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Research and Development

The Effects of Decreased Nutrient Loading on the Limnology of Diamond Lake, Oregon

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June 1979

THE EFFECTS OF DECREASED NUTRIENT LOADING ON THE LIMNOLOGY OF DIAMOND LAKE, OREGON

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake and stream systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report documents the effects of diversion of domestic wastewater from a freshwater lake.

James C. McCarty
Acting Director, CERL

ABSTRACT

Responding to accelerated recreational pressure at Diamond Lake, Oregon, in 1969 the U.S. Forest Service began installation of a wastewater diversion system which would eventually carry 85 to 90% of the sewage out of the watershed. From 1971 through 1977 the U.S. Environmental Protection Agency conducted a program of research on the lake to determine its trophic status and identify changes that might be the result of the diversion.

The lake is quite productive as the result of natural loading from tributaries, groundwater and bottom sediments. Cultural influence, initially speculated to be significant, was discovered to have a relatively minor impact on the lake. Total phosphorus and chlorophyll a levels reached a low in 1973, but by 1977 had increased to levels comparable to 1971. Species composition of the benthic macroinvertebrate population was the same in 1976/77 as it was at the beginning of the study.

Recommendations include an adaptation of the Dillon and Rigler system for determining the development capacity of lakes.

The report covers a period from June 4, 1971 to October 27, 1977.

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Jerry Bauer of the Oregon Department of Fish and Wildlife provided data generated from their studies at Diamond Lake.

INTRODUCTION

Many mountain lakes in Oregon and Washington are subject to heavy recreational use during the non-winter months. Intensive use frequently results in greatly increased nutrient flux to lakes with a consequent acceleration of eutrophication rates and degradation of water quality. This study documents the impact of a waste-water interception program at Diamond Lake, Oregon, with emphasis on defining the nutrient budget and describing the benthic macroinvertebrate population. Recommendations are made which could provide a basis for scientific lake management.

HISTORICAL BACKGROUND

Diamond Lake lies at an elevation of 1580 m in the Cascade Mountains approximately 24 km north of Crater Lake, Oregon. The lake resulted from the melting of an extensive glacier held behind a lava flow from Mt. Thielson, perhaps 10,000 years ago (Purdom, 1964).

Development around Diamond Lake began in the 1920's. The first building permit was issued in 1922 for a lodge at the northeast corner of the lake (Cleator, 1924). A private resort complex now encompasses 15 ha of land including approximately 250 m of shoreline. Guest capacity is 384 persons. Another service facility occupying approximately 0.6 ha is located near the southeast corner of the lake. A trailer park, also near the southeast corner, can accomodate 115 trailers on 6.5 ha (U.S. Forest Service [USFS], 1970).

At one time a YMCA camp occupied approximately 4 ha at the southwest corner of the lake. It consisted of a lodge and 14 cabins, but has not been used since 1971 (USFS, 1970). The first private recreation residence was approved in 1923. Presently there are 102 such dwellings occupying 19 ha of a designated 75 ha plot on the west side of the lake (USFS, 1970). A buffer strip of vegetation, including tall conifers, was left between the dwellings and the lake to maintain the integrity of the shoreline.

About 1948 four cabins were built next to the outlet to accommodate personnel from the Diamond Lake fishegg-taking station. These buildings are now used occasionally by the Oregon Department of Fish and Wildlife (DFW).

The USFS, which primary has responsibility for land management of the Diamond Lake area, maintains three campground complexes totaling approximately 88 ha. The largest of these, East Shore Campground, occupies 40 ha in a narrow strip on the east shoreline. It has 190 trailer/ tent and 50 tent only sites. Two picnic areas, comprising more than 6 ha, are also part of the development (USFS, 1970). All development immediately around the lake is shown in Figure 1.

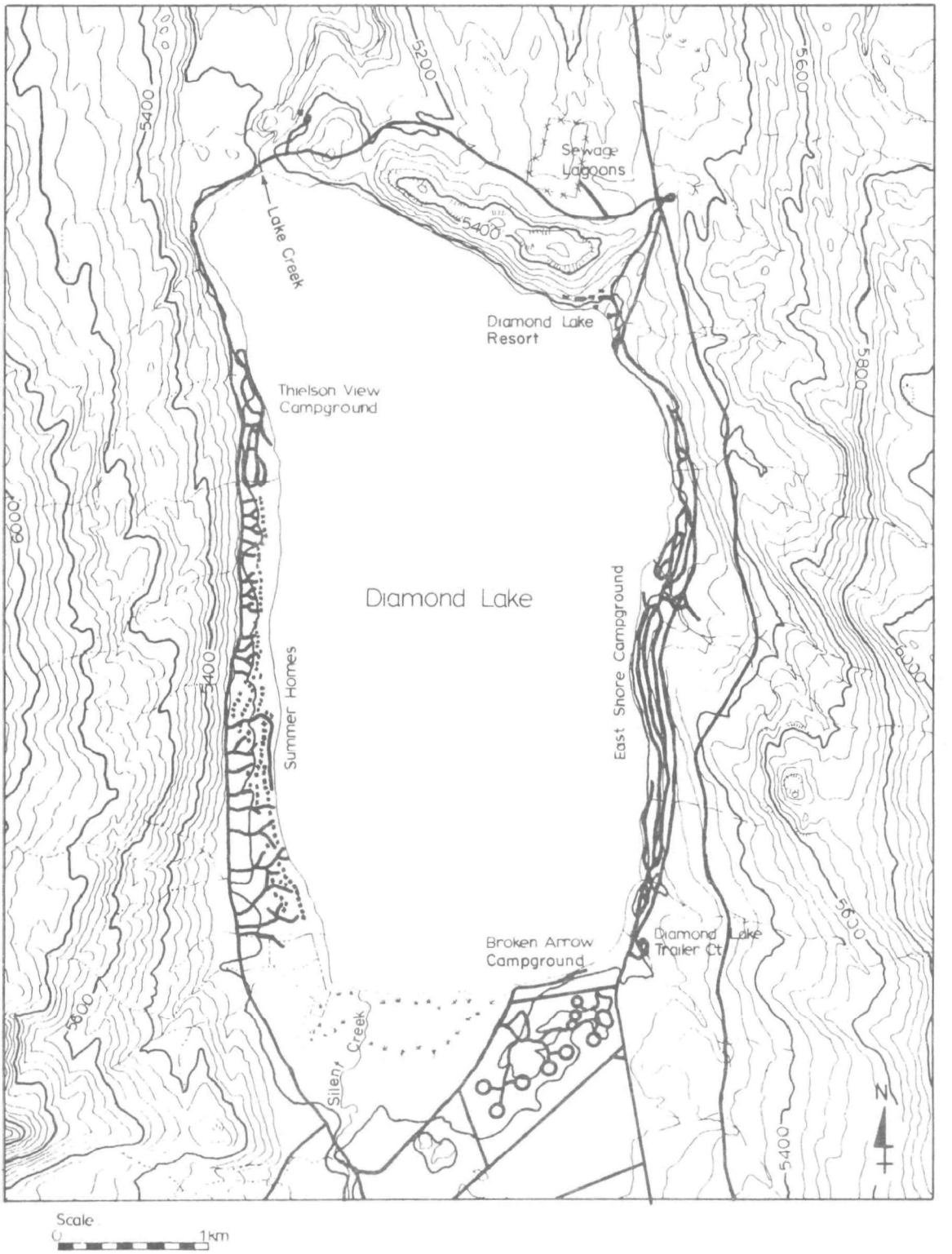

Figure 1. Topography and development around Diamond Lake (elevations in feet).

Recreational use of Diamond Lake has increased rapidly: it has become one of the most popular areas in Oregon. In 1923 slightly more than 9,000 people were estimated to have visited the lake (Cleator, 1924). The campgrounds show a visitor-day (12 hr) increase from less than 30,000 to over 104,000 from 1956 to 1963 (Oregon State Game Comm., 1963). By 1965 the USFS reported use of all developed areas at over 307,000 visitor days (Robertshaw & Thorpe, 1965) and by 1977 the figure had more than doubled to 670,000 (R. Sawyer, District Engineering Asst., Diamond Lake Ranger Dist., USFS, pers comm.). Heaviest use occurs in the summer during the fishing season but snow-oriented recreation is increasing.

The USFS has maximized the recreation value of the Diamond Lake area. Around 1913 they stocked the lake with trout (Bauer, 1976). Grazing sheep in the meadows was discontinued in the 1920's. Timber harvesting is limited to only the salvage and removal necessary to promote recreation (USFS, 1970).

The DFW (formerly the Oregon State Game Commission) began intensive study and management of the fishery in 1946 in response to an apparent decline in the size and number of rainbow trout, Salmo gairdneri (Locke, 1947). Spot poisoning of the roach, Siphateles bicolor bicolor, apparently introduced in the early 1930's (Bauer, 1976), was initiated in 1946 to reduce competition with trout. In September 1954 the roach was completely eradicated by intensive rotenone application. The lake was restocked in June 1955 with Canadian rainbow trout (Oregon State Game Comm. 1954, 1955). Data regarding fishing pressure and success, fish growth and fish food production are gathered by the DFW to direct management policies.

A mosquito control program was initiated in the early 1960's. DDT was used initially but discontinued when mayfly nymph numbers dropped, substantially reducing an important fish food (J. Bauer, District Fishery Biologist, DFW, pers. comm.). Benzene hexachloride was applied in 1968 and 1969. The present program involves one application of MLO Flit (a thin oil) on the marsh immediately after snow melt and weekly application of Malathion in the campgrounds from June thru August by the Douglas County Sanitation Department (G. Ferell, Sanitarian, Douglas County, OR, pers. comm.).

The USFS recognized the potential deleterious effects of cultural eutrophication resulting from increased visitor use. Periodic blooms of algae were noted at Diamond Lake even in the 1930's (Hughes, 1970). In 1966 the waste collection and treatment needs were evaluated. Considering visitor use projections and possible health and aesthetic consequences of continued use of the existing septic tank and pit toilet facilities, a plan was designed for an improved sanitation system including "modern comfort stations, sewer connections for house trailers and camper trucks, improved water supply connections and services, fish cleaning facilities and other conveniences" (Burgess, 1966). Wastes from the campgrounds at the south and east sides of the lake, the trailer court and the resort along the east and northeast section were to be diverted to a series of lagoons outside the watershed. Along the west shore of the lake, the former YMCA camp, summer homes and Thielson View Campground would not be connected but pit or septic tank-type systems would be replaced with vaults which could be periodically pumped. In 1970 the first use was made of on-line facilities at East Shore Campground. By December 1975 all planned connections had been completed (Table 1).

TABLE 1. VISITOR USE AND CHRONOLOGY OF WASTEWATER DIVERSION

Site	Date of Diversion	Visitor Days ($x10^3$) 69	70	71	72	73	74	75	76	77
East Shore Campground	4 stages: 9/69, 11/70 11/72, 06/73	179.4	178.8	210	207.3	221.9	201.4	247.0	247.0	221.0
South Shore Picnic Area	11/72	5.4	7.7	3.3	4.6	5.4	7.0	4.3	2.4	3.3
Broken Arrow Campground	08/74	27.7	24.4	15.5	3.8	13.7	closed	10.4	34.9	63.0
Diamond Lake Improvement Co.	06/75	221.4	209.7	138	136	146	160*	182.7	226.8	235.1
Diamond Lake Trailer Court	12/75	67.8	72.0	63.4	64	59.5	64.6	37.8	46.6	46.6
Thielson View Campground	---	8.8	14.2	20	27.7	38.9	49.9	58.0	52.7	52.0
Noble Fir	---	---	0.2	0.1	0.1	0.1	0.1	0.1	0.1	---
Summer Homes	---	39.2	40.0	18.2	20.2	36.8	43.8	49.8	58.2	47.2
YMCA	---	5.3	5.3	2.5	0	0	closed	closed	closed	closed
Totals	---	555.0	552.3	471.0	463.7	522.3	526.8	590.1	668.7	668.2

* Our interpolation - not USFS data

In 1971 the USFS and the U.S. Environmental Protection Agency (EPA) signed a Memorandum of Agreement for a study to determine the existing lake trophic status, sources of nutrients or other pollution, and whether significant improvement could be detected as a result of the new waste collection and treatment system. The National Eutrophication Research Program, established within EPA as a result of national interest in water quality, had as one of its objectives the determination of the effectiveness of various lake restoration techniques. The Diamond Lake project offered an excellent opportunity to assess the effects of nutrient diversion on lake trophic condition.

The raw data generated during this study is reported in an Appendix as the Environmental Protection Agency's Special Report EPA-600/8-79-017b. The data report is available from the National Technical Information Service, Springfield, VA 22161.

CONCLUSIONS

1. Diamond Lake is mesotrophic to eutrophic as a result of natural nutrient loading from the tributaries, groundwater and sediments.

2. The nutrient contribution from cultural activities in the watershed is, at present, relatively insignificant compared to natural sources.

3. During the period of this investigation no change was found in the trophic status of the lake that could be attributed to the wastewater diversion system.

4. The trophic status of Diamond Lake is appropriate in satisfying present recreational demands.

RECOMMENDATIONS

The present trophic status of Diamond Lake should be perpetuated. Cultural activity and development should be managed to minimze the artificial nutrient supply to the lake.

Surveillance of Diamond Lake's trophic status should continue. It is recommended that during the summer, from June through September, monthly samples be collected from the center station at 1 meter for nutrient and chlorophyll analysis, and that Secchi disc measurements be made. More frequent sampling would be preferable. Sampling and analytical techniques should be comparable to those cited here.

A nutrient budget should be developd before implementation of a plan to alter the trophic status of any lake and should include an accurate assessment of the groundwater contribution.

When applying predictive models precise field measurements should be used whenever available instead of estimates and generalizations.

STUDY DESIGN AND PROCEDURES

The EPA field program began in June 1971. Seven lake sampling stations were established. Silent Creek, the major inlet, and Lake Creek, the only outlet, were sampled for chemical characterization and to aid in determining a nutrient budget. Hydrologic information was provided by the U.S. Geological Survey (USGS). Three lake stations were on the central axis and four around the periphery, adjacent to the campgrounds, summer homes and resort. At the three deeper, center stations, water was collected at 5-meter depth intervals starting at the surface (e.g., 0, 5, 10, 13 m at the deepest station). Samples were collected at the surface and 5 m from the peripheral stations.

In 1973 sampling of Short Creek was initiated, but the number of lake sampling sites was reduced to 4 by eliminating the Thielson View, north-center and south-center stations. A two way analysis of variance, with dates and sites as the factors, demonstrated no significant chemical differences between lake stations at the 0.05 level of significance. In 1974 water sampling at the 3 peripheral stations was discontinued for the same reason, but benthic macroinvertebrate sampling was continued. This same year, intermittent tributaries were added. Camp, Dry, Porcupine, Rabbit, Spruce and Two Bear Creeks were sampled to lend more precision to the nutrient budget. The four lake sampling stations retained throughout the study are shown in Figure 2.

Sampling was monthly from soon after ice-out until the weather became restrictive, usually in October. Winter samples were collected through the ice in 1972 and 1975.

Lake water was collected with a PVC Van Dorn bottle and distributed to polyethylene containers. Tributaries were sampled by dipping the polyethylene containers directly. Specific conductance, pH and dissolved oxygen (DO) determinations were done in the field, *in situ* when possible. From 1975-77, a multiple parameter sensing unit was used. The New England Research Associates, Inc. Model 4 Environmental Monitor (NERA Inc, Bedford, MA) recorded *in situ* temperature, conductance, pH, DO, redox potential and depth. Earlier DO analysis followed the azide modification of the Winkler method. Data were recorded at 1 m intervals from surface to bottom at the center station. Transparency was measured with a 20 cm Secchi disc.

Chemical analyses generally were done at the EPA laboratory in Corvallis. Samples for nutrient and metals analysis were field stabilized with mercuric chloride and nitric acid, respectively, before transportation. Standard EPA methodology (EPA, 1971) generally was followed.

Chlorophyll analyses were conducted according to Strickland and Parsons (1965) as modified by EPA (1973), and primary productivity was assessed by the ^{14}C method described by Goldman *et al*. (1971). Light was measured with a

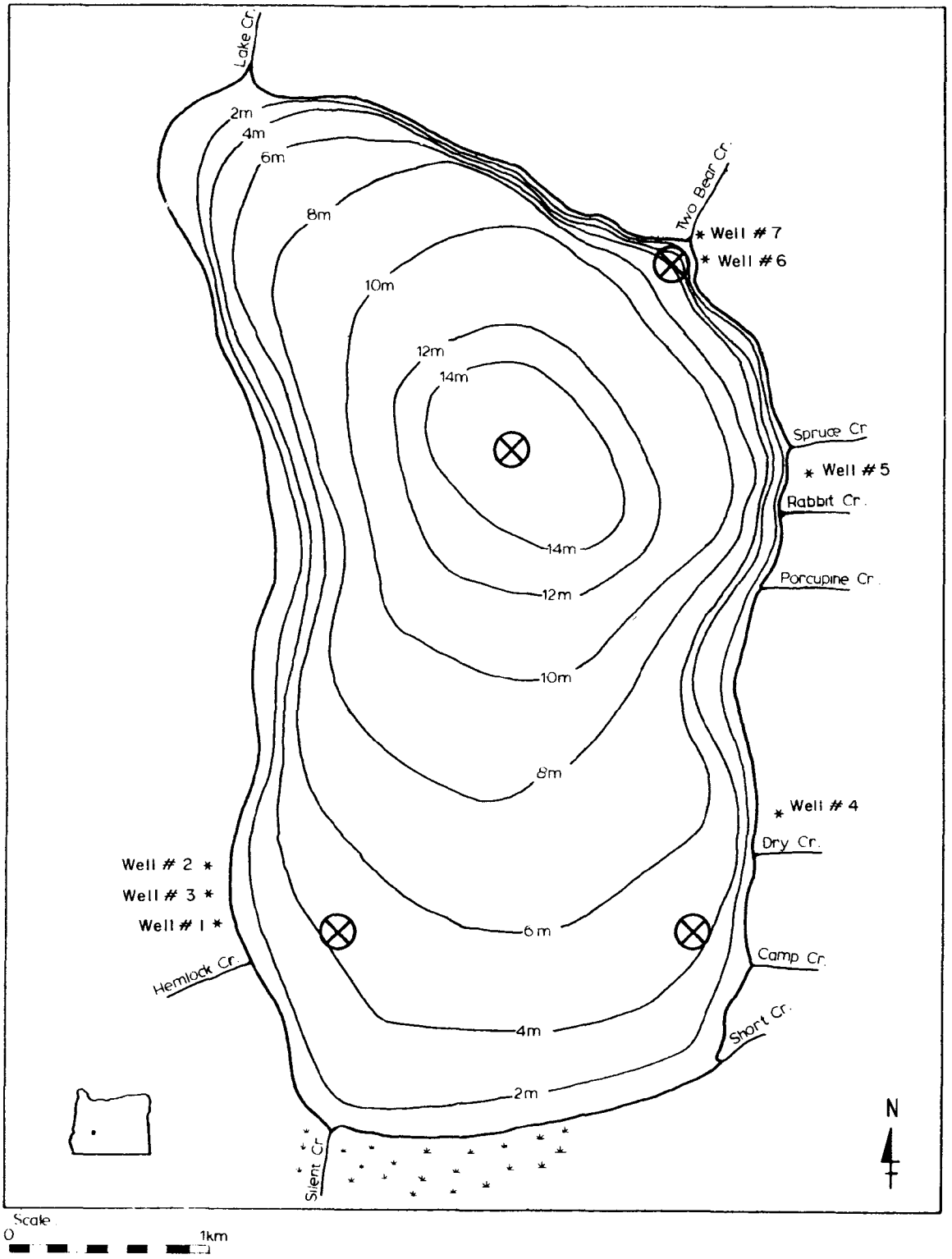

Figure 2. Lake bathymetry and sampling sites.

Lambda Instruments LI 185 Quantum/Radiometer/Photometer with a LI 192S underwater quantum sensor. Measuring sensitivity was between approximately 400 and 700 nm.

Phytoplankton samples were collected along with those for chemical analysis. From 1971 to 1973 they were preserved in 3-5% formalin and counted using a Sedgewick-Rafter counting cell in a modification of the clump count (American Public Health Association, 1971). The modification involved determining an average number of cells for all filamentous forms and multiplying this by the number of filaments to give a final estimated cell number.

Samples collected from 1974 through 1977 were preserved with Lugol's solution and counted and identified using an inverted microscope (Lund, 1958, EPA, 1973). Direct cell counts were made except in the case of forms such as Eudorina, Pandorina, Coelastrum and Gloeotrichia where colonies were counted. Counts of Melosira and Oscillatoriaceae were expressed as number of 100 µm lengths and included with the cell counts.

Center station profiles have been reduced to a volume weighted mean (VWM) for the lake. Using a bathymetric chart a volume was associated with each of the depths sampled. For example, the volume associated with the 10 m sample is:

$$V_{10} = [(A_{7.5} + A_{11.5})/2] \times (11.5 \text{ m} - 7.5 \text{ m})$$

where $A_{7.5}$ = the area associated with the 7.5 m contour and $A_{11.5}$ = the area of the 11.5 m contour. The solution (V_{10}) would be the volume of a cylinder with base area $(A_{7.5} + A_{11.5})/2$ and length (11.5 m - 7.5 m). A similar calculation was made for the other sample depths using appropriate contour areas and lengths of water column. The whole lake VWM for any parameter, then, would be:

$$\bar{x} = \sum_{i=0}^{4} V_i \cdot x_i \ / \ V_L$$

where V_i = the volume of the sampled strata; x_i = the concentration of the sampled strata and V_L = the sum of the volumes of the 4 strata (the volume of the lake).[1] Chemistry samples were generally collected at 0, 5, 10, and 13 m. Primary productivity and chlorophyll a were usually measured at 0, 1, 4, 7, 10, and 13 m. The calculation strategy is the same for both regimes. All lake concentrations and phytoplankton cell numbers discussed are VWM's unless otherwise defined. The average concentrations for the various tributaries are arithmetic means - not volume weighted according to flow.

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1 Hutchinson (1957) describes the formula for volume of a lake stratum as

$$V_{n-m} = (A_m + A_n = \sqrt{A_m \cdot A_n})(n-m)/3$$

Calculations demonstrate that while the volume of the discreet strata do differ by as much as 6%, the VWM's do not change.

Triplicate benthos samples were collected in 1971 and 1972 with a Ponar grab, washed in the field through a U.S. Standard No. 30 (0.59 mm) mesh screen and preserved in 10% formalin. In subsequent years, four samples were collected at each site. A U.S. Standard No. 60 (0.25 mm) mesh screen was used in laboratory sample rinsing to reduce the loss of small forms. The retained organisms were preserved in 70% alcohol, and, where possible, identified to species.

Benthic community structure was characterized with several common measures or indices. Estimates of richness (number of species) and diversity (a function of richness and species frequency distribution) were calculated from only the number of identified species plus taxa apparently composed of only one species rather than the total number of taxa, to increase the reliability of station-to-station comparisons.

Species areal richness, expressed here as the number of species per single grab was calculated according to Hurlbert (1971). The following indices were calculated from pooled replicate grab samples at each station. Dominance concentration as indicated by Simpson's diversity index (Simpson, 1949) gives the probability that any two individuals drawn from a multispecies assemblege will be the same. This index is not greatly affected by sample size; its complement (McIntosh, 1967) was calculated to relate it positively to diversity:

$$1 - S.I. = \sum_{i=1}^{S} \frac{n_i (n_i - 1)}{N (N - 1)}$$

Where N is the number of individuals, n_i is the number of individuals in the ith species and S is the number of species.

Species diversity, as indicated by the popular Shannon-Weaver expression (Pielou, 1970)(a measure of the mean diversity per individual integrating concepts of both richness and species frequency), was calculated by:

$$H' = -\sum_{i=1}^{S} \frac{n_i}{N} \log_{10} \left(\frac{n_i}{N}\right)$$

Numerical classification or cluster analysis of the data (Boesch, 1977; Swartz, 1978) was performed using the program CLUSTER on Oregon State University's CDC 3300 computer to describe spatial and temporal faunal homogeneity between collections.

DIAMOND LAKE CHARACTERISTICS

STUDY SITE

Diamond Lake has a surface area of 1243 ha and a total watershed of approximately 142 km^2. Maximum depth is 14.3 m while the average is 7.2 m. The volume is approximately 9.02×10^7 m^3. Hydraulic retention time averages 1.5 years. The lake is elongated on a north-south axis, approximately 5.5 km long by 2.5 km wide (Figure 2). Basin morphometry is regular with a single central depression.

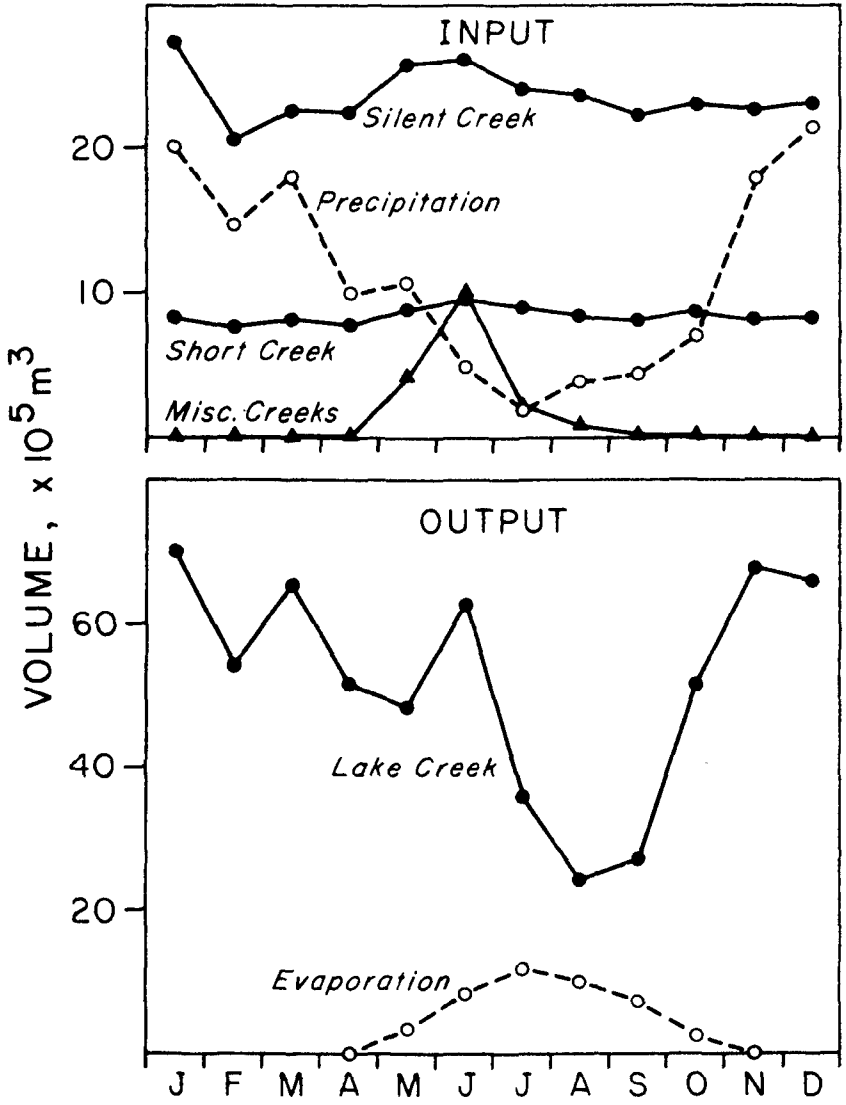
The topography and geology of the area is dominated by its volcanic history. The basin is flanked by the High Cascade volcanoes, Mt. Thielson (2799 m) and Mt. Bailey (2549 m). Timber Crater (2256 m) marks the southern point of the watershed. The soils are in the "Crater Lake Series," porous and well drained, with greater than 1.5 m volcanic ash and pumice (D. Hanson, Soil Scientist, Douglas Co. OR, pers. comm.). They include glacial debris, pumice and ash from the eruption of Mt. Mazama which collapsed to form the caldera containing Crater Lake (Purdom, 1964). The bedrock is basaltic, the remnant of lava flows from Mts. Bailey and Thielson.

The watershed contains mostly coniferous forest with lodgepole pine (*Pinus contorta*), mountain hemlock (*Tsuga mertensiana*), and firs (*Abies* sp.) predominating. The groundcover includes huckleberry (*Vaccinium* sp.), grasses (Graminae), sedges (*Carex* sp.), and manzanita (*Arctostaphylos* sp.) (Meyerhoff, 1977). At the south end of the lake is a 60 ha marsh.

HYDROLOGY

Silent Creek drains an area of approximately 36 km^2 at the southwest corner of the lake's watershed, accounting for about 25% of the total. The water is generally very cold and clear. After a storm in 1977, however, the stream was humic brown, suggesting an influence from the marsh through which it flows. Silent Creek accounted for an average of 56% of the total measurable inflow during the study. Percent contribution ranged from 26% during a month of extreme precipitation to 78% when precipitation was negligible. Maximum recorded flow was 3.233×10^6 m^3/mo for June 1972, while the minimum was 1.715×10^6 m^3/mo recorded for February 1974. The average annual input for the study period was 28.005×10^6 m^3/yr (Figure 3).

The other major tributary, Short Creek, averaged 20% of the measurable inflow. The range for monthly flow over the study period was 0.613×10^6 m^3/mo to 1.370×10^6 m^3/mo with an annual average of 10.007×10^6 m^3/yr. The stream originates as a large spring only a few hundred meters from the lake and runs extremely cold and clear throughout the year.



MONTH	Vol. ($\times 10^5 m^3$) IN	OUT
Jan	56.14	69.91
Feb	42.85	53.72
Mar	49.06	65.26
Apr	39.42	51.17
May	49.31	51.06
Jun	51.04	70.53
Jul	37.49	47.34
Aug	36.37	33.97
Sep	34.85	33.98
Oct	38.79	53.72
Nov	48.97	67.83
Dec	53.05	65.46

Figure 3. Average monthly hydrological budget (1972-1977).

The intermittent tributaries to Diamond Lake have significant flow only during snow melt. Their maximum contribution was 30% of the directly measurable inflow, 1.863 x 10^6 m^3/mo in June 1974. The average annual contribution was only 3%.

Precipitation was measured as water falling directly onto the lake. In November 1973 it accounted for 64% of that month's directly measurable input at 5.084 x 10^6 m^3/mo (41 cm). Maximum contribution generally occurred in the winter (Figure 3). Yearly precipitation ranged from a low of 65 cm in 1976 to a high of 127 cm in 1975, averaging 19% of the measurable input over the study period.

Groundwater input was estimated by subtracting measurable inflow from measurable outflow. Over the six-year study period an average 21% of the outflow was unaccounted for by measured inflow and was attributed to groundwater.

Water loss has three possible significant components: surface outflow, evaporation and groundwater export. The USGS supplied data for the first two but no estimate for groundwater export could be gained. Since measured outflow was greater than inflow throughout the study, groundwater losses were assumed to be zero.

Surface outflow is continuous but the rate is regulated by the DFW. Flashboards are generally installed in Lake Creek after spring runoff to maintain the lake level during the summer, then removed in the fall. Maximum outflow is generally in the winter (Figure 3) but the highest flow gaged was in June 1974, at 10.711 x 10^6 m^3/mo. Minimum flow measured was 1.040 x 10^6 m^3/mo in September 1975.

Greatest evaporation occurs in July or August. The maximum reported over the study period was 1.431 x 10^6 m^3 for July 1973. In August 1974, evaporation was reported equal to Lake Creek outflow.

NUTRIENT BUDGET

Major nutrient sources to Diamond Lake include tributaries, groundwater, precipitation, bottom sediments and human activities. Total natural load is defined as the sum of the loads from the tributaries, precipitation and groundwater.

Silent Creek, the dominant hydrologic influence, is also the main source of phosphorus (P). Over the study period the average total phosphorus concentration (TP) for Silent Creek was 0.056 mg/l. Its average yearly P contribution was 1549 kg, accounting for an average 61% of the total measurable natural load (Table 2).

The P contribution from Short Creek averaged 22% of the total natural load from 1972 through 1977 (Table 2). The average concentration was approximately 0.055 mg P/l resulting in an average yearly load of 548 kg.

TABLE 2. NUTRIENT CONTRIBUTIONS FROM NATURAL SOURCES

	Silent Cr.		Short Cr.		Interm Str.		Precip.		Ground H_2O		TOTAL
					Phosphorus						
	kg	%tot	kg	%tot	kg	%tot	kg	%tot	kg	%tot	kg
1972	1766	57	691	22	162	5	125	4	353	11	3097
73	1586	65	527	22	6	0	129	5	201	8	2449
74	1320	57	409	18	105	5	126	5	341	15	2301
75	1429	56	589	23	58	2	137	5	341	13	2554
76	1528	64	522	22	57	2	71	3	218	9	2396
77	1662	67	549	22	16	1	96	4	143	6	2466
Avg	1549	61	548	22	67	3	114	4	266	10	2544
					Inorganic Nitrogen						
	kg	%tot	kg	%tot	kg	%tot	kg	%tot	kg	%tot	kg
1972	262	4	259	4	60	1	515	7	6271	85	7367
73	640	13	338	7	1	0	529	10	3564	70	5072
74	412	6	200	3	43	1	516	7	6055	84	7226
75	457	6	168	2	24	0	565	8	6046	83	7260
76	355	8	177	4	27	1	291	6	3871	82	4721
77	313	9	133	4	5	0	395	12	2531	75	3377
Avg	407	8	213	4	27	1	469	8	4723	80	5837

The average concentration of the intermittent streams from 1973 through 1976 was 0.033 mg P/l. The intermittent streams were not sampled before 1973 and only Two Bear Creek had significant flow in 1977. Two Bear Creek exhibited the highest average TP of all sources measured, approximately 0.071 mg/l. It drains the resort complex. The TP contribution from the intermittent streams was only about 3% of the total, insignificant compared to the major tributaries and groundwater.

Groundwater loading was estimated from analyses of well water (Table 3, Figure 2) together with surface outflow minus inflow volume calculations. The P load was based on total dissolved phosphorus (TDP) rather than TP since the turbid well water resulted in unrealistically high TP concentrations (mean = 0.287 mg/l, n = 26, excluding 2 values of 11.9 and 5.1 mg/l). Average TDP was 0.020 mg/l (n = 27, one value of 0.48 mg/l excluded). The groundwater contribution, then, averaged an estimated 10% of the external P load. Average yearly load was 266 kg.[1]

Precipitation, while averaging approximately 19% of the yearly inflow, contributed only about 4% of the annual P load. Total phosphorus concentration of precipitation was estimated from analyses of composited snow cores collected in the springs of 1973, 74, 75 and 76 (Table 4). The average was <0.009 mg P/l. Loading from direct precipitation on the lake averaged 114 kg/yr.

TABLE 4. SNOW ANALYSIS

Date	TP	TSP	DOP	NH_3	NO_2	NO_3	KjlN
12/15/73	<.005	<.005	.004	.021	.001	.018	.3
05/10/74	.01	<.005	.01	--	--	--	.3
03/05/75	<.01	<.01	<.005	.024	--	--	<.1
06/05/75	<.01	<.01	<.005	.005	--	--	.1
05/20/76	.01	.01	.005	.03	--	--	.15
AVG	<.009	<.008	<.006	.02	--	--	<.19

Sediment samples collected in 1971 averaged 520 µg P/g dry sediment with a range of 340 to 700 µg/g (Sanville and Powers, 1971). Interstitial water averaged 250 µg ortho phosphate-P/l. No attempts were made to measure P contribution from sediments directly. Yearly nutrient loading calculations for 1972 through 1976 show an average retention of approximately 40% of the external P load. In 1977, however, it appears that 2% more left the lake than entered (Table 5).

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1 Short Creek might be representative of groundwater. The creek is essentially a spring which enters the lake after flowing above ground only a few hundred meters. If Short Creek data were used, the average TP load from groundwater would be 746 kg/yr or an average of 25% of the total load.

TABLE 3. WELL WATER ANALYSIS

		1 Summer Homes #1	2 Summer Homes #2	3 Summer Homes #3	4 Campsite R6	5 Trailer Disposal	6 Resort Cabins	7 Resort Parking
TP (mg/l)	06/14/72	.003	.08	.16	.94	.029	5.1	.082
	06/26/72	.03	.208	.381	11.9	.243	1.57	.4
	07/10/72	.002	.054	.077	.115	.008	.055	.058
	07/25/72	.016	.050	.075	.385	.32	.240	1.87
TSP (mg/l)	06/14/72	.012	.004	.002	.005	.015	.001	.008
	06/26/72	.001	<.001	<.001	.004	.002	<.001	.014
	07/10/72	.001	.002	<.001	.003	<.001	<.005	.022
	07/25/72	.056	.11	.061	.072	.084	.053	.48
TIN (mg/l)	06/14/72	.113	.043	.055	.197	.357	.164	.936
	06/26/72	.032	.025	.049	.324	.875	.143	1.226
	07/10/72	.032	.060	.053	.395	.838	.184	1.683
	07/25/72	>.003	.055	.054	.308	.868	.171	>.177

TABLE 5. PHOSPHORUS INPUT* MINUS OUTPUT

Year	Input (kg TP)	Output (kg TP)	In-Out	% Retention
1972	3097	2619	478	+ 15
73	2449	1499	950	+ 39
74	2301	858	1443	+ 63
75	2554	1256	1298	+ 51
76	2396	1510	886	+ 37
77	2466	2514	-48	-2

* Refers to "natural" input by tributaries, groundwater and precipitation.

One indirect approach for determining sediment P contribution involves accounting for the change in the mass of P in the water over some time period, the load into the lake and the export from the lake (Schindler et al., 1973). Total mass of P at any time is calculated from the lake volume and the TP volume weighted mean. For application of this approach two time periods were distinguished, summer and winter. Since tributaries were not sampled during the winter, concentrations were estimated by averaging the last three analyses of the preceding summer with the first three of the succeeding summer (e.g., August 18, September 15 and October 14, 1976 with April 28, June 2 and July 20, 1977). Winter external loading (import and export) values are not as reliable as those for summer and may limit confidence in the sediment P release calculations. (Note: Two TP analyses of Silent Creek were uncharacteristic, 0.310 mg/l on October 7, 1971, and 0.270 mg/l on August 7, 1974, and were disregarded as outliers in all loading and budget calculations.)

Sediments showed a net P accumulation from September 1971 to October 1977 (Table 6). However, substantial quantities were apparently released in the winters of 1973-74 and 1976-77. The greatest calculated release was 2316 kg during the winter of 1976-77. Considering that the greatest sediment P contribution probably originates below 13 m where low DO is common, this quantity is comparable to P release determined by Larsen et al. (1978) in Shagawa Lake, Minnesota. Maximum accumulation of P also appeared to occur during winter periods--the winter of 1971-72 being highest at 7063 kg.

Rooted aquatic vascular plants might be another possible internal nutrient load source. At maximum density approximately 30-50% of the bottom of Diamond Lake is covered by vegetation. This area occupies the zone roughly between 2 and 8 meters. No attempts were made to measure P contribution from this source, but excretion of P by aquatic vascular plants is well documented (e.g., McRoy et al., 1972 and DeMarte and Hartman, 1974). Death and decay of the plants in the fall would also add to the phosphorus pool. Large mats of Elodea and Potomogeton wash up on the shore during storms, indicating the potential for a large nutrient influx. Every fall waterfowl arrive in great numbers at Diamond Lake. Feeding on aquatic weeds, they hasten the decomposition of the plants and the recycling of the contained nutrients.

TABLE 6. SEDIMENT CONTRIBUTION TO TP

Period	Δ Lake TP Mass (kg)	In-Out (kg)*	Sediment Release (-) or Accumulation (+)
09/27/71-05/24/72	-8209	-1146	+7063
05/24/72-08/22/72	+ 451	+ 326	- 125
08/22/72-05/23/73	-2345	+ 719	+3064
05/23/73-10/18/73	- 541	+ 506	+1047
10/18/73-06/05/74	+1804	+ 234	-1570
06/05/74-10/09/74	+ 631	+ 532	- 99
10/09/74-06/05/75	+1083	+ 909	- 174
06/05/75-10/22/75	- 541	+ 535	+1076
10/22/75-05/20/76	-2255	+ 311	+2566
05/20/76-10/14/76	+ 631	+ 456	- 175
10/14/76-04/28/77	+2706	+ 390	-2316
04/28/77-10/27/77	-1804	+ 99	+1903
		Net	+12,260 kg

* Refers to "natural" input by tributaries, groundwater and precipitation minus output by Lake Creek.

Analysis of rainbow trout taken from the lake indicated a dry weight concentration of 1.7% P. Table 7 shows that the annual fish harvest removes a substantial amount of P. The record catch of 1973 removed approximately 550 kg P. Stocking of trout is a minor nutrient source. The average yearly total mass of fish stocked from 1971 through 1977 was 3450 kg, amounting to only approximately 15 kg P.

Fishing practices can contribute to the nutrient load. McHugh (1972) reported an estimate of one ton (~900kg) of cheese used in Diamond Lake in less than one week as bait. Assuming 10,400 angler days in a busy week (July 2, 3, 4, 1977, recorded 4472 angler days)(J. Bauer, District Fishery Biologist, DFW, pers. comm.) and 0.77% P in pasteurized processed American cheese (wet weight)(Adams, 1975), the 1977 fishing season (102,043 angler days)(J. Bauer, pers. comm.) could have added nearly 70 kg P to the lake. This quantity is about the same as the annual contribution from all intermittent streams averaged over the study period.

Total inorganic nitrogen (TIN) appears to be dominated by the groundwater. Analyses of unfiltered well water averaged 0.355 mg TIN/l (Table 3). While all other surface sources averaged less than 10% of the yearly load (Silent Creek and precipitation each averaged 8%) the groundwater averaged 80% (Table 2).[1] The average total yearly load was 5837 kg TIN/yr, however, no attempt was made to quantify nitrogen fixation and denitrification, processes that greatly complicate N dynamics in an aquatic system.

Maximum P and N diverted by the wastewater system were estimated. Samples of wastewater collected at the main pumping station between 1973 and 1976 averaged 5.59 mg P/l (Table 8). Information supplied by the USFS (R. Sawyer, District Engineering Assistant, Diamond Lake Ranger District, USFS, pers. comm.) showed that lagoon influent totaled 5.96×10^4 m^3 in 1976 with 5.58×10^5 visitor days and 5.67×10^4 m^3 in 1977 with 5.69×10^5 visitor days (avg. = 0.103 m^3/visitor day). Total influent includes groundwater intrusion to the system. The maximum P diverted for 1976 and 77 was approximately 333 and 317 kg, respectively, or 14 and 13% of the natural loadings for those years. Total inorganic nitrogen averaged greater than 12.39 mg/l, equivalent to a maximum diversion of over 738 kg in 1976 and 703 kg in 1977.

Algal assays of water collected from Diamond Lake in July 1971 showed P to be the potential limiting or algal growth controlling nutrient at that time (Miller et al., 1974). A sample collected at the end of March 1972, also showed potential P limitation (T. Shiroyama, unpublished data). Other analyses by Shiroyama indicated N limitation in March and August 1973. The National Eutrophication Survey (EPA, 1978) reported N limitation in July and October 1975, based on N:P ratios. The nutrient limiting algal growth does commonly change in productive lakes (Greene et al., 1976). Phosphorus could become limiting during a bloom as it is incorporated in the biomass. Relative

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1 TIN from Short Creek averaged approximately 0.021 mg/l. Using this value the average load from groundwater would be approximatly 280 kg TIN/yr or 20% of the average total load which would be reduced to about 1400 kg/yr. See note p. 16.

TABLE 7. FISHERY CONTRIBUTION TO PHOSPHORUS BUDGET

	1971	1972	1973	1974	1975	1976	1977
Wet Weight Fish Stocked (kg)	3640	2712	2091	3688	5922	3037	3057
Phosphorus Content Fish Stocked (kg) *	16.0	11.9	9.2	16.2	26.1	13.3	13.5
Wet Weight Fish Caught (kg)	87,276	76,271	128,122	127,959	91,953	75,397	94,749
Net to (+) or from (-) Lake (kg TP)	-368.0	-323.7	-554.5	-546.8	-378.5	-314.4	-403.4

* Analysis of Diamond Lake Trout showed: P = 1.68% x dry weight, and
Dry Weight = 26.4% x wet weight
Therefore, P = 0.0044 x wet weight

Stocking and harvest data from Jerry Bauer, Ore. DFW

TABLE 8. TP AND TIN IN WASTEWATER

Date	TP (mg/l)	TIN (mg/l)
05/24/73	0.06	0.005
06/19/73	5.15	28.14
07/17/73	8.75	22.27
08/15/73	6.6	---
08/26/73	0.97	5.59
09/12/73	2.7	15.12
03/05/75	0.8	>2.1
08/14/75	14.5	>21
09/19/75	9.5	>9.1
08/19/76	---	≥14
10/15/76	6.9	---
04/29/77	---	6.61
Avg.	5.59	>12.39

to the nutritional requirements of algae, however, (Miller et al., 1976) the external loading figures suggest that N is proportionately less well supplied to Diamond Lake than is P. Nitrogen limitation of algal growth might be expected.

PHYSICAL AND CHEMICAL PROPERTIES

The lake is a temperate, dimictic water body which completely mixes in the spring and fall, stratifying in the summer and in winter under ice. It has been described as mesotrophic to eutrophic based on identification of diatom frustules in the sediments (Meyerhoff, 1977). Sanville and Powers (1971) characterized the lake as "quite productive" but not extremely eutrophic.

Total phosphorus concentrations decreased from 1971 to 1973 (Figure 4). Averages for those years were 0.062 and 0.028 mg P/l respectively, a reduction of over 50%. After 1973, however, there was a gradual increase, reaching 0.051 mg/l for 1977. The maximum TP, 0.133 mg/l on September 27, 1971, is uncharacteristic.

Total phosphorus data from 1971 through 1975 were pooled and compared by "t" test at the 0.05 level of significance to pooled data from 1976 and 1977 when the diversion was complete. The 1976/77 average, 0.05 mg/l, was significantly higher than the average of the previous five years, 0.03 mg/l (excluding the 0.133 mg/l value from 1971). The 1977 average, again approximately 0.05 mg/l, is different at the 0.01 level under the same condition.

The reasons for the increase are unclear: natural variability is probably the dominant factor. At approximately 670,000 visitor days, 1976 and 1977 are only about 13% higher than the 1975 recreation use total and virtually all of that increase was served by the wastewater diversion system (Table

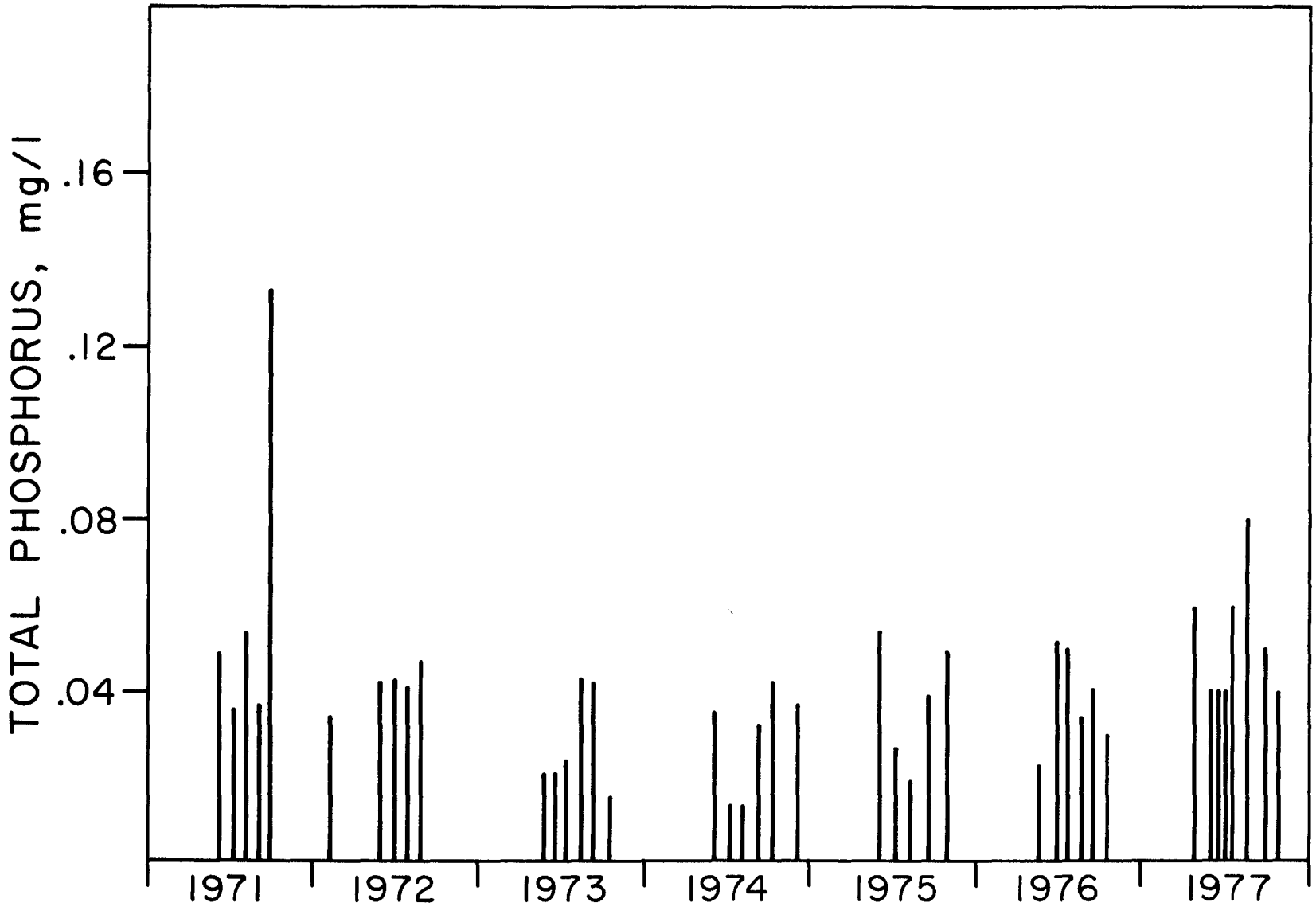

Figure 4. Total phosphorus volume weighted means.

1). Inflow dropped by over 20% from 1975 to 1976 and another 10% from 1976 to 1977. This would extend the hydraulic retention time of the lake which would tend to exacerbate eutrophic conditions. At the same time, however, the natural nutrient loading decreased with the inflow (Table 2). The data show (Table 5) that in 1977 P washout exceeded natural input and Table 6 indicates that the sediments are responsible for releasing large amounts of P. Sediment release apparently provided sufficient P to stimulate and maintain a large phytoplankton population during the summer of 1977. Apparently it reaccumulated in the sediments by the end of the summer.

Total inorganic nitrogen yearly averages show no particular pattern (Figure 5). The maximum concentration was 0.389 mg TIN/l on August 14, 1973 and relatively high values were found in 1972, 1976 and 1977. Over the whole study period, however, 28 of the 34 values were less than 0.060 mg/l (Table 9). Total inorganic nitrogen was not determined in 1974.

The initial Secchi disc measurement each year was at or near the lowest value for that year (Figure 6). The lowest recorded transparency was 2.1 m on September 27, 1971, but similar measurements were made in June 1971 and April 1977. Highest values for any given year generally occurred in early summer, with a maximum of 10.5 m observed on June 27, 1972, and again on July 10, 1974. The highest yearly average was 7.4 m in 1974; the lowest was 4.1, in 1971.

The Secchi disc data suggest an improvement in water transparency. The proportion of measurements >5 m is higher for 1976/77 than for 1971-75. In 1977 the average summer Secchi disc reading was 6.3 m (SD 1.99, n = 7). The DFW measured transparency biweekly in the summer of 1963; their average was 6.0 (SD = 2.60, n = 7). On July 18, 1961 they reported 11.6 m, the highest value recorded, but that same year they also reported the lowest value, 1.8 m on August 21.

Dissolved oxygen depletion occurs below 10 m in both summer and winter. Values less than 5 mg/l were recorded each summer at 13 m, with a low of 0.1 mg/l on August 18, 1977 (Table 10). Lowest summer DO was recorded in either July or August of each year except 1971 when 0.2 mg/l was measured at 13 m on September 1. September storms generally caused overturn and reoxygenated the lower strata. Winter DO was measured under the ice on February 2, 1972 and March 3, 1975. Bottom DO was very low in both cases, 0.5 and 1.5 mg/l, respectively. Values <5 mg/l extended as high as 10 m in July and August of 1971 and 1977 as well as in both winter samplings. Low DO in the hypolimnion was apparent as early as 1946. In August of that year the DFW reported 4.8 and 0.3 mg DO/l at 13.7 and 15.2 m, respectively (Locke, 1947).

Diamond Lake pH ranged from a high of 9.8 at the surface on June 4, 1971 to a low of 5.5 at 13 m on August 22, 1972. The highest value for any day usually occurred between 4 and 7 m, while the lowest was at the bottom.

PRIMARY PRODUCERS

Algal cell counts from 1971 through 1973 can not be compared to 1974 through 1977 numbers because of different counting techniques (the latter period generating higher numbers). However, the pattern of phytoplankton numbers

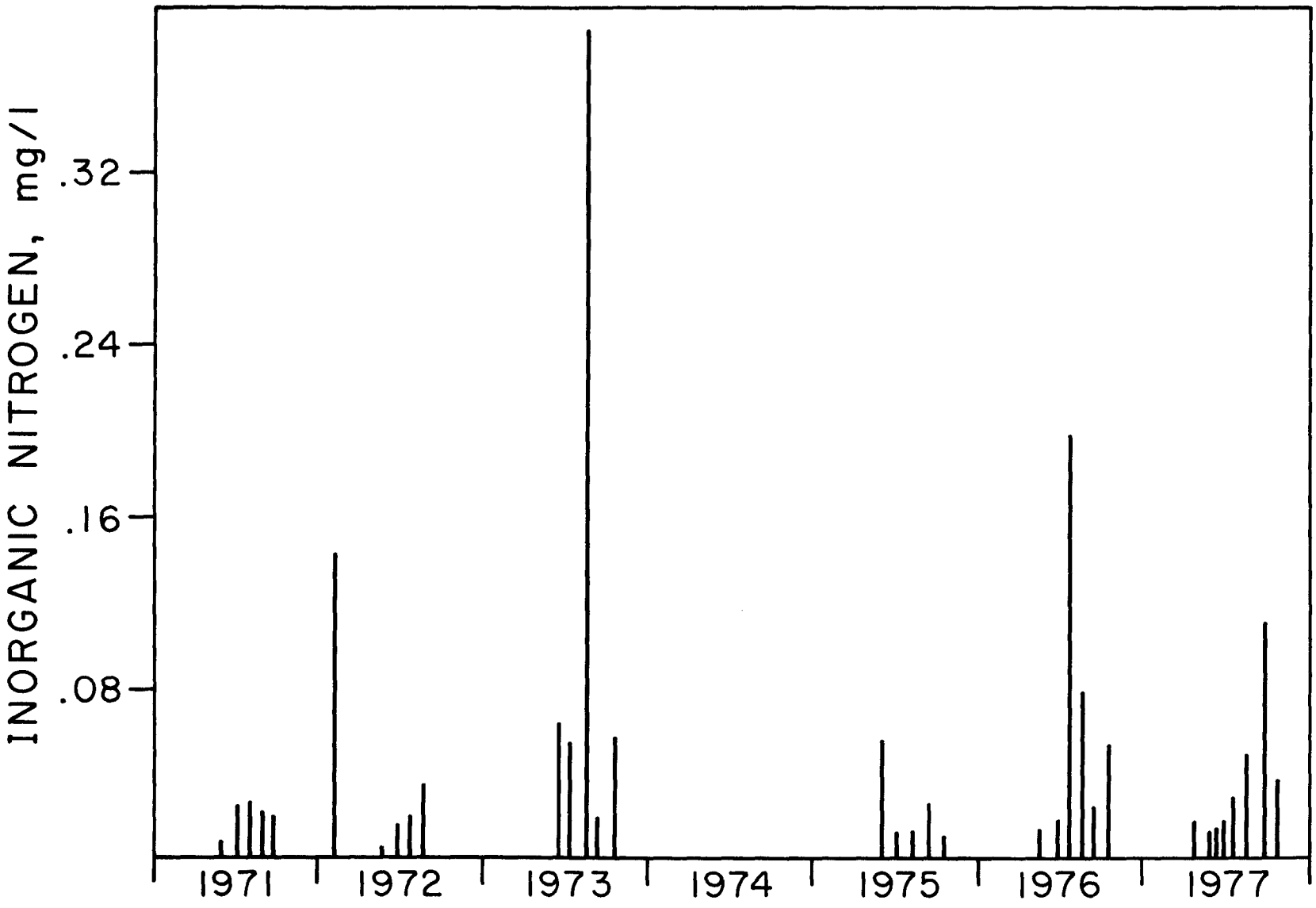

Figure 5. Total inorganic nitrogen volume weighted means.

TABLE 9: TP AND TIN VOLUME WEIGHTED MEANS (MG/L)

									Annual Average
	1971								
	06/03	07/07	08/03	09/01	09/27				
TP	.048	.036	.054	.037	.133				.062
TIN	.006	.024	.025	.021	.019				.019
	1972								
	02/02	05/24	06/29	07/24	08/22				
TP	.034	.042	.043	.041	.047				.041
TIN	.143	.003	.014	.019	.035				.043
	1973								
	05/23	06/18	07/10	08/14	09/11	10/18			
TP	.021	.021	.024	.043	.042	.015			.028
TIN	--	.064	.055	.389	.018	.058			.117
	1974								
	06/05	07/10	08/07	09/12	10/09	12/03			
TP	.035	.013	.013	.032	.042	.037			.029
TIN	--	--	--	--	--	--			--
	1975								
	03/04	06/05	07/09	08/13	09/18	10/22			
TP	--	.054	.027	.019	.039	.048			.037
TIN	--	.056	.011	.012	.025	.012			.023
	1976								
	05/20	06/29	07/21	08/18	09/15	10/14			
TP	.023	.052	.050	.034	.041	.030			.038
TIN	.013	.017	.199	.079	.024	.054			.064
	1977								
	04/28	06/02	06/15	06/30	07/20	08/18	09/27	10/27	
TP	.06	.04	.04	.04	.06	.08	.05	.04	.051
TIN	.017	.012	.014	.017	.029	.050	.111	.037	.036

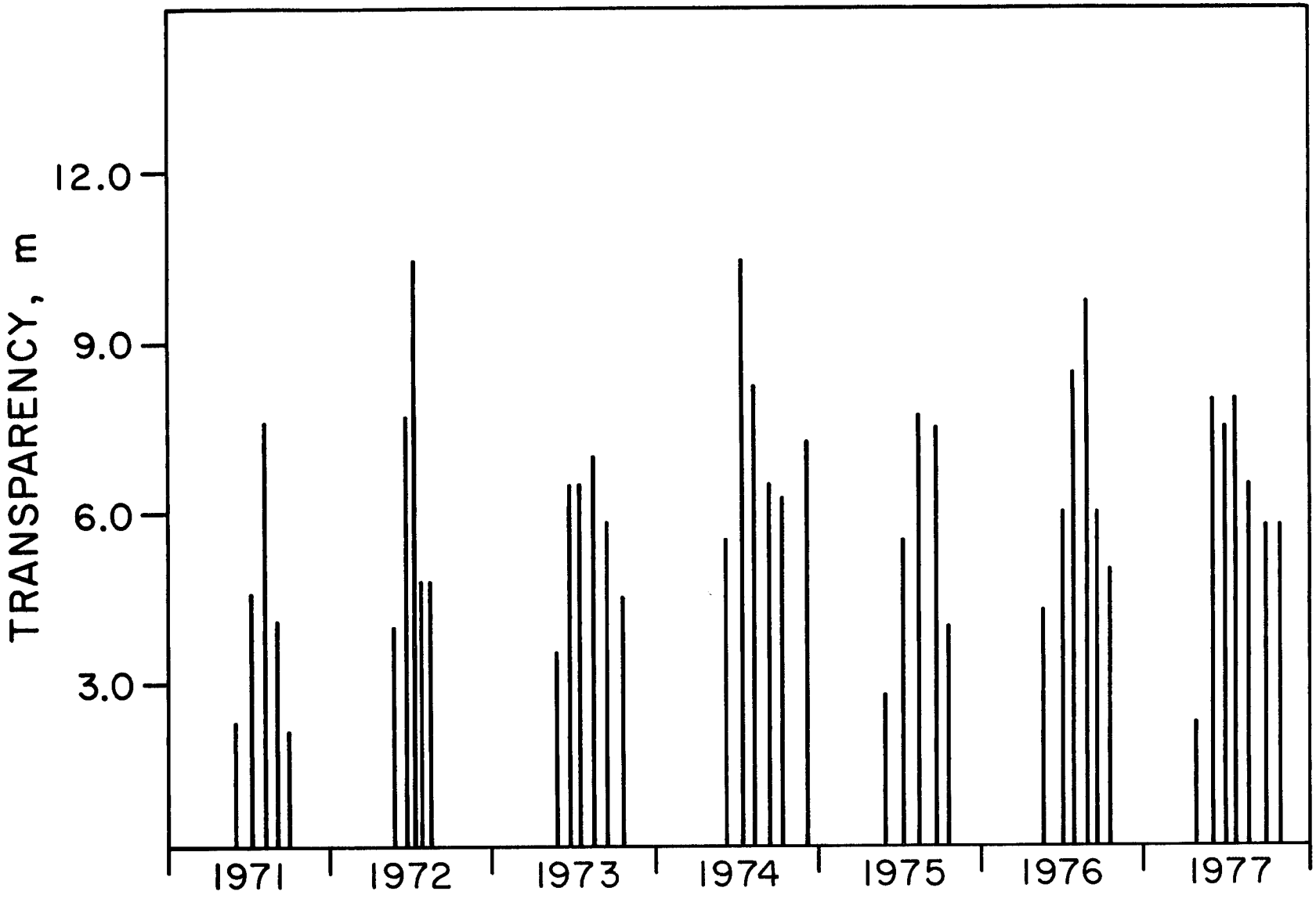

Figure 6. Secchi disc transparency.

TABLE 10. DISSOLVED OXYGEN AT 13 M (MG/L)

1971

Date	06/03	07/07	08/03	09/01	09/27
D.O.	9.9	1.9	0.7	0.2	7.8

1972

Date	02/02	05/24	06/29	07/24	08/22	09/25
D.O.	0.5	5.3	5.0	2.6	7.6	7.8

1973

Date	05/23	06/18	07/10	08/14	09/11	10/18
D.O.	9.2	4.0	5.4	2.9	6.0	9.4

1974

Date	06/05	07/10	08/07	09/12	10/09	12/03
D.O.	8.6	4.9	4.0	--	--	10.5

1975

Date	03/04	06/05	07/09	08/13	9/18	10/22
D.O.	1.7	2.6	7.2	1.2	2.7	9.1

1976

Date	05/20	06/29	07/21	08/18	09/15	10/14
D.O.	8.3	8.4	0.3	5.0	--	--

1977

Date	04/28	06/02	06/15	06/30	07/20	08/18	09/27	10/27
D.O.	11.1	8.7	--	2.5	1.7	0.1	8.3	8.7

over the study period is similar to the TP curve (Figure 7). Total cell numbers, averaged over each year, decreased from 1971 to 1973 and rose from 1974 to 1977, when the average reached approximately 9,000 cells/ml.

Initial samplings each year yielded relatively high counts, usually due to an early bloom of the diatom, Asterionella formosa (Table 11). The highest count of this species, 17,000 cells per ml, was recorded on June 4, 1971.

Almost exclusively Anabaena circinalis was the predominant blue-green alga in Diamond Lake, generally reaching substantial numbers by July or August and often the most numerous alga in September or October. Its earliest predominance was June 18, 1973, and it remained the most numerous alga for the rest of that season. The highest density recorded for Anabaena was 12,000 cells/ml on August 18, 1977.

Green algae dominated the phytoplankton on only a few occasions. The maximum concentration was 1200 cells/ml.

A Chrysophyte, Chromulina sp., seemed to become much more significant in the phytoplankton community after 1973, perhaps because of the change in counting technique. Its maximum concentration was 8200 cells/ml on July 10, 1974. In about one-half of the post-1973 samplings Chromulina was the dominant alga, including all of the 1977 samplings except August 18, when it was second to Anabaena.

Maximum chlorophyll a (Chl a) was 39.8 mg/m^3 on April 28, 1977. The highest annual average, 14.0 mg/m^3, also occurred that year. The lowest annual average was 4.8 mg/m^3 in 1973. The years 1976 and 1977 were unusual compared to previous years because spring Chl a was high at the initial sampling (Figure 8). Relatively high values at the end of the summer are characteristic of all years. The plot of Chl a resembles the pattern of TP and phytoplankton numbers.

Summer Chl a and TP were positively correlated at the 0.05 level over the whole study period. The average of pooled epilimnetic Chl a (not volume weighted) from 1976/77 was significantly greater than the 1971-1975 period, also at the 0.05 level, but 1976 alone is not significantly different from the preceding period suggesting that it is a transition year (R. Vollenweider, Senior Scientist, Canada Center for Inland Waters, pers. comm.).

Primary productivity (PP) peaked in 1973 with an annual average of 19.8 mg C fixed/m^3/hr. It then decreased through 1976, suggesting a response to the diversion. In 1977, however, a substantial increase again occurred (Figure 9). The highest PP was 31.3 mg C fixed/m^3/hr on September 11, 1973.

The distribution patterns of PP and Chl a are quite different. Primary productivity, a rate function, is affected by many variables during the incubation period while Chl a is essentially an instantaneous measurement, the result of an integration of variables. Phytoplankton self-shading could reduce PP and, correspondingly, the ratio of PP to Chl a. The species composition of the phytoplankton population could also affect the ratio as certain species have relatively less Chl a than others.

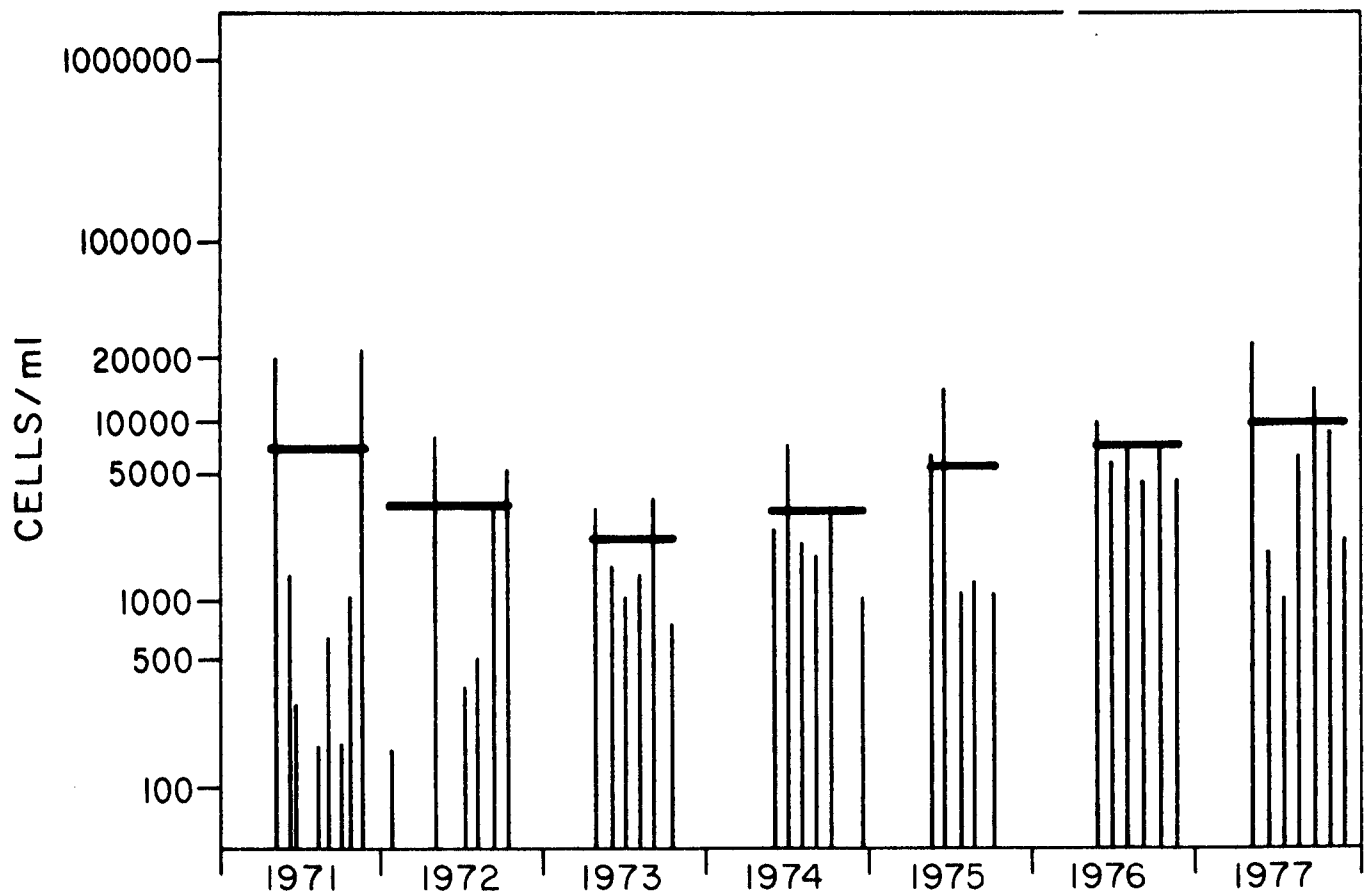

Figure 7. Total phytoplankton volume weighted means (horizontal bars indicate yearly means).

TABLE 11. DOMINANT PHYTOPLANKTON AT CENTER STATION, VOLUME WEIGHTED MEANS (EXPRESSED AS NUMBERS PER ML X 10^2)

	1971				1972						1973					
	06/03	07/07	08/03	09/11	02/02	05/24	06/28	07/25	08/22	09/26	05/23	06/18	07/10	08/14	09/11	10/18
Anabaena		8.5		1				3.6	27	26		15	2.6	13	35	5.3
Anacystis				0.2												
Ankistrodesmus	6.3															
Asterionella	170	3.5			1.3	59	3.1				32	5				
Chlamydomonas																
Chromulina																
Cryptomonas					0.3					0.5						
Cyclotella	5.2															
Dactylococcopsis			0.3													
Dinobryon cysts																
Fragilaria								0.6					0.7			
Golenkinia																
Heteromastix																
Melosira								0.1					0.4			
Nephroselmis																
Ochromonas																
Oocystis			0.7					0.2					0.5		0.8	
Rhodomonas																
Schroederia																
Sphaerocystis			0.5			0.1		0.3								
Staurastrum									1.0							
Stephanodiscus	5.2									0.4					1.1	1.7
Stipicoccus																
Synedra		0.1							3.9				1.2			1.2
Westella																
Green Flagellates	12	0.7	0.1	0.2	6.8					0.4				0.7		
Unident Flag's																
Unident Coccoids																
Unknown																

(Continued)

Table 11. Continued

	1974						1975						1976			
	06/05	07/10	08/07	09/12	10/09	12/04	03/03	06/05	07/09	08/13	09/18	10/15	05/20	06/30	07/21	08/17
Anabaena				10	8.4				12	3.2	2.2	6			42	
Anacystis																
Ankistrodesmus																
Asterionella	2.2							25	130				22	41	13	
Chlamydomonas					0.7	0.9										
Chromulina		82	0.6	3	11	5.1				3.5	2.1	2	20	43	12	21
Cryptomonas				1.1	6.2						1.5					
Cyclotella								17								
Dactylococcopsis																
Dinobryon cysts	3.4							5.1								
Fragilaria																
Golenkinia	2															
Heteromastix			12	1					4							
Melosira										2						
Nephroselmis																
Ochromonas	3.4		0.8				0.5				0.7					
Oocystis					1.7					2						
Rhodomonas	3.6		0.6	1.7		0.6										
Schroederia											2					7
Sphaerocystis			1.4		1					0.5						
Staurastrum																
Stephanodiscus												2.5	30			
Stipoccus																
Synedra												1.4				
Westella											1.2					
Green Flagellates														0.2		
Unident Flag's	5.3								5							
Unident Coccoids													7			
Unknown							14									

(Continued)

Table 11. Continued

	1976 (Cont'd) 09/15	10/14	1977 04/28	06/02	06/29	07/20	08/18	09/28	10/27
Anabaena	30	40				20	120	30	
Anacystis									
Ankistrodesmus									
Asterionella			92	0.8	0.4				
Chlamydomonas		4					10	12	
Chromulina	40	2	130	13	9	33	11	41	20
Cryptomonas		1.3							
Cyclotella									
Dactylococcopsis									
Dinobryon cysts									
Fragilaria									
Golenkinia									
Heteromastix									
Melosira									
Nephroselmis				3	0.5				
Ochromonas									
Oocystis									
Rhodomonas									
Schroederia									
Sphaerocystis									
Staurastrum									
Stephanodiscus			82						
Stipicoccus									
Synedra									
Westella									
Green Flagellates									
Unident Flag's									
Unident Coccoids									
Unknown									

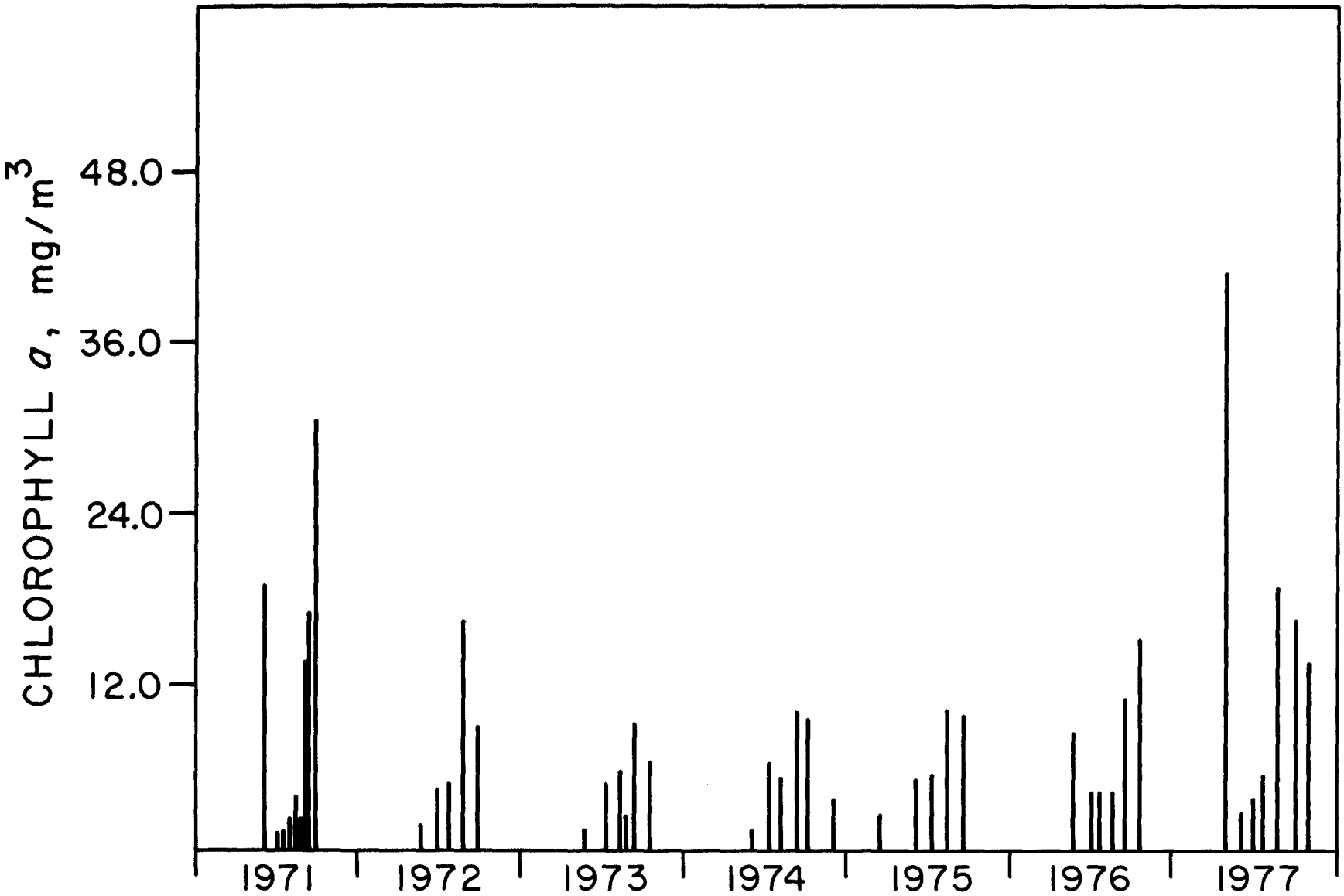

Figure 8. Chlorophyll a volume weighted means.

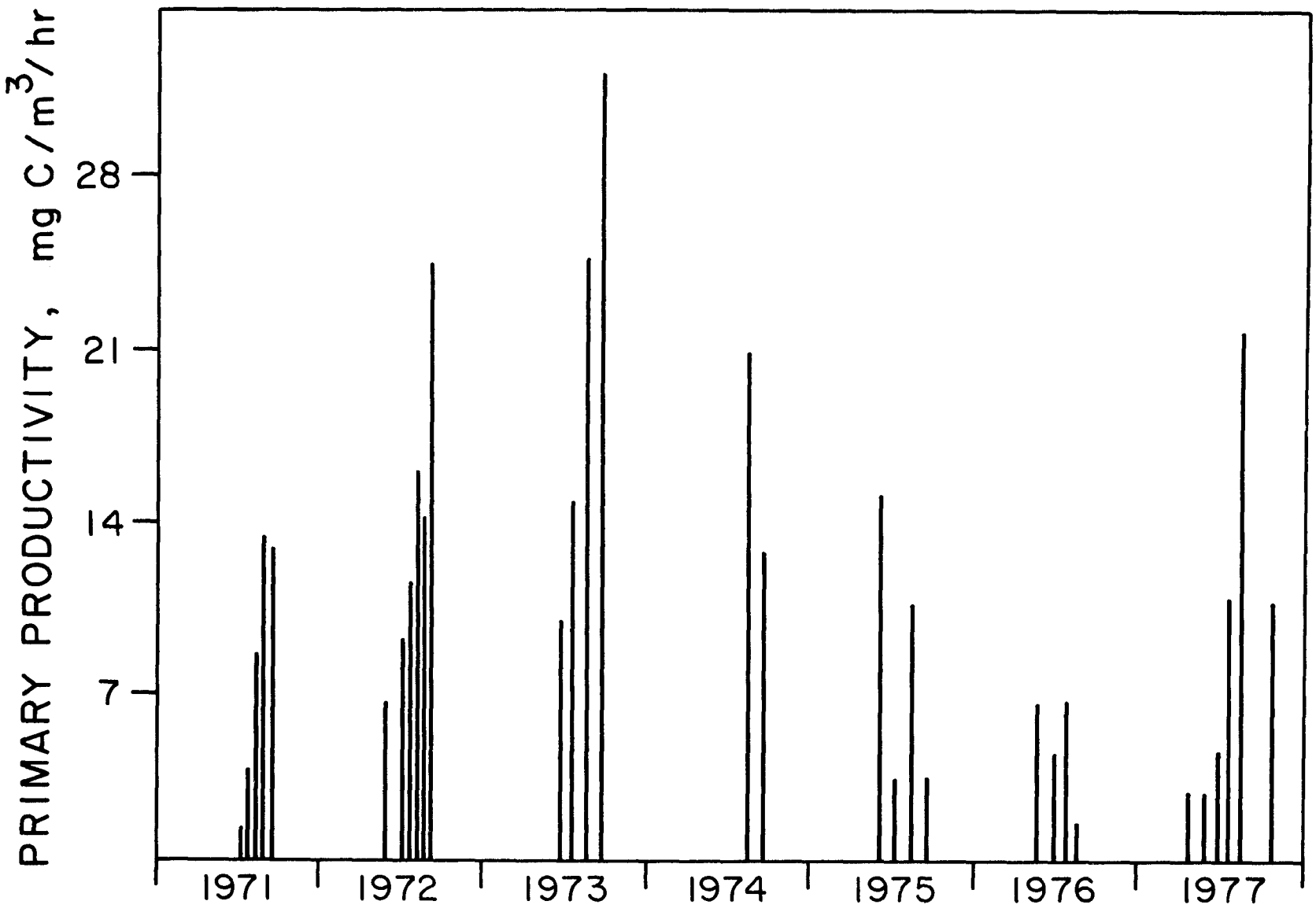

Figure 9. Primary productivity volume weighted means.

A substantial part of the primary producer biomass was contained in the aquatic vascular plants and macrophytic algae. Quantitative sampling was not done but transect studies were conducted with SCUBA to determine the general community structure. A well defined community was observed from approximately 2 to 8 meters, the transects showing three distinct bands. From approximately 2 to 4 m Elodea canadensis was the dominant form. Potomogeton praelongis and E. canadensis co-dominated between 4 and 6 m, the zone of maximum density, while Nitella sp. dominated from 6 to 8 m.

BENTHIC MACROINVERTEBRATES

The sediments at the center station were typically flocculent, gray to brownish organic silt. The peripheral station sediments were generally flocculent, light brown and often contained macrophytes.

Only those benthic macroinvertebrate samples collected continuously from 1971 through 1977 at the deep center station and three of the peripheral stations are considered in this report (Figure 2). The coefficient of variation (CV) of total number of organisms for all samples (N = 515) was almost 38, ranging from 4 to 101 for each set of replicates. The CV for the center station averaged 23 while the inshore stations averaged from 42 to 46. Data from the peripheral stations in 1971 have not been included in the following comparisons due to the small number of samples collected that year.

The temporal pattern of benthos population density was similar for all four stations, a decrease to a low in 1974 followed by higher populations in 1976 and 1977 (Figure 10). Densities fluctuated greatly within single years. The highest mean population, over 11,000/m^2, was reached at the east shore camp station in August, 1972. The lowest mean population, 450/m^2 was collected at the resort station in October, 1974. Yearly population means were largest at the center station, never lower than 5700/m^2.

Amphipods, chironomids, gastropods, leeches and oligochaetes comprised the major faunal groups of the Diamond Lake benthos. Forty different taxa were identified (Table 12). The predominant species and the percent composition of the major groups on a yearly basis are given in Table 13.

There were strong contrasts in predominant species between the center and peripheral stations but little yearly temporal change in predominant species within any one station. The midge, Chironomus decorus and the oligochaete, Limnodrilus hoffmeisteri spiralis dominated the center station while along the periphery the midge, Tanytarsus sp., the leech, Holobdella stagnalis and the amphipod, Hyallela azteca occurred most frequently. The relative percentages of the major groups varied yearly at each station. While a change in group proportions coincided with the 1974 population dip, composition in 1976 and 1977 tended to resemble that before 1974.

Richness and diversity values (Table 14) tend to be low for 1972 since oligochaetes were not identified to species that year. Mean areal richness decreased at the peripheral stations to a low in 1974 of 7 to 10 before peaking in 1977 at over 14. The lowest value for the center station, about 4, was reached in 1975. By 1977 richness had increased to the 1973 level of about 7.

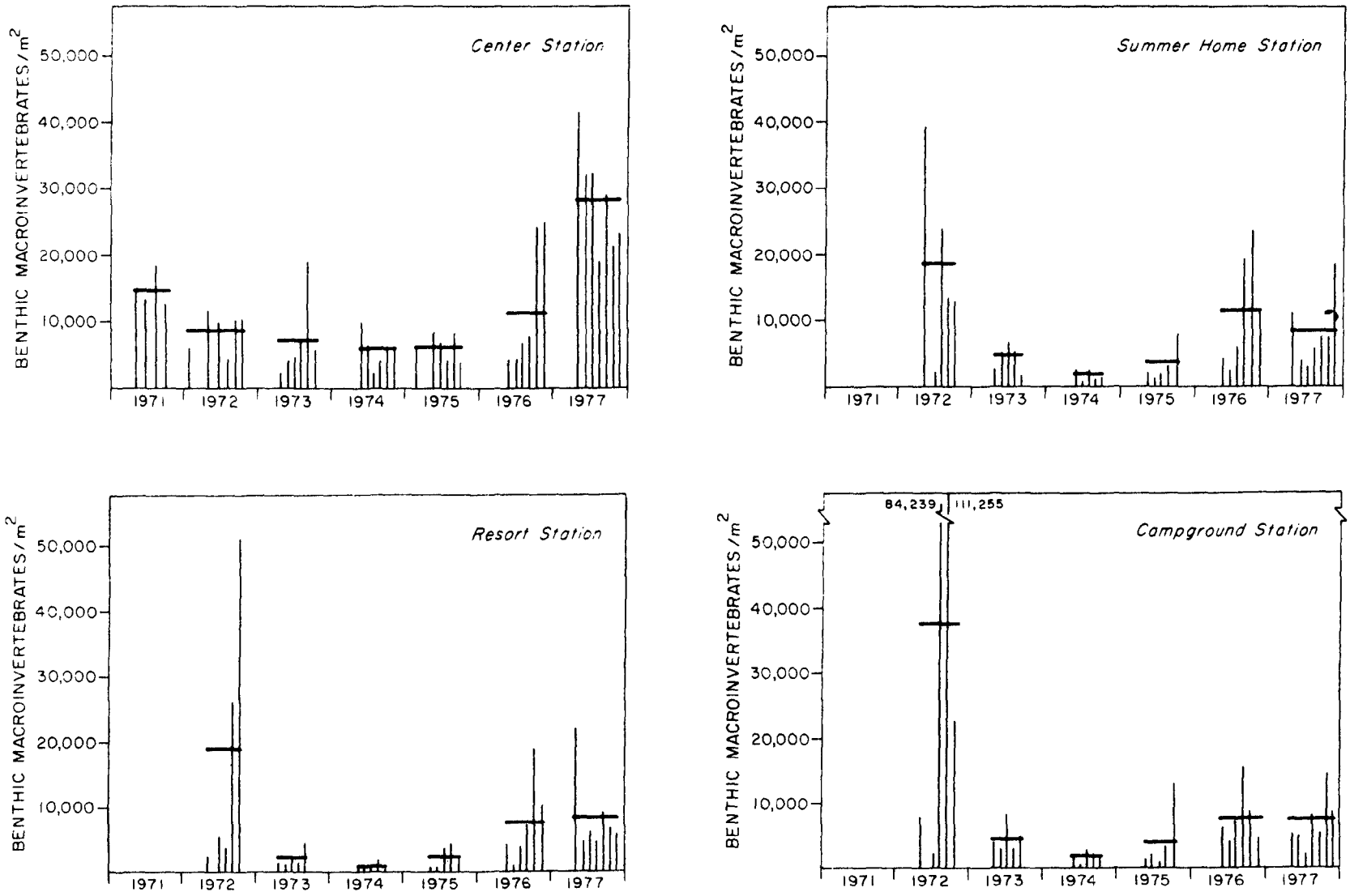

Figure 10. Mean number benthic macroinvertebrates per square meter (horizontal bars indicate yearly means).

TABLE 12. DIAMOND LAKE BENTHIC MACROINVERTEBRATES

Diptera
- Ablabesmyia monilis (Linnaeus)[1]
- Chironomus decorus (= attenuatus of authors) group[1]
- Cladotanytarsus Kieffer[1]
- Cricotopus Wulp[1]
- Cryptotendipes amachaerus (Townes)[2]
- Dicrotendipes californicus Johannsen[2]
- Glyptotendipes Kieffer (prob. G. lobiferus (Say))[1]
- Pagastiella Brundin (prob. P. orophila (Edwards))[1]
- Palpoymia Megerle group
- Parachironomus abortivus (Malloch) group[2]
- Procladius culiciformis (prob. P. sublettei Roback) group[1]
- Psectrocladius Kieffer[1]
- Tanytarsus Wulp

Oligochaeta
- Dero digitata (Müller)[3]
- Ilyodrilus templetoni (Southern)[3]
- Limnodrilus hoffmeisteri spiralis Claparede[3]
- Lumbriculus Grube
- Naididae unidentified
- Nais simplex Piguet
- Pristina Ehrenberg
- Stylaria lacustris (Linnaeus)

Amphipoda
- Crangonyx richmondensis occidentalis Hubricht and Harrison[4]
- Hyallela azteca (Saussure)

Hirudinea
- Erpodellidae unidentified[5]
- Glossiphonia complanata (Linnaeus)
- Helobdella elongata (Castle)[5]
- Helobdella stagnalis (Linnaeus)

Pelecypoda
- Pisidium Pfeiffer

Gastropoda
- Menetus opercularis Gould[6]
- Physa Draparnaud
- Valvata humeralis Say[6]

Trichoptera
- Agraylea Curtis
- Oecetis inconspicua (Walker)

(Continued)

Table 12 (Cont.)

Ephemeroptera
  Caenis Stephens
  Callibaetis Eaton

Zygoptera
  Coenagrion Kirby
  Ishnura Charpentier

Turbellaria

Hydracarina

Nematoda

[1] Identified by J.E. Sublette, Eastern New Mexico Univ.
[2] Identified by W. T. Mason, USEPA, Cincinnati
[3] Identified by J.K. Hiltunen, USFWS
[4] Identified by J.R. Holsinger, Old Dominion Univ.
[5] Identified by D. J. Klemm, USEPA, Cincinnati
[6] Identified by H. van der Schalie, Univ. Michigan

TABLE 13. BENTHIC MACROINVERTEBRATE SUMMARY, 1971-1977

Group	1971 Mean No./m²	1971 %	1972 Mean No./m²	1972 %	1973 Mean No./m²	1973 %	1974 Mean No./m²	1974 %	1975 Mean No./m²	1975 %	1976 Mean No./m²	1976 %	1977 Mean No./m²	1977 %
CENTER STATION														
Amphipoda			3	0.03	35	0.50	5	0.09	11	0.18	20	0.17	17	0.06
Chironomidae	9,453	64.80	3,894	45.20	4,741	66.70	4,038	70.60	3,681	60.40	7,643	64.20	16,153	57.30
Gastropoda	2	0.01			134	1.90	4	0.07	4	0.06	7	0.59	6	0.02
Hirudinea	3	0.02	3	0.03	194	2.70	34	0.60	12	0.20	133	1.10	46	0.16
Oligochaeta	5,012	34.40	4,677	54.30	1,705	24.00	1,516	26.50	2,346	38.50	4,012	33.70	11,886	42.10
Others	114	0.80	32	0.4	299	4.20	118	2.10	39	0.64	90	0.76	89	0.30
Total	14,584		8,609		7,108		5,715		6,093		11,905		28,197	
Predom. species	a,i		a,b		b,i,g		b,i,g		b,i,g		b,i,g		b,g	
RESORT STATION														
Amphipoda			1,510	8.00	982	44.70	494	53.80	661	28.50	1,295	17.20	1,053	12.60
Chironomidae			14,451	76.90	443	20.10	84	9.10	365	15.80	4,847	64.40	4,869	58.40
Gastropoda			284	1.50	44	2.00	90	9.80	622	26.80	437	5.80	257	3.10
Hirudinea			1,308	6.90	579	26.40	173	18.80	286	12.30	435	5.80	704	8.40
Oligochaeta			727	3.90	46	2.10	1	0.10	36	1.50	54	0.70	857	10.30
Others			520	2.80	103	4.70	78	8.50	347	15.50	448	6.00	590	7.10
Total			18,800		2,197		918		2,317		7,516		8,330	
Predom. species			k,e,j		f,e,k		f,e,c		f,h,e,k		k,f		k,j,f,e	
SUMMER HOMES STATION														
Amphipoda			615	3.30	940	21.20	266	15.10	278	8.10	59	0.50	617	7.70
Chironomidae			14,064	76.50	1,589	35,80	274	15.60	1,595	46.80	9,341	82.90	4,939	61.70
Gastropoda			103	0.60	700	15.70	367	20.90	358	10.50	411	3.60	1,074	13.40
Hirudinea			1,981	10.80	909	20.50	731	41.60	915	26.80	1,144	10.10	821	10.30
Oligochaeta			1,580	8.60	153	3.40	45	2.60	56	1.60	133	1.20	169	2.10
Others			46	0.20	147	3.30	74	4.20	206	6.00	172	1.50	380	4.70
Total			18,389		4,438		1,757		3,408		11,260		8,000	
Predom. species			k,e		k,d,f,e,h		e,h,f,k		d,e,h,k		k,e		k,d,e,h	

(Continued)

TABLE 13. (Cont.)

Group	1971 Mean No./m²	1971 %	1972 Mean No./m²	1972 %	1973 Mean No./m²	1973 %	1974 Mean No./m²	1974 %	1975 Mean No./m²	1975 %	1976 Mean No./m²	1976 %	1977 Mean No./m²	1977 %
CAMPGROUND STATION														
Amphipoda			1,336	2.80	1,317	27.10	897	44.30	631	14.50	1,057	13.20	1,495	20.40
Chironomidae			41,096	85.90	1,586	32.60	69	3.40	2,190	50.60	4,326	53.90	3,609	49.20
Gastropoda			351	0.70	327	6.70	251	12.40	418	9.60	488	6.10	475	6.50
Hirudinea			3,814	8.00	1,389	28.60	705	34.90	890	20.50	1,160	14.40	989	13.50
Oligochaeta			1,136	2.40	153	3.10	10	0.50	74	1.70	72	0.90	204	2.80
Others			97	0.20	88	1.80	90	4.40	125	2.90	925	11.5	561	7.60
Total			47,830		4,860		2,022		4,328		8,028		7,333	
Predom. species			k,e		k,f,e		f,e,h		k,e,f		k,e,f		k,f,e	

Predominant Species

a. Chironomidae
b. *Chironomus decorus*
c. *Crangonyx richmondensis occidentalis*
d. *Dicrotendipes californicus*
e. *Helobdella stagnalis*
f. *Hyallela azteca*
g. *Limnodrilus hoffmeisteri spiralis*
h. *Menetus opercularis*
i. Oligochaeta
j. *Pagastiella orophila*
k. *Tanytarsus*

TABLE 14. BENTHIC MACROINVERTEBRATE AREAL SPECIES RICHNESS (S_{AR}), SHANNON-WEAVER DIVERSITY (H') AND COMPLEMENT OF SIMPSON'S INDEX (1-S)

	1972*	1973	1974	1975	1976	1977
			CENTER STATION			
S_{AR}	3.051	6.806	5.076	4.366	5.436	7.494
H'	0.057	0.424	0.247	0.238	0.324	0.406
1-S	0.046	0.495	0.278	0.240	0.373	0.522
			RESORT STATION			
S_{AR}	10.822	9.356	8.011	10.754	12.291	14.738
H'	0.595	0.640	0.761	0.817	0.724	0.804
1-S	0.587	0.646	0.762	0.791	0.703	0.764
			SUMMER HOME STATION			
S_{AR}	10.810	12.598	10.024	10.939	11.937	14.698
H'	0.518	0.711	0.713	0.795	0.668	0.868
1-S	0.540	0.692	0.678	0.778	0.680	0.804
			CAMPGROUND STATION			
S_{AR}	11.675	11.013	7.577	9.379	14.264	14.840
H'	0.464	0.552	0.550	0.560	0.813	0.810
1-S	0.476	0.574	0.621	0.573	0.762	0.765

* Oligochaetes not identified to species

Shannon-Weaver diversity (H') and the complement of Simpson's index (1 - S.I.) were similar both in numerical value at the peripheral stations and in temporal distribution at all four stations. The three peripheral stations did not show a decrease in diversity corresponding to the population dip of 1974; the center station, however, was lower in 1974 and 1975. There seemed to be a general trend toward regaining or surpassing the 1973 levels for these indices by 1977. Values for the latter year ranged from 0.4 to 0.5 for the center and 0.7 to 0.8 for the other stations.

The 1977 dendrogram (Figure 11) indicates two highly dissimilar groups in the benthos (Bray-Curtis coeffcient of dissimilarity >0.8). The cluster on the right is composed entirely of center station collections, and the large group on the left is composed of the other stations with no clear pattern of sub-grouping. Single dendrograms for the other years and a dendrogram utilizing all the collections from 1972 through 1977 were all very similar in appearance to Figure 11. The 1972-77 dendrogram indicates a possible tendency toward some seasonal or yearly clustering.

This study has documented two aspects of the benthos of Diamond Lake: that it is very diverse and that populations in the deeper part of the lake are significantly different from those in the nearshore areas. Effects of the diversion upon the benthic community are conjectural. However, there are indications that few significant changes have taken place during the course of this investigation. Had there been large temporal or spatial changes in population composition or distribution, the clustering analyses should have shown a much stronger tendency for the collections to group into more discrete clusters. Predominant species were little changed at each station through time. While there were some temporal fluctuations in percentage species composition, perhaps due partly to predator-prey relationships coincident with the 1974 population dip (as indicated by changes in the chironomid-leech populations), composition in 1976 and 1977 was similar to pre-1974 levels. Areal species richness declined with the population dip but was little changed from previous levels at the end of the study. There were few changes in species diversity, although yearly averages suggested an upward trend.

The amount of food available for benthic macroinvertebrate populations from settled material would naturally be expected to be influenced by the phytoplankton. The coincident decrease in benthos and phytoplankton in 1973 and 1974 in Diamond Lake may thus be related. The decrease in benthic populations in the mid-part of this study may also be part of larger or longer term cyclic processes not evident by the extent of our investigation.

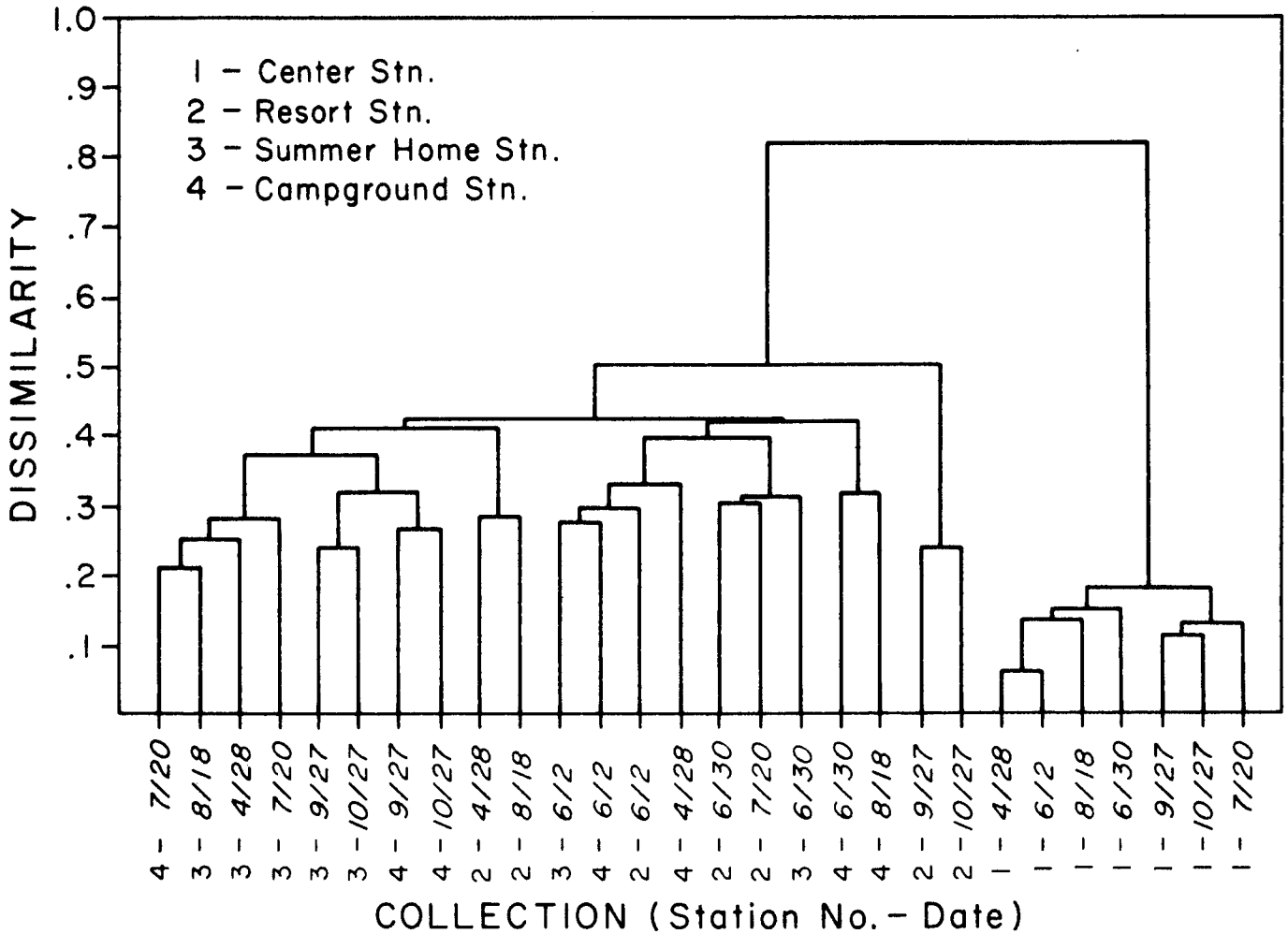

Figure 11. Dissimilarity of benthic macroinvertebrate population, 1977.

MANAGEMENT APPLICATIONS OF THIS RESEARCH

Meyerhoff (1977) found indications of recently accelerated eutrophication in sediment cores from Diamond Lake. He attributed this acceleration to increased human activity in the watershed which he assumed to begin about 1930. One of the projected benefits of the waste diversion system was to ameliorate the impact of this still burgeoning activity. Reducing the nutrient load was expected to result in an improved trophic state or at least a reduced rate of eutrophication. Based on flushing rate and an approximation of the sedimentation rate (Dillon and Rigler, 1975) Diamond Lake could be expected to respond to the reduced loading after approximately 1-1.7 years. The diversion was completed in December, 1975. Therefore, some change should have been detectable in 1977, provided that the nutrient load had been altered sufficiently. Calculations have shown that the probable maximum load reduction was only 10-15%. This would probably not noticeably affect the trophic status of the lake. Fluctuations in natural loading and unpredictable sediment contributions could compensate for the reduction and continued leaching of residual nutrients from sanitary drain fields could effectively reduce the percentage diversion and delay lake response.

Our data suggest a relatively small cultural impact, even during recent years when visitor use approached two orders of magnitude higher than that reported in 1924. Diamond Lake appears to be quite productive as a result of nutrient loading from natural sources. While the tributaries may occasionally receive nutrients from human activities the impact seems to be minimal.

A major management concern is whether the lake can withstand additional development without suffering accelerated eutrophication. Dillon and Rigler (1975) developed an approach to making such a decision based on relationships between nutrient loading and water quality characteristics. With a preconception of the desired trophic state, in terms of water clarity and the type of recreation to be promoted, a manager can use their system to estimate an acceptable nutrient load. Methods for identifying the natural and artificial components of the existing load are described which allow calculation of a permissible increase (or a necessary decrease). The step-by-step system has been applied to Diamond Lake (Table 15). Measurements from our seven-year study were used instead of certain generalizations in the Dillon and Rigler system.

Dillon and Rigler describe four classes of lakes based on maximum permissible summer average Chl a level. With respect to the cold water fishery and the high mean transparency, Diamond Lake fits the Level 1 category (cold water fishery, mean Secchi disc $\geq$5 m). However, the lake does not conform to permissible Chl a and the corresponding spring TP for this level (Tables 9, 15). The permissible P for Level 1 would be about 1800 kg/yr (Table 15). With the exception of 1974 the nutrient budget shows that the P from Silent and Short

TABLE 15: ACCEPTABLE P LOAD AND CAPACITY FOR DEVELOPMENT ACCORDING TO DILLON AND RIGLER (1975)

Step 1: Choose Maximum Permissible Summer Average Chl a

Level 1: 2 mg Chl a/m^3; promoting body contact water recreation cold water fishery desirable; high mean Secchi disc transparency ($\geq$ 5 m).

Level 2: 5 mg Chl a/m^3; general water recreation; cold water fishery not imperative; mean Secchi disc transparency 2-5 m.

Level 3: 10 mg Chl a/m^3; body contact recreation not important; emphasis on fishery (bass, bluegill); danger of fish kill in winter due to oxygen depletion; Secchi disc transparency 1-2 m.

Level 4: 25 mg Chl a/m^3; suitable only for warmwater fishery; considerable danger of fish kill; Secchi disc transparency < 1.5 m.

Step 2: Calculate Permissible Spring Phosphorus Concentration

$$\log_{10} [P] = (\log_{10} [\text{Chl } a] + 1.14)/1.45$$

Level 1: 9.9 mg P/m^3
2: 18.5 mg P/m^3
3: 29.9 mg P/m^3
4: 56.3 mg P/m^3

Step 3: Determine Lake Surface Area (A_o in m^2), mean depth ($\bar{z}$ in m) and Volume (V in m^3).

$A_o = 1.243 \times 10^7$ m^2
$\bar{z} = 7.2$ m
$V = 9.02 \times 10^7$ m^3

Step 4: Determine Area of Watershed (A_d in m^2)

$A_d = 1.42 \times 10^8$ m^2 - 1.24×10^7 m^2
$= 1.296 \times 10^8$ m^2

Step 5: Determine total annual runoff for watershed ($m^3/yr/m^2$)

Unnecessary for Diamond Lake

(Continued)

TABLE 15. (Cont.)

Step 6: Determine total outflow volume Q (m^3/yr)

Measured avg. 1972-1977 = 6.14×10^7 m^3/yr
and Flushing Rate $\rho = Q/V$ (yr^{-1})

$(6.14 \times 10^7\ m^3/yr)/(9.02 \times 10^7\ m^3) = 0.68/yr$

Step 7: Calculate the Areal Water Load, q_s (m/yr)

$$q_s = Q/A_o$$
$$= (6.14 \times 10^7\ m^3/yr)/1.243 \times 10^7\ m^2$$
$$= 4.94\ m/yr$$

Step 8: Calculate the Retention Coefficient (R)

$$R = 0.426 \exp(-0.271\ q_s) + 0.574 \exp(-0.00949\ q_s)$$
$$= 0.6594$$

Step 9: Calculate the Response Time to a Change in Loading

$$\text{Response Time} = (3 \rightarrow 5)\ 0.69/(\rho + 10/\bar{z})$$
$$= 1.0 \rightarrow 1.7\ yr$$

Step 10: Calculate the Permissible Phosphorus load, L_{perm} ($mg/m^2/yr$).

$$L_{perm} = ([P] \cdot \bar{z} \cdot \rho)/(1-R)$$

Level 1: $= (9.9 \times 7.2 \times 0.68)/(1-.6594) = 142.3\ mg/m^2/yr$
Level 2: $= (18.5 \times 7.2 \times 0.68)/(1-.6594) = 265.9$
Level 3: $= (29.9 \times 7.2 \times 0.68)/(1-.6594) = 429.8$
Level 4: $= (56.3 \times 7.2 \times 0.68)/(1-.6594) = 809.3$

and the Permissible Supply, J_{perm} (kg/yr)

$$J_{perm} = (L_{perm} \cdot A_o)/10^6$$

Level 1: = 1767 kg/yr
Level 2: = 3305
Level 3: = 5342
Level 4: = 10,060

Step 11: Determine the Phosphorus Supply from the Land

(from nutrient budget, Silent Cr., Short Cr. and Intermittent Str.)

$$J_E = 2164\ kg/yr$$

(Continued)

TABLE 15. (Cont.)

and the Load

$$L_E = J_E/A_o = 24.0 \text{ mg/m}^2\text{/yr}$$

(Groundwater contributed approximately 266 kg/yr in addition to the above)

Step 12: Determine the Phosphorus Supply from Precipitation (from nutrient budget)

$$J_{PR} = 114 \text{ kg/yr}$$

Step 13: If the Natural Supply, J_n, is greater than or equal to the Permissible Supply, J_{perm}, allow no further development.

$$J_N = J_E + J_{PR} \text{ (+ Groundwater Supply)}$$
$$= (2164 + 114 + 266) \text{ kg/yr}$$
$$= 2544 \text{ kg/yr}$$

(Greater than Level 1 but less than Level 2)

Step 14: Determine the Present Number of Cottages, N_c, and Permanent Dwellings, N_D.

N_c = 102 Recreation Residences (Cottages)

N_D = 0 (all facilities on east shore are on interceptor line)

and calculate the number of capita years per year at the lake, N_{CY}.

Average (1969-77) Visitor Days to Summer Homes

= 29,200/yr (12 hr days)

N_{CY} = 54 ca. yrs/yr

Step 15: Calculate the Phosphorus Supplied to the lake from the Cottage Units (Artificial Supply, J_A).

$$J_A = (0.8 \text{ kg/ca.yr}) (N_{CY})$$
$$= 43 \text{ kg/yr}$$

Step 15: Calculate the Present Total Supply of Phosphorus, J_T.

$$J_T = J_N + J_A$$
$$= 2544 \text{ kg/yr} + 43 \text{ kg/yr}$$
$$= 2587 \text{ kg/yr}$$

(Still less than J_{perm} = 3305 kg/yr)

(Continued)

TABLE 15. (Cont.)

Step 17: Calculate the Total Permissible Number of Cottages, N_{perm}

$$N_{perm} = (J_{perm} - J_N)/0.53 \times 0.8$$
$$= 1795 \text{ (for level 2)}$$

Step 18: Calculate the Additional Number of Cottages, N_{add}

$$N_{add} = N_{perm} - N_c$$
$$= 1693 \text{ (for level 2)}$$

Creeks exceeds this allowable limit. The yearly supply from all measured natural sources averaged over 2500 kg indicates that Level 1 cannot be maintained. It should be noted that the transparency sometimes remained greater than 5 m even during rather heavy blue-green algal blooms as a result of algal clumping. Also, the cold water fishery is supplemented through intensive management by the DFW. Provision for such an intensive management program is not made by Dillon and Rigler.

Level 2 is described as having maximum summer average Chl a of 5 mg/m^3 and an average Secchi disc transparency of 2-5 m. A cold water fishery is not characteristic of a Level 2 lake (Table 15). Diamond Lake still exceeds the desired Chl a average. The average summer (June-Sept.) values over the study period were between 5 and 10 mg/m^3, corresponding to Level 3. It seems, however, that the most desirable status consistent with recreational demands is Level 2. The present degree of productivity is essential in maintaining the large population of rapidly growing trout. Substantially reducing the primary productivity would probably adversely affect the fishery and reduce the attraction of the lake. Allowing the lake to assume Level 3 status would be even less desirable because the greater productivity would probably result in seasonal fish kills due to low DO and an increase in blue-green algal blooms.

Vollenweider (1976) suggested from data gathered from a large number and variety of lakes that the "loading tolerance" of a lake can be determined if the hydraulic load (total yearly water discharge divided by the lake surface area) and the mean depth are known. Using his relationship the critical loading for Diamond Lake is calculated to be approximately 1350 kg P/yr (Table 16). At this rate the lake could probably maintain oligotrophic characteristics. Loading in excess of about twice this amount would result in a eutrophic system. This is more restrictive than the Dillon and Rigler projections, suggesting that the trophic status of Diamond Lake might be even more vulnerable.

TABLE 16: CRITICAL PHOSPHORUS LOAD ACCORDING TO VOLLENWEIDER (1975)

$$L_c \ (mgP/m^2/yr) = 10\ (\bar{z}\ Q_y/V)(1 + \sqrt{V/Q_y})$$

L_c = critical loading level in P controlled lake

$\bar{z}$ = mean depth (Diamond Lake [DL] = 7.2 m)

Q_y = yearly outflow (DL = $6.145 \times 10^7\ m^3$)

V = Volume of lake (DL = $9.02 \times 10^7\ m^3$)

L_c = 108.5 mg $P/m^2/yr$
= 1349 kg P/yr (for Diamond Lake)

Bortleson et al. (1974) developed a system for rating the trophic condition and the potential for eutrophication of lakes and reservoirs in the State of Washington, taking into account various physical and water quality characteristics and cultural influences. Table 17 shows that with this system,

TABLE 17. RATING OF FACTORS AFFECTING PRESENT AND POTENTIAL TROPHIC STATUS ACCORDING TO BORTLESON (1974)

Physical Factors	Value	Rating	Notes	Cultural Factors	Value	Rating	Notes	Water Quality Factors	Value	Rating	Notes
Mean depth (m)	7.2	3		Point Sources of Domestic Sewage	0	1		TP upper water (μg/l)	38	5	0-10 m; not vol. wtd; '71-77 avg.
Water volume (hm^3)	90.2	1		Nonpoint Sources (kg TP per Km^2 of lake per year)	200	2	from nutrient budget	TP ratio, bottom to upper water	2.6	3	
Bottom slope (%)	0.36	5		Volume of water per nearshore home (hm^3)	0.88	2	not full year residences	TIN upper water (μg/l)	38	1	0-10 m; not vol. wtd; '71-77 avg excl. 8/14/73, 5 m, 697 μg/l
Shoreline Configuration	1.19	2		% nearshore land developed for residential use	21	3	not full year residences	TIN ratio, bottom to upper water	3.1	4	
Ratio of drainage area to lake volume (m^2/m^3)	1.57	3						Organic N, upper water (μg/l)	345	3	0-10 m; not vol. wtd; '71-77 avg.
Altitude (m)	1580	1						Specific Conductance (μmhos at 25°C)	25-30	2	
Water renewal time (yrs)	1.37	3	includes groundwater					Secchi disc (m)	6.1	2	'71-77 avg.
								DO near bottom (mg/l)	3.6	3	13 m; 6/15-9/15; '72-77 avg.
								Water temperature near bottom (°C)	12.6	4	13 m; 6/15-9/15; '72-77 avg.
								% lake surface in emergent, rooted aquatic plants	1-10	2	estimate
								% shoreline in emergent, rooted aquatic plants	< 10	1	estimate

Diamond Lake is of an intermediate trophic status. Barring a substantial change in cultural influence the lake should remain stable.

The three evaluations have important management implications. The natural nutrient loading precludes an oligotrophic system. It is unlikely that oligotrophy would be the management objective but minimizing the cultural influence would help maintain the lake's present status. This would include control of land disturbance and soil erosion. Pearl and Goldman (1972) and Goldman (1974) have demonstrated that trophic status can be affected by increased erosion and siltation. Terrestrial wildlife, human health and aesthetics should also be considered.

As part of a lake management plan it is extremely important that water quality/nutrient supply relationships be defined. A nutrient budget with its concomitant hydrologic information is vital to this understanding. "Point" sources of nutrients need to be quantified to assess artificial or cultural impact. An acceptable nutrient supply could be estimated if, additionally, the lake surface area and volume are known.

Nutrient loading from non-point sources can be estimated if funds and/or time limitations prevent actual field measurements. Land use type/stream nutrient concentration regressions (Omernik, 1977) together with flow data can provide an estimate of loading from a watershed. These flow data are reported annually in the USGS Water Resources Data publication for each state. Flow data from a specific stream not included in the report could be extrapolated from another gaged stream if watersheds are similar and drainage areas are known. For most accurate extrapolation, one should consider proximity, altitude and exposure (N, S, E, W). Rainfall isolines (NOAA, 1974) would help identify a proper watershed for extrapolation purposes.

Table 18 illustrates the use of estimations rather than actual field values when applying the Dillon and Rigler and Vollenweider critical loading calculations to Diamond Lake. Only two field measurements were used, maximum depth and the number of summer homes. These calculations indicate that for an oligotrophic system loadings of 2825 kg P/yr (Dillon and Rigler) and 2382 kg P/yr (Vollenweider) are acceptable. However, calculations based on actual measurements (Tables 15 and 16) indicate that these numbers are far too high. The factor most responsible for this discrepancy is the outflow volume (Q). The estimate used in Table 18 is over twice the measured flow which doubles the calculated flushing rate, thereby increasing the "permissible" nutrient supply. The value of precise field measurements is evident.

TABLE 18. DETERMINING ACCEPTABLE P LOAD WITH A MINIMUM OF FIELD MEASUREMENTS

Dillon and Rigler

Step 1: See Table 15

Step 2: See Table 15

Step 3: $A_o = 1.216 \times 10^7\ m^2$ (from USGS, 1:62,500, Diamond Lake, Oreg., 1956)

$V = 1/2\ A_o \times Z_{max}$ (H. Mercier, personal comm. 10/27/78)

$= 8.69 \times 10^7\ m^3$ (Z_{max} obtained by measurement)

Equation assumes the cross-sectional area to be a linear function of depth. It appears to work well for basins with a regular shape. A contour map should be made for irregular basins.

$\bar{Z} = V/A_o$

$= 7.1\ m$

Step 4: $A_d = 1.447 \times 10^8\ m^2 - 1.216 \times 10^7\ m^2 = 1.325 \times 10^8\ m^2$ (from USGS, 1:62,500, Diamond Lake, Oregon, 1956)

Step 5: $r = 4.409 \times 10^8\ m^3/440\ km^2 \cdot yr$

$= 1.00\ m^3/m^2\ yr$ (USGS, 1971-77, North Umpqua River below Lemolo Lake, average discharge, cal. years 1970-76)

The drainage area for this gage is on the same rainfall isoline as Diamond Lake and actually includes the Diamond Lake watershed.

Step 6: $Q = A_d \cdot r$

$= (1.325 \times 10^8\ m^2)\ (1.00\ m^3/m^2\ yr)$

$= 1.325 \times 10^8\ m^3/yr$

$\rho = Q/V$

$= (1.325 \times 10^8\ m^3/yr)/(8.69 \times 10^7\ m^3)$

$= 1.52\ yr^{-1}$

Step 7: $q_s = Q/A_o$

$= (1.325 \times 10^8\ m^3/yr)/(1.216 \times 10^7\ m^2)$

$= 10.90\ m/yr$

Step 8: $R = 0.426 \exp(-0.271\ q_s) + 0.574 \exp(-0.00949\ q_s)$

$= 0.540$

Step 9: Response Time $= (3 \rightarrow 5)\ 0.69/(\rho + 10/\bar{z})$

$= 0.7 \rightarrow 1.2\ yr$

(Continued)

TABLE 18. (Cont.)

Step 10: $L_{perm} = ([P] \cdot \bar{z} \cdot \rho)/(1-R)$

Level 1: 232.3
Level 2: 434.0
Level 3: 701.5
Level 4: 1320.8

$J_{perm} = (L_{perm} \cdot A_o)/10^6$

Level 1: 2825 kg
Level 2: 5277
Level 3: 8530
Level 4: 16,061

Step 11: (from Omernik, 1977, p. 55)

No Agriculture
∿ 5% urban area in intermittent stream watersheds (4.350×10^7 m^2)

$[P] = 0.032$ mg/l
$E_1 = (0.032 \text{ mg/l})(1000 \text{ l/m}^2\text{/yr}) = 32.0 \text{ mg/m}^2\text{/yr}$

No urban area in remainder of watersheds (8.900×10^7 m^2)

$[P] = 0.028$ mg/l
$E_2 = 28.0 \text{ mg/m}^2\text{/yr}$

$J_E = (E_1)(A_{d1}) + (E_2)(A_{d2})$
$= 1.392 \times 10^9 \text{ mg/yr} + 2.492 \times 10^9 \text{ mg/yr}$
$= 3884$ kg/yr

$L_E = J_E/A_o$
$= 319.4 \text{ mg/m}^2\text{/yr}$

Step 12: 5 μg TP/l in precipitation at Waldo Lake, OR (Malueg et al., 1972)
Average Annual Precipitation near Diamond Lake
∿ 24 inches/yr (NOAA, 1974)

$J_{PR} = (0.61 \text{ m/yr})(A_o = 1.243 \times 10^7 \text{m}^2)(5 \text{ mg/m}^3)$
$\simeq 38$ Kg/yr

Step 13: $J_N = J_E + J_{PR}$
$= 3922$ kg/yr

$L_N = L_E + L_{PR}$
$= 322.5 \text{ mg/m}^2 \text{ yr}$

(Continued)

TABLE 18. (Cont.)

Step 14: $N_c = 102$
$N_D = 0$
$N_{CY} = (0.69)(102)$
$= 70$

Step 15: $J_A = (0.8)\ N_{CY}$
$= 56$ kg/yr

Step 16: $J_T = J_N + J_A$
$= 3978$ kg/yr

Step 17: $N_{perm} = (J_{perm} - J_N)/(0.69 \times 0.8)$
$= 2455$ (for level 2)

Step 18: $N_{add} = N_{perm} - N_c$
$= 2353$ (for level 2)

Vollenweider

$$L_c = 10\ (\bar{z}\ Q_y/V)(1 + \sqrt{V/Q_y})$$

$$= 10\ (7.1)(1.325 \times 10^8)(1 + \sqrt{8.69 \times 10^7/1.325 \times 10^8})/(8.69 \times 10^7)$$

$$= 195.9\ \text{mgP/m}^2\text{/yr}$$

$$= 2382\ \text{kg P/yr (for Diamond Lake)}$$

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16. ABSTRACT
Responding to accelerated recreational pressure at Diamond Lake, Oregon, in 1969 the U.S. Forest Service began installation of a wastewater diversion system which would eventually carry 85 to 90% of the sewage out of the watershed. From 1971 through 1977 the U.S. Environmental Protection Agency conducted a program of research on the lake to determine its trophic status and identify changes that might be the result of the diversion.
The lake is quite productive as the result of natural loading from tributaries, groundwater and bottom sediments. Cultural influence, initially speculated to be significant was discovered to have a relatively minor impact on the lake. Total phosphorus and chlorphyll a levels reached a low in 1973, but by 1977 had increased to levels comparable to 1971. Species composition of the benthic macroinvertebrate population was the same in 1976/1977 as it was at the beginning of the study. Recommendations include an adaptation of the Dillon and Rigler system for determining the development capacity of lakes.

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