitial water from surface sediment samples contained from 5 to 9 mg ortho P/l and 20 to 86 mg $\text{NH}_3\text{-N/l}$.

In August 1970, the motion of the boat over the water was sufficient to bring pieces of O. princeps and accompanying sediment to the surface. Laboratory aquarium experiments predicted that this phenomenon could occur in the lake before it was actually observed in the lake.

Nutrient release in some lakes is expected to occur when anaerobic conditions develop at the bottom during prolonged ice cover. Chemical analysis of water just over the sediments during the period of ice and snow cover on Upper Klamath Lake did not reveal significantly higher concentrations of phosphorus and nitrogen compounds over that found in the water just below the ice, even

though the dissolved oxygen content was less than 1 mg/l about 1 meter over the sediment surface for at least two weeks and no mixing occurred from wind action. No explanation for this can be given except that the lake does not follow the classical description of the iron-manganese-phosphate cycle during periods of low and high dissolved oxygen. Manganese is present in only small concentrations in the lake water (0.004 to 0.2 mg Mn/l) and total iron is less than 0.1 to 0.2 mg Fe/l. Iron in the interstitial water may attain a concentration of 0.2 mg Fe/l.

The effect of wind upon mixing and resuspension of the sediments with the overlying water has been described by Bond, Hazel, and Vincent (1968). They concluded that the sediments were resuspended when the water mass movement had a velocity greater than 0.02 feet per second; this occurred when wind velocities were two to five miles per hour. With the concentrations of soluble phosphorus and nitrogen available in the sediment interstitial water, the wind mixing process would appear to be an important factor in nutrient interchange.

DISCUSSION AND CONCLUSIONS

The total phosphorus, carbon, and nitrogen content of the sediments of Upper Klamath and Agency Lakes are not at a particularly high level as compared to other lakes described by Konrad (1970), and Williams (1970), but measurements of total quantities are not really valid criteria for judging the effect of sediments upon a lake system.

The soluble nutrient content in Upper Klamath Lake sediment interstitial water is much higher, particularly from Howard Bay, than that in ten other oligotrophic and eutrophic lakes we tested throughout the United States (Gahler, 1969a). The fact that the soluble nutrient content in sediments perhaps could vary throughout the year down to a level of about 1.5 meters suggests that this phenomenon is probably a result of biological activity. If only the top layer of sediment had shown this change, it could be assumed to be a result of other factors, such as mixing with lake water, precipitation or dissolution, some physical phenomenon, or perhaps benthic activity.

Although knowledge of the concentration of soluble nutrients in sediment interstitial water does not lead to a quantitative value for nutrient interchange, the measurements do relate to experiments in laboratory aquaria to determine the effect of sediments upon algal growth. Sediments from different locations in Upper Klamath Lake and in Shagawa Lake, Minnesota, which are lower in soluble nutrient content in the sediment interstitial water, do not support as luxuriant algal growth as do the sediments which contain higher concentrations of nutrients.

POSSIBLE APPLICATION OF RESULTS TO LAKE RESTORATION

Although it is not yet possible to relate quantitatively the uptake or release of nutrients from bottom sediments to the overlying lake water, data of the types presented here do yield pertinent information for evaluation of lake restoration methods for lakes such as the Upper Klamath Lake system.

A restoration program on the Upper Klamath Lake system would require that the soluble nutrients in the upper layer of sediments be immobilized. Any technique involving nutrient inactivation would require that the nutrients be held at the sediment interface and that no nutrients diffuse into the water. This would be difficult because of the flocculent nature of the interface. A material would need to be applied which would form an adsorptive film or stable layer at the interface to adsorb the nutrients and to prevent the fluffy upper layer from mixing with the lake water. Application of aluminum salts probably would be ineffective because of the physical nature of the precipitate. Application of adsorptive materials of too high density would result in loss through the interface.

Dredging would be of little benefit in Upper Klamath Lake, since it is not possible to remove a layer so that a new low-nutrient surface would be exposed to the water. During the dredging operation, the loose bottom sediments would be stirred which would result in release of nutrients from the interstitial water to the overlying water. Although the marsh areas have been successfully reclaimed, the sediments in the bay areas are relatively low in nutrient content for raising crops and of undesirable texture when dry so that these areas could not be easily reclaimed for agricultural purposes.

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TABLE 1. Physical properties of two Upper Klamath Lake sediments.

Sediment	Organic Matter %	Water* %	Texture %			Textural Class
			Sand	Silt	Clay	
			2.0- 0.05 mm	0.002- 0.05 mm	0.002 mm	
Howard Bay	18.4	91.3	3.1	40.6	56.3	Silty Clay
Buck Island	14.2	91.1	4.9	52.3	42.9	Silty Clay

*Wet basis

TABLE 2. Sand and silt particle size distribution of two Upper Klamath Lake sediments.

Particle size distribution (% of 2 mm)							
Sample	Sand				Silt		
	Very Coarse		Medium	Fine	Very Fine		Fine
	2-1	1-0.5			.1-.05	.05-.02	
Howard Bay	0.02	.08	.08	.04	2.49	3.96	36.63
Buck Island	0.01	.11	.09	.49	4.16	4.42	47.84

TABLE 3. Carbon-14 dating of cores from Upper Klamath Lake.

Core depth (cm)	Age (Years B. P.)*		
	Location		
	R19d	V7d (Buck Island)	Y1b (Pelican Marina)
15	2060 \pm 270	----	Modern
30	----	1940 \pm 220	1260 \pm 200
60	4040 \pm 570	----	1350 \pm 180
90	2425 \pm 375	4110 \pm 210	4370 \pm 220

*B. P. (Before Present) = Before A. D. 1950

TABLE 4. Chemical composition of lake sediment cores.

Depth-cm	Site P12a (Howard Bay) 10-23-68			Site 09d (Howard Bay) 10-23-68		
	0-30	60-90	120-150	0-30	60-90	120-150
Constituent in %						
<u>Dry basis</u>						
P	.028	.026	.024	.064	.060	.064
N	.65	.65	.65	1.1	.92	.92
C	4.4	5.3	4.7	7.2	7.2	7.3
Fe	.98	1.1	1.5	1.2	1.1	1.0
Mn	.007	.008	.008	.008	.008	.007
Al	2.2	2.4	2.7	2.5	2.2	2.2
Mg	.13	.15	.16	.19	.19	.20
Ca				.47		
<u>Wet basis</u>						
H ₂ O	90	88	85	92	87	88

TABLE 4 continued

Site V7d (near Duck Island) 9-24-68						
Depth-cm	0-30	30-60	60-90	90-120	120-150	150-165
Constituent in %						
<u>Dry basis</u>						
P	.026	.020	.025	.024	.038	.058
N	.55	.55	.55	.55	.55	.74
C	4.0	4.1	3.9	4.2	4.3	6.8
Fe	.90	1.0	1.4	1.6	2.2	1.9
Mn	.008	.008	.009	.012	.026	.040
Al	2.0	2.0	2.3	2.6	3.8	3.7
Mg	.15	.13	.15	.20	.28	.29
Ca	.55					
<u>Wet basis</u>						
H ₂ O %	90	83	82	85	80	76
N-NH ₃ mg/kg	33	49	64	82	126	180
N-organic mg/kg	660	760	780	940	1100	1880

TABLE 4 continued

Depth-cm	Site R13a (Howard Bay) 10-23-68			Site Q11c (Howard Bay) 10-23-68		
	0-30	60-90	120-150	0-30	60-90	120-150
Constituent in %						
<u>Dry basis</u>						
P	.032	.022	.042	.024	.022	.030
N	.74	.74	.65	.55	.74	.55
C	5.3	5.3	4.4	4.1	4.4	3.9
Fe	1.0	1.0	1.4	1.0	1.4	1.7
Mn	.007	.008	.011	.008	.010	.015
Al	1.9	1.9	2.4	1.9	2.6	3.4
Mg	.14	.14	.18	.14	.18	.24
<u>Wet basis</u>						
H ₂ O	91	90	86	88	84	81

TABLE 4 continued

Site Y1b (Pelican Marina) 9-24-68					
Depth-cm*	0-30	30-60	60-90	90-120	120-150
Constituent in %					
<u>Dry basis</u>					
P	.040	.032	.028	.046	.072
N	.74	.65	.55	.74	<.1
C	5.1	5.1	3.6	6.4	.7
Fe	1.3	1.4	1.9	1.9	2.1
Mn	.009	.009	.008	.014	.018
Al	2.7	3.1	3.2	4.4	6.3
Mg	.19	.22	.19	.31	.40
Ca	.60				
<u>Wet basis</u>					
H ₂ O**	88	88	85	79	55

*Layer of pumice at 100-cm level

**All moisture results except for the 120-150 cm level are average of a composite of two cores taken 8-27-68

TABLE 4 continued

Depth-cm	Site V19b					
	11-7-68					
	0-30	30-60	60-90	90-120	120-150	150-160
Constituent in %						
<u>Dry basis</u>						
P	.022		.032		.053	.060
N	.46	.38	.42	.23	.23	.11
C	3.7	3.5	3.7	1.8	1.9	1.5
Fe	1.2		2.1		2.0	1.9
Mn	.012		.025		.054	.048
Al	2.3		4.4		6.5	6.3
Mg	.22		.50		1.0	1.0
<u>Wet basis</u>						
H ₂ O	89	87	79	67	63	70

Note: A section containing pumice occurred at the 100-115 level. Core from 90 to 150 cm level was darker than the top 90-cm section and the sediment below 150 cm.

TABLE 4 continued

Depth-cm	Site U15c 11-7-68					
	0-30	30-60	60-90	90-120	120-150	150-160
Constituent in %						
<u>Dry basis</u>						
P	.040		.024		.024	.025
N	.89	.75	.53	.59	.63	.71
C	6.3	5.2	3.6	4.7	4.6	4.4
Fe	1.3		.95		1.0	1.0
Mn	.009		.008		.008	.009
Al	2.0		1.9		2.0	2.0
Mg	.16		.13		.13	.13
<u>Wet basis</u>						
H ₂ O	91	91	89	88	86	86

TABLE 4 continued

Depth-cm	Site S18d			Site M20a		
	11-7-68			11-20-68		
	0-30	60-90	120-150	0-30	60-90	120-150
Constituent in %						
<u>Dry basis</u>						
P	.042	.028	.026	.036	.022	.024
N	.80	.53	.63	.80	.71	.71
C	5.6	4.5	3.9	5.8	5.1	4.8
Fe	1.1	1.0	1.7	1.1	1.0	1.7
Mn	.009	.007	.010	.006	.005	.006
Al	2.0	1.9	2.6	1.6	1.6	2.1
Mg	.16	.13	.17	.14	.12	.13
<u>Wet basis</u>						
H ₂ O	91	90	84	90	90	88

TABLE 5. Variations in composition of sediment interstitial water (site 09d, Howard Bay).

Date	Ortho-P	TSP	Cond	N-NH ₃	N-TKjel	Alk.	Total Hardness	Sol. Silica	Total Carbon	SNOC*	pH	Total Fe % dry wt	Total P % dry wt
June 12, 1968	2.9	3.1	525	30	30	234	155	46	59	10	7.5	1.29	.088
June 25, 1968	6.2	6.2	704	46		325	144	54	75	11	7.4		
July 10, 1968	6.2	6.2	658	39				57		15	7.8		
Aug. 14, 1968	9.0	9.0	893	54	63	452	189	96	117		7.7		
Aug. 20, 1968	10.5	10.5	1076	86	86	559	203	91	141	19	8.1	1.10	.058
Aug. 27, 1968	9.5	9.5	939	67	123	450	207	97			7.9		
Sept. 11, 1968	8.5	9.0	1008								8.1		
Sept. 25, 1968	7.0	7.2	889								7.7		
Oct. 23, 1968	8.5	8.5	1022	85	72		189	63			7.7	1.20	.064
Dec. 10, 1968	7.9		726	48							8.0		
Apr. 2, 1969	7.1	11.2	944	64	66			42	106	12	7.2	1.45	.116
May 7, 1969	.72	1.4	386	4.0		165	128	38			7.7		.064
June 3, 1969	.32	.40	188	2.3	3.9	85	60	31			8.0		
June 12, 1969	6.0	6.0	775	38.5	40.8	362	192	56			7.9		
July 16, 1969	.30	.45	148	3.6	6.1	65		37			7.9		
Aug. 5, 1969	.64	.64	244	8.8	8.2	88		39			7.9		
Aug. 27, 1969	1.8	1.8	426								7.7	1.40	.076
Sept. 9, 1969	2.6	8.0	462	22	27	209		48			7.5	1.35	.064
Sept. 30, 1969	4.6	4.6	596	30	35	288		50			7.5		
Oct. 21, 1969	6.4	6.4	761	58	69			48			7.2		
Jan. 13, 1970	1.3	1.5	457	16	17	189		43	53	13	7.2		
Mar. 26, 1970	3.0	3.2	511	20	19	255		46	72	20	6.8		
Apr. 27, 1970	5.5	5.3	648	40	38	319	126	50			7.1		
June 3, 1970	4.0	4.0	469	20	22	231	123	48			7.3		
July 7, 1970	4.0		562								7.7		

Note: Concentrations expressed in mg/l.
Total Fe and P determined on dried sample.

TABLE 5 continued. Variations in composition of sediment interstitial water (site V7d, Buck Island).

Date	Ortho-P	TSP	Cond	N-NH ₃	N-TKjel	Alk.	Total Hardness	Sol. Silica	Total Carbon	SNOC	pH	Total Fe % dry wt	Total P % dry wt
June 12, 1968												.98	.033
June 25, 1968	.07	.15	124	1.6		56	35	26	22	6	6.7		
Aug. 20, 1968	.11	.27	191	9	10.7	79	47	72	37	13	7.4		
Sept. 11, 1968	.08	.21	133										
Sept. 24, 1968	.07	.17	191	8.5	10.4	82	37	49			6.9	.90	.026
Oct. 23, 1968	.75	.75	276	6.2	9.6	97	76	51	26	19	7.4	1.22	.060
Nov. 6, 1968	.58	.62		5.2	5.4		65	55	33	6			
Nov. 19, 1968	.31	.37	178								8.2		
Apr. 2, 1969	.06	.12	187	2.3	4.4			34	31	11	6.4	1.35	.065
May 7, 1969	.14	.36	132	2.0	5.5	60	38	36			7.7		
June 3, 1969	.12	.21	137	2.4	4.5	58	38	36			7.7		
June 12, 1969	.30	.36	134	2.2	3.9	62	50	38			7.8		
July 16, 1969	.13	.21	116	1.8	4.1	49		8			7.8		
Aug. 5, 1969	.18	.24	122	2.8	4.8	54		36			7.9		
Aug. 27, 1969	.21	.40	117								7.9	1.25	.062
Sept. 9, 1969	.16	.37	118	2.0	4.4	46		40			7.9	1.35	.058
Sept. 30, 1969	.26	.59	121	1.9	6.0	54		44			8.2		
Oct. 21, 1969	.10	.21	129	1.3	3.7			40			7.4		
Feb. 24, 1970	.08	.16	120	1.9	3.5	61		33			6.6		
Mar. 26, 1970	.04	.14	124	1.4	2.5	60		33	20	5	6.6		
Apr. 27, 1970	.05	.07	120	1.3	2.6	57	34	27			7.7		
June 3, 1970	.08	.22	135	1.4	3.2	64	42	28			7.4		
July 7, 1970	.02		147								7.2		

TABLE 5 continued. Variations in composition of sediment interstitial water (site Y1b, Pelican Marina).

Date	Ortho-P	TSP	Cond	N-NH ₃	N-TKjel	Alk.	Total Hardness	Sol. Silica	Total Carbon	SNOC	pH	Total Fe % dry wt	Total P % dry wt
June 25, 1968	.06	.16	138	24		60	40	27	19	6	7.4	1.35	.045
Aug. 27, 1968			221	22	22	102	9	78	37	7	8.1		
Sept. 24, 1968	.03	.05	209				14				7.8	1.30	.040
Feb. 6, 1969	1.8	1.9	317								7.3		.080
Apr. 2, 1969	.45	.45	204	5.5	7.8			40	27	6	6.7	1.70	.072
May 7, 1969	.52	1.0	211	8.1	9.9	95	50	40			7.7		
June 3, 1969	.12	.18	107	2.1	3.2	44	35	33			8.2		
July 16, 1969	.53	.55	165	6.6	8.9	71		44			7.9		
Aug. 5, 1969	.20	.26	130	5.0	5.0	55		36			7.8		
Aug. 28, 1969	.26	.41	129								7.8	1.50	.070
Sept. 9, 1969	.21	.32	134		6.0	57	39				7.9	1.55	.052
Sept. 30, 1969	.23	.26	149	1.9	4.8	50		48			8.1		
Oct. 21, 1969	.10	.20	145	2.3	5.4			42			7.5		
Jan. 13, 1970	1.3	1.3	398	23	33	164		44	60	11	7.0	1.60	.086
Feb. 24, 1970	.06	.10	121	2.6	3.9	56		33	34	6	6.4		
Mar. 26, 1970	.04	.14	124	1.9	3.1	61		31	22	7	6.7		
Apr. 27, 1970	.05	.13	121	1.7	3.1	56	33	26			7.3		
June 3, 1970	.11	.21	139	1.8	3.7	64	39	25			6.6		
July 7, 1970	.10		156								8.0		

TABLE 6. Composition of interstitial water in core samples from Upper Klamath Lake.

Depth-cm	Site 09d Howard Bay 8-20-68				Site 09d Howard Bay 10-23-68				Site 09d Howard Bay 8-5-69				
	0-45	45-90	90-135	Overlying lake water	0-30	60-90	120-150	Overlying lake water	0-15	30-45	60-75	90-105	120-135
<u>Constituent</u>													
Cond	1076	1297	1474	121	1022	1363	1659	180	285	411	362	382	402
pH	8.1		8.2	8.7	7.7	7.8	7.8	6.9	8.0	8.2	8.1	8.2	8.2
P-ortho	10.5	14.5	12.0	.01	8.5	16.5	17.5	.22	.84	2.4	2.2	1.7	.98
P-total sol	10.5	14.8	12.0		8.5	17.0	18.2	.3*	.90	2.4	2.4	1.7	1.1
N-NH ₃	86	107	126	.15	85	119	146	.5					
N-Total Kjehl.	86	102	122	5.8									
N-NO ₃					<.03	<.03	<.03	<.03					
N-NO ₂					<.02	<.02	<.02	<.02					
Hardness, T	141		177	36	189	246	264	39					
Silica, sol.	91	92	86	42	56	60	58	38					
Alkalinity	559	678	757	58									

Notes: Constituents expressed in mg/l.

Conductivity expressed in micromhos/cm.

*Total P

TABLE 6 continued

Depth-cm	Site 09d Howard Bay 4-27-70					Site V19b 11-7-68					
	0-30	30-60	60-90	90-120	120-150	0-30	30-60	60-90	90-120	120-150	150-160
<u>Constituent</u>											
Cond	842	1105	1184	1341	1578	153	217	248	262	281	
pH	7.4	7.6	7.9	8.0	7.9	7.9	8.0	8.1	8.1	8.1	
P-ortho	7.3	10.3	11.5	15.5	13.5	.04	.45	.09	.08	.06	.08
P-total sol	8.5	10.5	11.8	17.3	14.0	.15	.59	.23	.23	.25	.27
N-NH ₃	60	84	96	116	140	4.2	7.8	10.1	10.6	11	
N-total Kjehl.						5.7	9.5	12.8		15.5	
N-NO ₃						.03	<.03	<.03	<.03	.03	
N-NO ₂						<.02	<.02	<.02	<.02	<.02	
Hardness,T						57	62	79	76	72	
Silica, sol.						44	52	51	42	40	
Alkalinity	427	565	633	742	877						
Carbon, T						17	46	55	71	90	
Carbon, SNOC						14					

TABLE 6 continued

Depth-cm	Site V7d Buck Island 9-24-68							Site Y1b Pelican Marina 8-27-68				
	0-30	30-60	60-90	90-120	120-150	150-165	Overlying lake water	0-30	30-60	60-90	90-120	Overlying lake water
<u>Constituent</u>												
Cond	191	231	266	298	306	211	122	221	364	417	472	122
pH	6.9	6.8	6.9	7.4	7.1	7.0		8.1	7.8	7.9	8.2	9.2
P-ortho	.07	.11	.08	.05	.03	.04	.08	(a).03	.14	.31	.10	.07
P-total sol	.17	.22	.27	.17	.19	.19	0.2*	.05	.24	.44	.24	
N-NH ₃	8.5	12	14.5	16	17	12.5	<.1	22	37	42	47	0.6
N-total Kjel	10.4	15	19.3	21.2	21.8	17.5		22	37	46	56	3.6
N-NO ₃	0.1	.08	.03	<.03	<.03	<.03	<.03					
Hardness, T	37	36	41	47	51	30	34	9	42	33	38	76
Silica, sol	49	49	49	43	41	42	47	78	81	76	50	41
Alkalinity	82	97	115	131	127		54	102	158	192	237	54

(a) data for Marina for oP and total soluble P taken 9-24-68

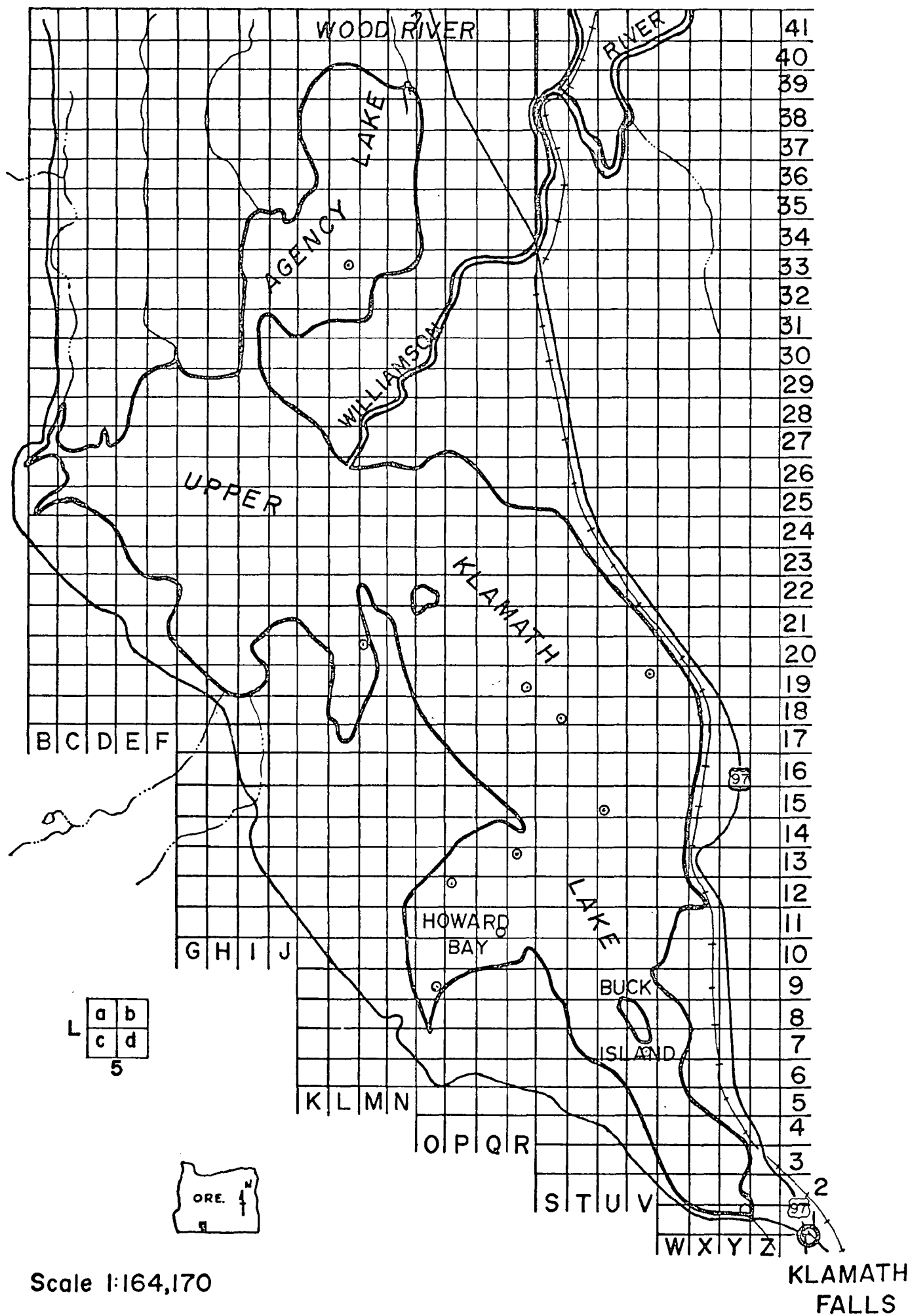
*Total P

TABLE 6 continued

	Site P12a			Site Q11d			Site S18d			Site R13a		
	10-23-68			10-23-68			11-7-68			10-23-68		
	0-30	60-90	120-150	0-30	60-90	120-150	0-30	60-90	120-150	0-30	60-90	120-150
<u>Constituent</u>												
Cond.	240	329	389	264	335	381	195	255	349	293	321	334
pH	7.2	7.9	7.2	7.0	7.2	7.1	8.0	8.0	8.2	7.2	7.2	7.7
P-ortho	.43	.59	.28	.44	.24	.20	.14	.11	.25	.40	.70	.53
P-total sol.	.53	.73	.49	.57	.40	.38	.18	.19	.34	.47	.83	.63
N-NH ₃	11	16.8	19.2	12.4	16	17.4	7.2	10.8	14.8	16.8	16.8	16.2
N-total Kjehl.	12.5	19.7	22.6	12.5	19.1	20.3	7.4	11		15.5	18.5	17.9
N-NO ₃	<.03	<.03	<.03	<.03	<.03	<.03	<.03	.03	<.03	.03	<.03	<.03
N-NO ₂	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02
Hardness, T	66	66	85	57	113	104				57	66	85
Silica, sol.	50	54	54	60	60	55	50	56	10.5	54	58	59
Carbon, T							31	42				

TABLE 6 continued

Depth-cm	Site M20a 11-20-68						Site U15c 11-7-68					
	0-30	30-60	60-90	90-120	120-150	150-160	0-30	30-60	60-90	90-120	120-150	150-160
<u>Constituent</u>												
Cond	208	236	245	250	268	234	230	288	314	309	300	231
pH	8.0	8.1	8.1	8.1	8.1	8.0	8.0	8.0	8.1	8.2	8.2	8.1
P-ortho	.41	.43	.18	.05	.03	.03	.09	.15	.15	.25	.11	.15
P-total sol.	.57	.63	.29	.22	.21	.14	.15	.21	.25	.34	.21	.28
N-NH ₃	9.3	10.9	12	12.6	13.4	11.8	11.4	15.9	17.1	17.1	16.8	
N-total Kjehl.	13.8	17.8	16.2	17.8	17.0	16.2	12.8	14.9	17.3	19.1	18.2	
N-NO ₃	.10	.05	.05	<.03	<.03	<.03	<.03	<.03	<.03	<.03	.06	
N-NO ₂	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	
Hardness, T	37	43	42	41	43	35	57	62	79	76	72	
Silica, sol.	53	56	52	50	48	46	46	52	49	8	42	
Carbon, T							37	48	53	58	59	
Carbon, SNOC							3	4	9	18	25	
Chloride	5	6	5	5	6							



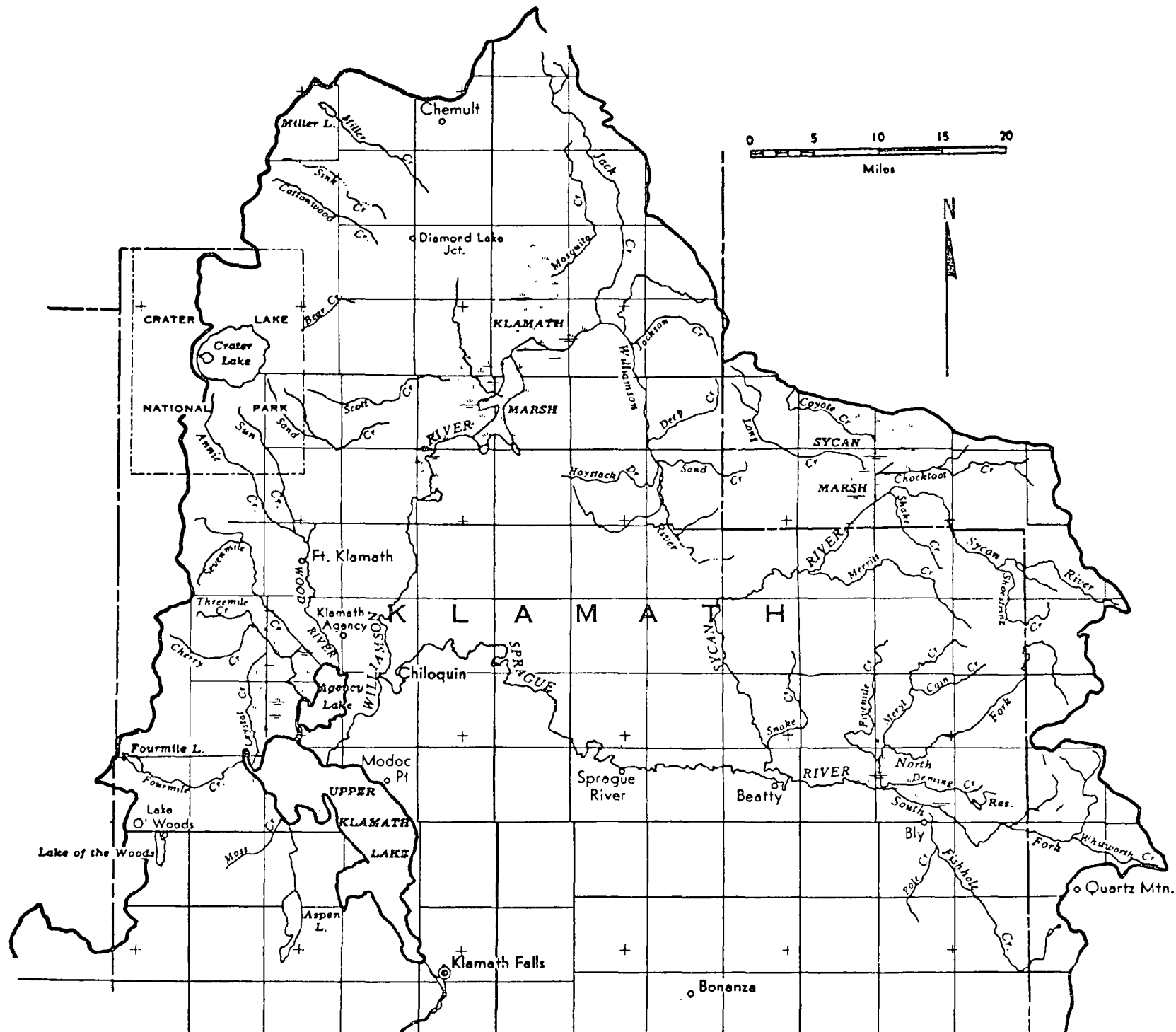


FIG. 2. Watershed of the Upper Klamath Lake System

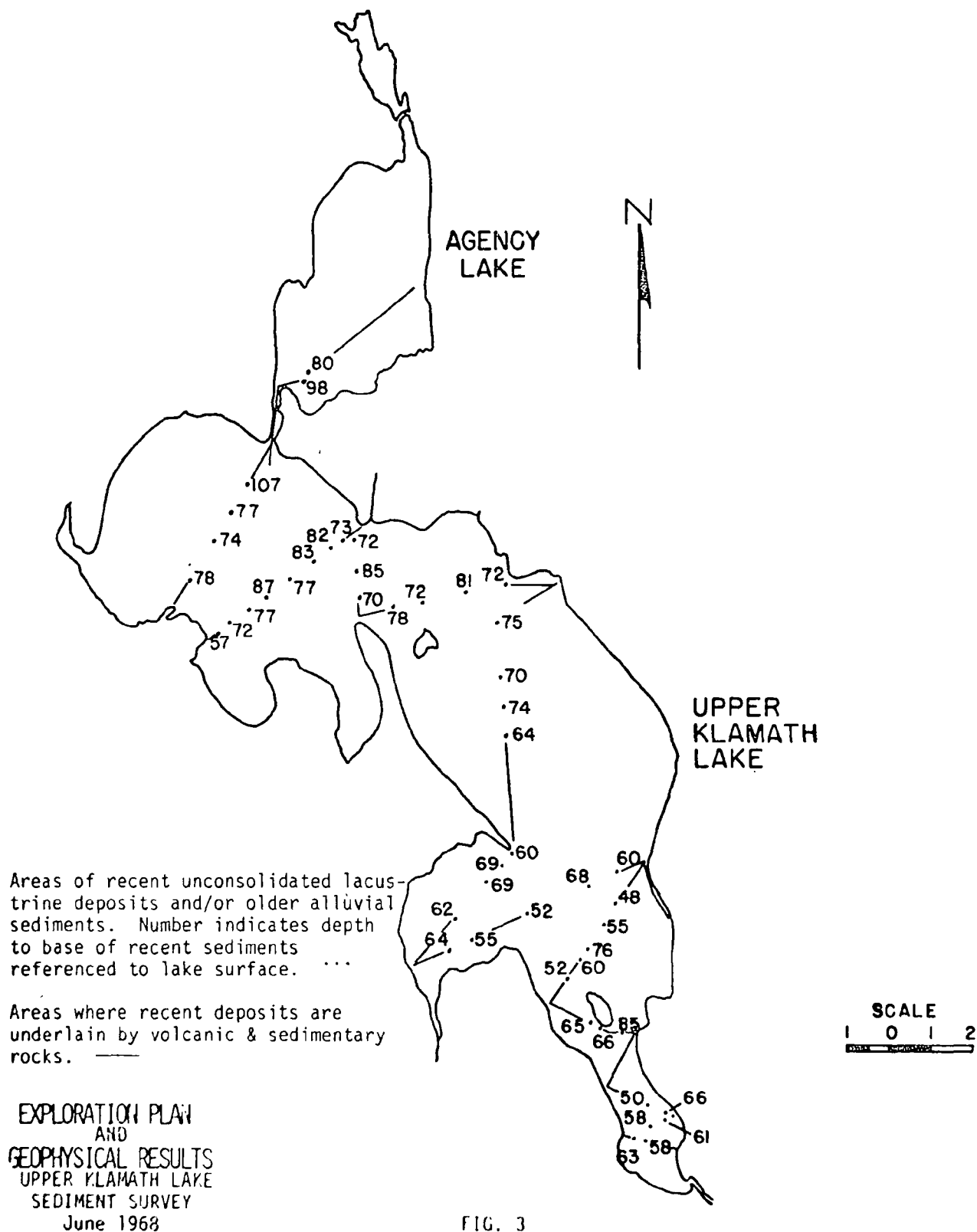
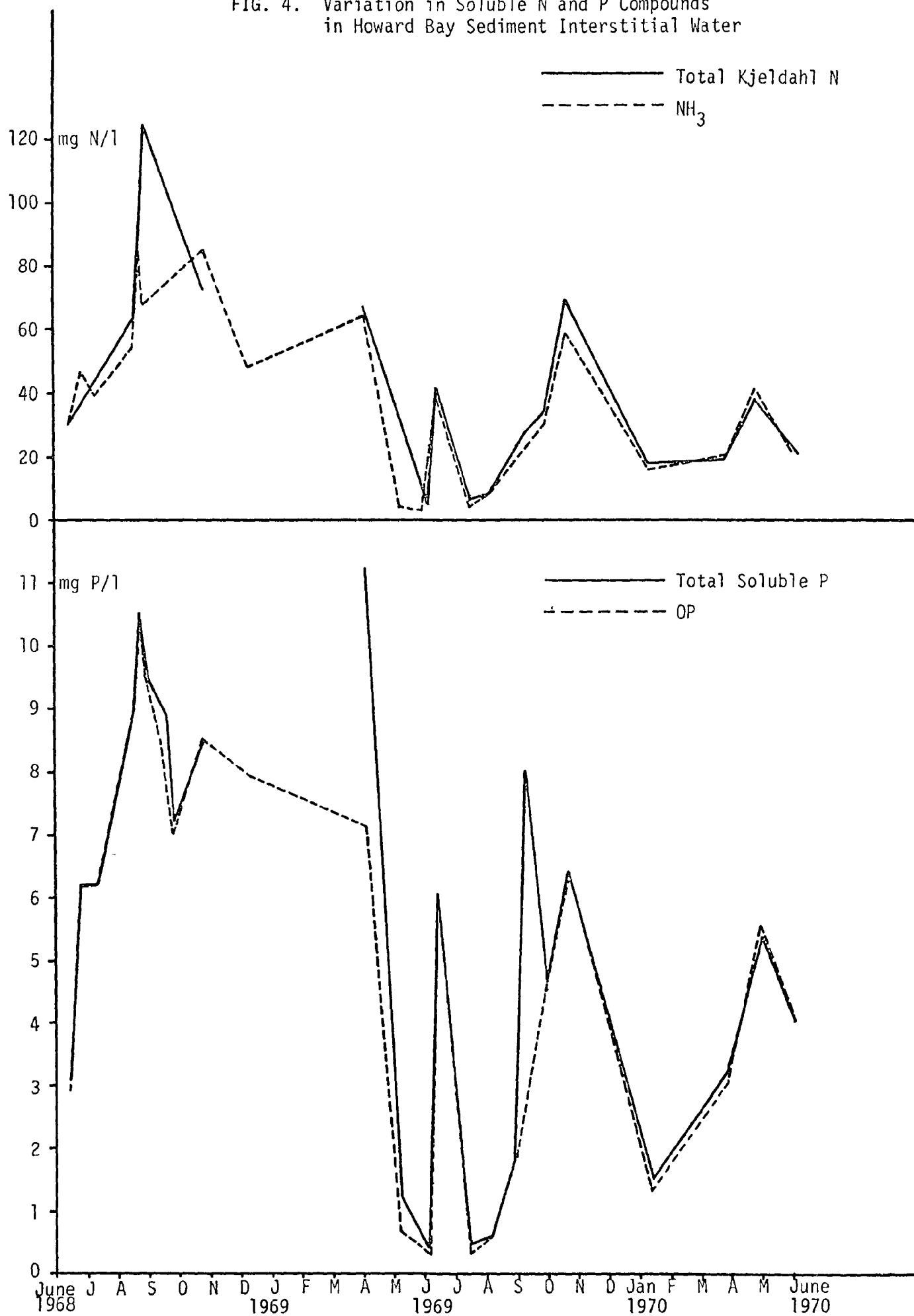


FIG. 4. Variation in Soluble N and P Compounds
in Howard Bay Sediment Interstitial Water



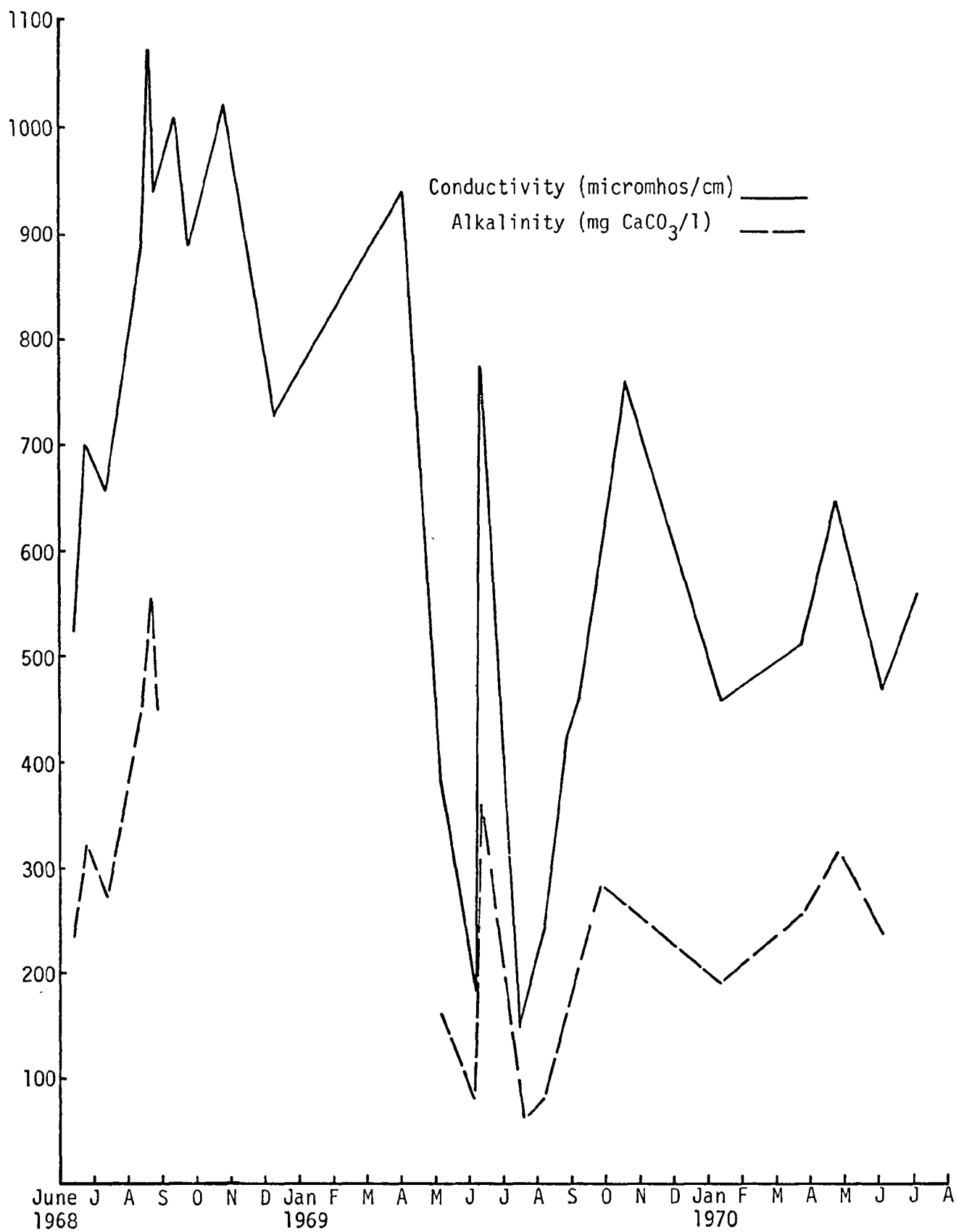


FIG. 5. Variation in Conductivity and Alkalinity in Howard Bay Sediment Interstitial Water

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