EUTROPHICATION OF NORTHEASTERN OHIO LAKES. I. INTRODUCTION, MORPHOMETRY, AND CERTAIN PHYSICO-CHEMICAL DATA OF DOLLAR LAKE

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ABSTRACT

Dollar Lake in Portage County, Ohio, has a volume of 86,400 cubic meters and an area of 22,212 square meters. The average depth is 3.89 meters, the maximum depth is 7.5 meters. Maximum width of the lake is 140 meters, the maximum length 215 meters. Except for brief periods in spring and fall, deep waters are depleted of dissolved oxygen. Secchi Disc transparency is frequently below one meter. Massive blooms of algae are often observed. The lake stratifies thermally in April, circulates in October, and re-stratifies in December after ice formation. Spring circulation occurs in March. Dollar Lake is a dimictic, second-class, eutrophic lake.

INTRODUCTION

Eutrophication is defined as the process of nutrient enrichment of lakes. A great deal is known about the response of a lake to allochthonous nutrients, such as phosphorus and nitrogen; the subject has been extensively reviewed by Stewart and Rohlich (1967). Nevertheless, in the broader ecological sense, it is not clear whether a small eutrophic lake in an advanced stage of hydrosere succession is actually more mature, on the basis of Margalef's (1963) criteria, than is a deeper and less enriched lake. Does a eutrophic lake, in contrast to commonly held theory, have the properties of an immature ecological community? Secondly, if the input of nutrients to a eutrophic lake is drastically curtailed or stopped, how will the lake respond? These problems have been discussed by Margalef (1964, 1968), E. P. Odum (1969), and Hasler (1969).

There are several methods of investigating these questions. One method is to accumulate a large amount of information about a small, very eutrophic lake, and about the activities on the nearby landscape which influence the lake. This lake can then serve as a basis for comparative studies with other larger, less eutrophic lakes. Or, in the event that the input of enriching materials is reduced or stopped, long-term "before and after" investigations about the lake and the surrounding landscape may be instructive. Finally, small lakes are amenable to experimentation, once base-line data have been obtained.

The small glacial lakes of the Twin-Dollar Lake region, located about four miles north of Kent, Ohio (fig. 1), are ideal lakes for the study of eutrophication. This group of lakes is influenced almost exclusively by the human activities within the small region around the lakes shown in Figure 1. Extensive clearing, plowing, and home-building have opened nutrient cycles, so that there is a large amount of runoff into the lakes. Fertilizers from lawns and possibly from small farms are added to natural sources of nitrogen and phosphorus. Finally, many houses

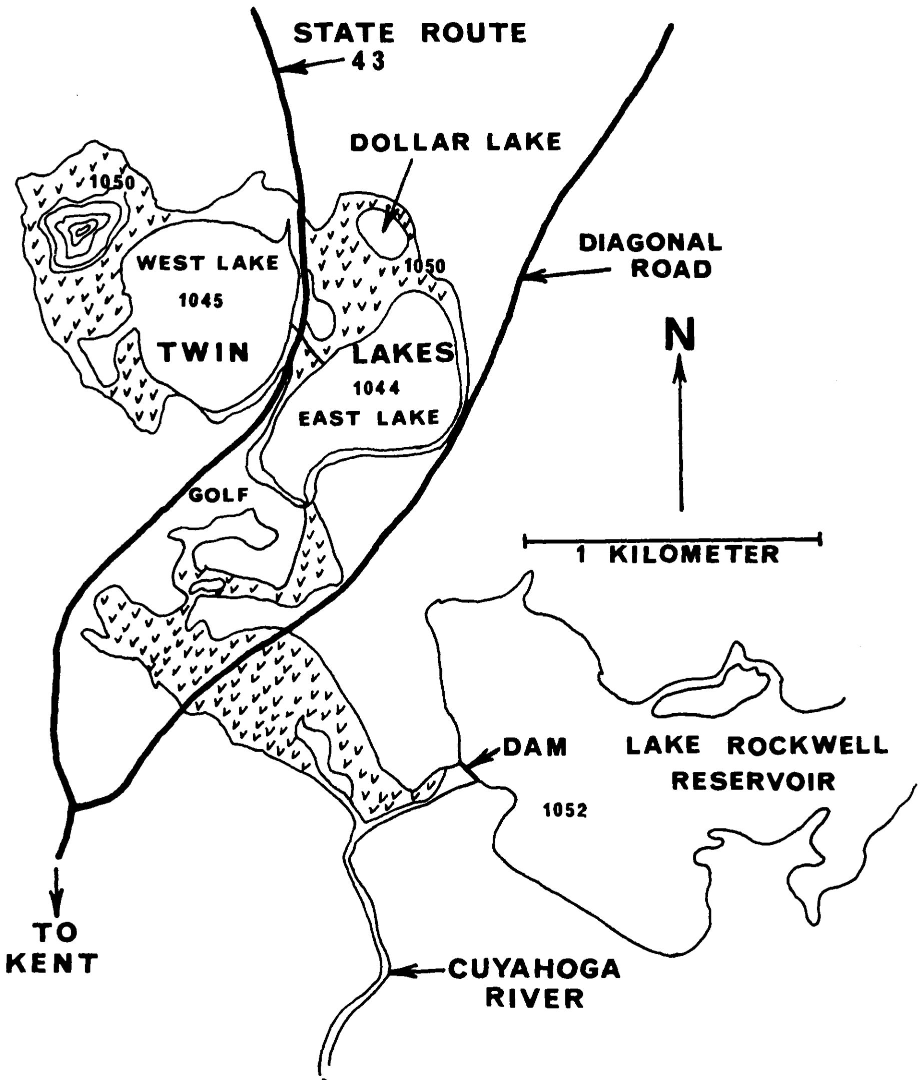

FIGURE 1. The Twin-Dollar Lake Area, Portage County, Ohio (from U.S. Geological Survey Topographic Map, NE4, Kent 15' Quadrangle. 1960). Elevations are in feet. Check marks indicate marshy areas.

have been constructed in the area, with their septic tanks located below the houses next to the lakes. The location and possibly the soil type have not been suitable for septic tanks because materials from the tanks have moved laterally toward the lakes and have thus been a major source of enrichment.

Of the three major lakes of the region, East Twin is the largest and deepest, and is perhaps the least eutrophic. West Twin is surrounded by more homes, is subject to considerable enrichment from a partially denuded forest and from runoff from lake dredgings, and is somewhat shallower than East Twin. Dollar Lake, an alkaline bog, is the smallest and shallowest, and has a high density of homes located on a hill above and to the north of it. Dollar Lake is probably the most eutrophic of the three lakes. Effluent overflows from some septic tanks and moves, with little or no leaching, into very small streams which then flow into the lake. Other septic-tank effluents soak into the soil, but eventually also reach the lake. Within the next few years, a sewer line will be completed around all of the lakes, thus gradually reducing the influence of the septic tanks.

This small lake region therefore offers an excellent opportunity, not only for comparisons between lakes in different stages of eutrophication within the same area, but for long-term "before and after" studies. The overall aim of this long-term investigation will be to provide, in a series of articles, a comparative morphometric, structural, and functional description of each of the lakes of the region, which will then be used as a basis for comparison with other lakes, and which can also be used as a "before" portion of a "before and after" study on the effects of the new sewer line on Dollar Lake. These comparative studies are ultimately directed towards the larger problem of a measure of the relative ecological maturity of any lake and its surrounding landscape in varying stages of eutrophication and disturbance.

In undertaking such a study, an important first step is to provide a careful morphometric description of the lakes, and to assemble basic eutrophication data, such as change in dissolved oxygen and its relationship to the annual temperature cycle. Since Dollar Lake is the most strongly influenced by human habitation and is the smallest of the lakes, it was selected as the model lake from which comparative observations can later be drawn. As the first of a series of articles, some basic eutrophication data of Dollar Lake are described here.

THE TWIN LAKES—DOLLAR LAKE AREA

The landscape around the Twin-Dollar Lake area is of a gently rolling knob-and-kettle topography. Marshy habitats, small ponds, mature forests, oldfields, and some cultivation are common, but homes, lawns, and a golf course dominate the area. West Twin and Dollar lakes drain into East Twin, and then the water drains slowly southward out of East Twin into a marsh and then into the Cuyahoga River to the southeast.

The geology of the area has been described by Rau (1969). Large blocks of ice were left during the retreat of the glacier, and lake basins were formed by the melting of these blocks (kettles). The large marshy areas between the lakes suggest that the Twin-Dollar Lake area may have once been a larger lake with three deep basins.

Dollar Lake is located adjacent to Franklin Township Highway 848 (Portage County), just north of East Twin and about 300 meters east of State Route 43. The 1960 Kent Quadrangle Topographic Map (United States Geological Survey) places the lake at 41°12′ N latitude and 81°21′ W longitude.

Dollar Lake, in contrast to East and West Twin Lakes, is an alkaline bog, undergoing hydrosere succession. Dexter (1950) has described the molluscs and the zonation of the vascular plants. No vascular plants are found in areas of the lake over three meters in depth, but in shallower water, according to Dexter (1950), there are four zones of submerged, floating, and emergent vascular plants. Around the edge of the lake he describes a floating *Sphagnum* mat, which forms a quaking bog shelf. Three concentric zones of vegetation are found on the shelf, beyond which there is a tamarack-bog community on the southwestern side of the lake, and a willow-swamp community on the northeastern shore. Recently, herbicides have been used extensively on lawns around the lake, and algicides have been applied to the lake itself. This may be associated with the recent decline and virtual disappearance of some of the species of vascular plants on the shelf. A mature hardwood forest, composed of red and white oak, beech, elm, and ash, is found on the steep hill around the north and northeastern sides of the lake.

Annual changes in pH have been described by Dexter (1942, 1946, 1950). In the summer, pH of surface waters regularly exceeds 8.0, and large blooms of blue-green algae develop, quite in contrast to the usual acid-bog lake. After periods of prolonged stratification and stagnation, pH of deep waters may drop to 6.8. Soil pH on the *Sphagnum* shelf ranges from 4.0 to 7.0.

Two small streams, which originate as springs on the hills to the north, enter the lake. Both streams are alkaline and carry a heavy load of septic-tank effluent. A small channel was cut between Dollar and East Twin Lake many years ago; these two lakes may also have an underground connection as well (Dexter, 1950).

MORPHOMETRIC STUDIES OF DOLLAR LAKE

Dollar Lake was mapped, using a surveyor's transit and a grid pattern, while ice was present. The outline of the lake (fig. 2) does not include any of the bog shelf, but only the open water. After mapping, soundings were taken, at intervals of one-half meter, on nine separate transects of the lake. A calibrated line and a medium-sized jar with enough weight to be just more than neutrally buoyant were used for the depth determinations. This device proved to be unusually sensitive in detecting the surface of the very soft bottom.

The area and the volumes within each contour stratum are shown in Figure 2, and are listed in Table I. Volume was computed by two different methods: (1) by computing the volume of each stratum according to the equation for the frustum of a pyramid or cone,

$$V = 1/3\ (A_1 + A_2 + \sqrt{A_1 A_2})\ h,$$

where h is the altitude in meters, A_1 is the area of the upper surface of a contour stratum, and A_2 is the area of the lower surface of the stratum; and (2) by integrating by the trapezoidal rule. The relationship between area and depth is

TABLE I

Area-Volume Relationships, Dollar Lake

Contour (meters)	Area (meters²)	Volume (meters³) of contour strata
Shore	22,212.5	0
1.0	20,537	21,156.86 (1.0–shore)
1.5	19,532	9,915.58 (1.5–1.0)
2.0	18,000	9,281.35 (2.0–1.5)
2.5	16,835	8,620.06 (2.5–2.0)
3.0	13,891	7,592.95 (3.0–2.5)
3.5	12,130	6,434.78 (3.5–3.0)
4.0	10,787	5,668.20 (4.0–3.5)
4.5	9,350	4,979.66 (4.5–4.0)
5.0	7,977	4,283.90 (5.0–4.5)
5.5	6,845	3,664.80 (5.5–5.0)
6.0	5,647	3,087.00 (6.0–5.5)
6.5	1,073	1,514.90 (6.5–6.0)
7.0	12	197.40 (7.0–6.5)
		86,399.54 meters³

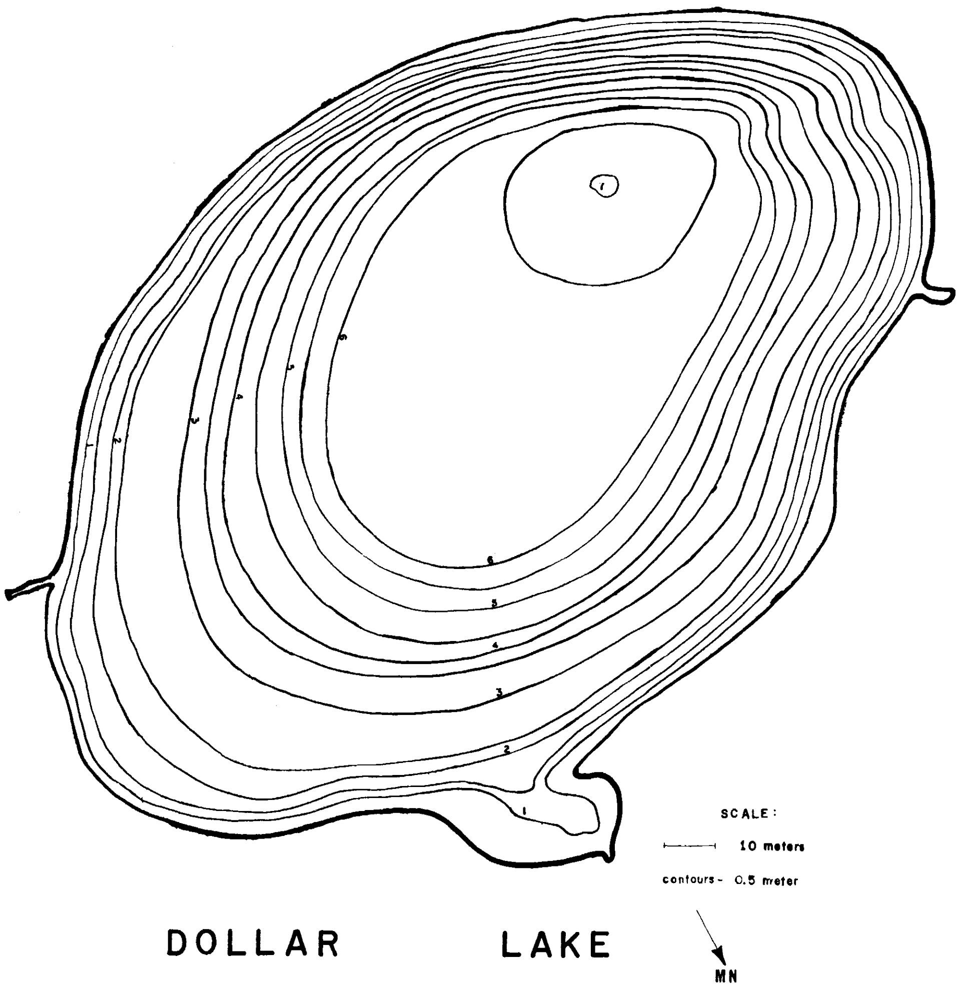

FIGURE 2. Morphometric map of Dollar Lake, Portage County, Ohio. Depths are shown in meters; contour interval is half a meter.

shown in the hypsographic curve (fig. 3); it is the area above the curve that was integrated. The two methods of computation differed by 860 cubic meters (less than 1% of the total volume).

The mean depth of the lake, computed by dividing the total volume by the area, is 3.89 meters. The maximum length of the lake is 215 meters, the maximum width is 140 meters.

ANNUAL TEMPERATURE-OXYGEN-TRANSPARENCY CHANGES IN DOLLAR LAKE

Between June, 1968, and the end of May, 1969, 40 trips were made to Dollar Lake for the purpose of measuring water temperature, dissolved oxygen, and transparency. Samples for water chemistry, plankton, biomass, and chlorophyll were also taken; results of these investigations will be described in a future article. Except during early and late winter when the ice was unsafe, the lake was visited at least three times per month and usually five or more times per month. All

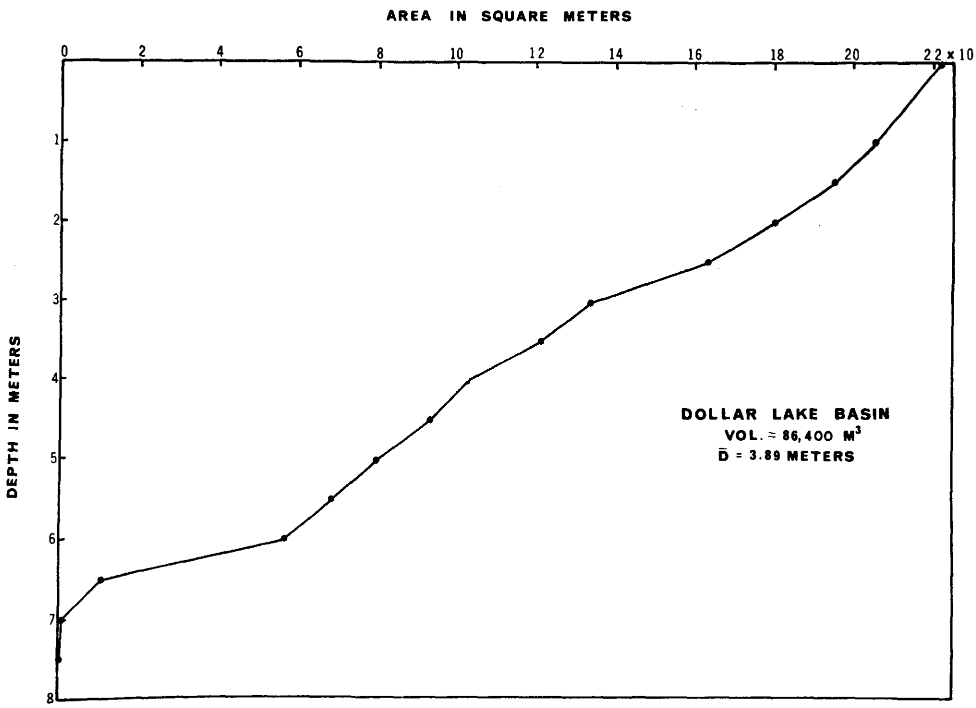

FIGURE 3. Hypsographic curve for the Dollar Lake basin showing the relationship between depth and area.

measurements and samples were taken from an area over the deepest portion of the lake. Representative values of the temperature, oxygen, and transparency measurements are plotted in Figures 4, 5, 6, and 7.

Water temperature was measured at one-meter intervals from surface to bottom with a Whitney Model TC–5A portable thermister thermometer (Montedoro Corporation, San Luis Obispo, California). Dissolved oxygen was measured titrimetrically, using the azide modification, in samples collected with a two-liter lucite Kemmerer sampler. Samples were allowed to overflow for 20 seconds before reagents were added, so that any bubbles which might have formed would be removed. A Secchi Disc, 20 centimeters in diameter, was used to measure transparency. Low-transparency values are interpreted (Hutchinson, 1957) to mean high seston content and reduced light penetration.

Variations in water characteristics were considered in terms of the positions of the epilimnion and hypolimnion. The epilimnion of a thermally stratified lake in summer is the circulating turbulent mass of water above the metalimnion, or the zone of most rapid temperature change. The lower boundary of the metalimnion gradually merges into a stagnant, deep, non-circulating mass of water termed the hypolimnion.

During the summer, the bottom of the epilimnion of Dollar Lake was rarely more than one meter deep (fig. 4). The maximum annual surface temperature was 28°C, which was reached in mid-August. The hypolimnion gradually warmed over the summer from a low, at the bottom of the lake, of just over 5.0°C in April and May to a high in August of almost 9.0°C at this depth. Hutchinson (1957) attributes this increase in hypolimnetic temperatures to a downward turbulent conduction of heat from warmer upper waters and to heating by chemically produced density currents.

Depletion of dissolved oxygen in the hypolimnion began immediately after the lake stratified thermally in April. In August both the middle and upper portions of the metalimnion and all of the epilimnion were oxygenated, but by mid-September, oxygen had been depleted from the upper layers of the metalimnion. Water-density differences within the metalimnion were apparently sufficient to prevent its complete mixing during the summer.

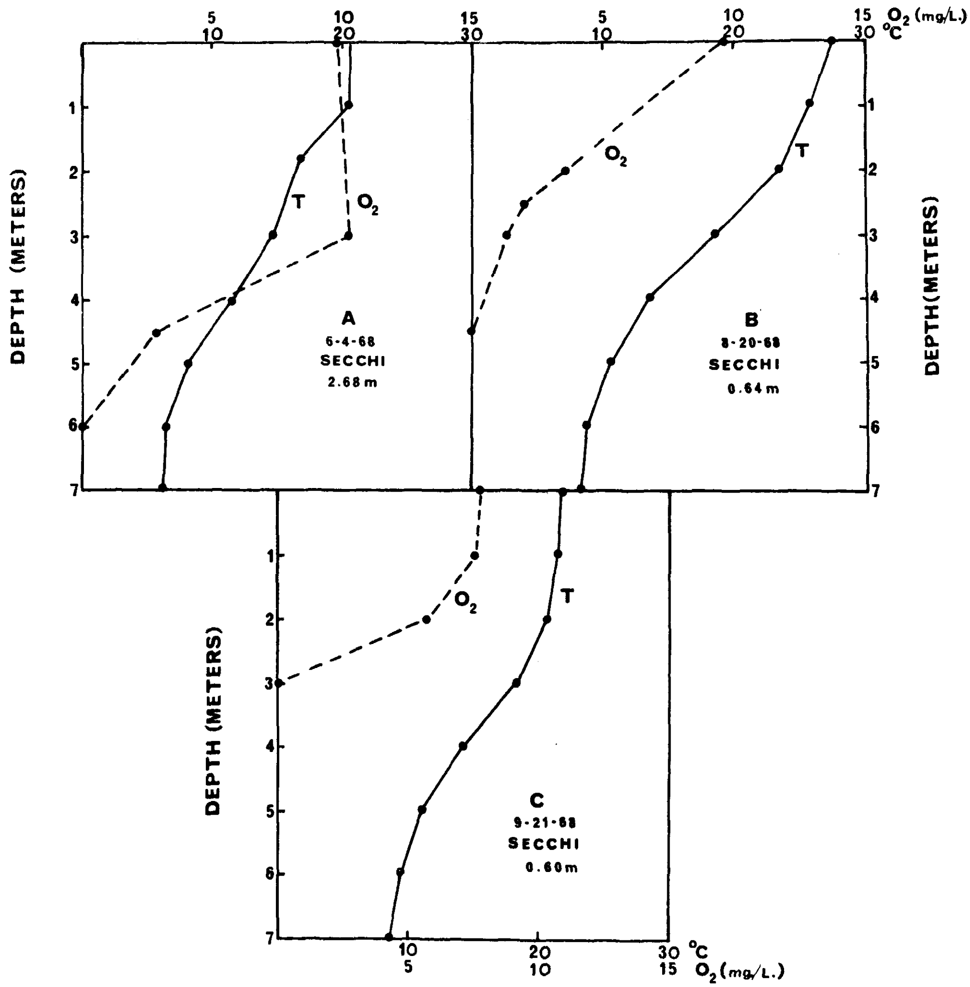

FIGURE 4. Representative dissolved oxygen, temperature, and transparency measurements of Dollar Lake, Summer, 1968.

Throughout the spring, summer, and early fall, tremendous blooms of dinoflagellates and blue-green algae developed. The blooms of one group (*Aphanizomenon flos-aquae* and *Ceratium* sp.) were confined to surface waters, while another bloom, consisting of a species of *Oscillatoria*, was in the hypolimnion. This deep population was heavily pigmented, but may have been heterotrophic, because Secchi Disc values (fig. 4, graphs B, C) indicate little or no light penetration to this depth, so that little or no photosynthesis was possible.

Beginning in late August, cool nights permitted loss of heat from the epilimnion, so that deeper mixing occurred as density differences were reduced. The depth of the epilimnion became greater until the metalimnion and hypolimnion were eliminated (fig. 4, graph C; fig. 5, graph A). In late October, lake temperature was uniform throughout its depths and the dissolved-oxygen stratification was nearly eliminated. The highest temperature of the bottom water during the study, 9.4°C, was recorded in October.

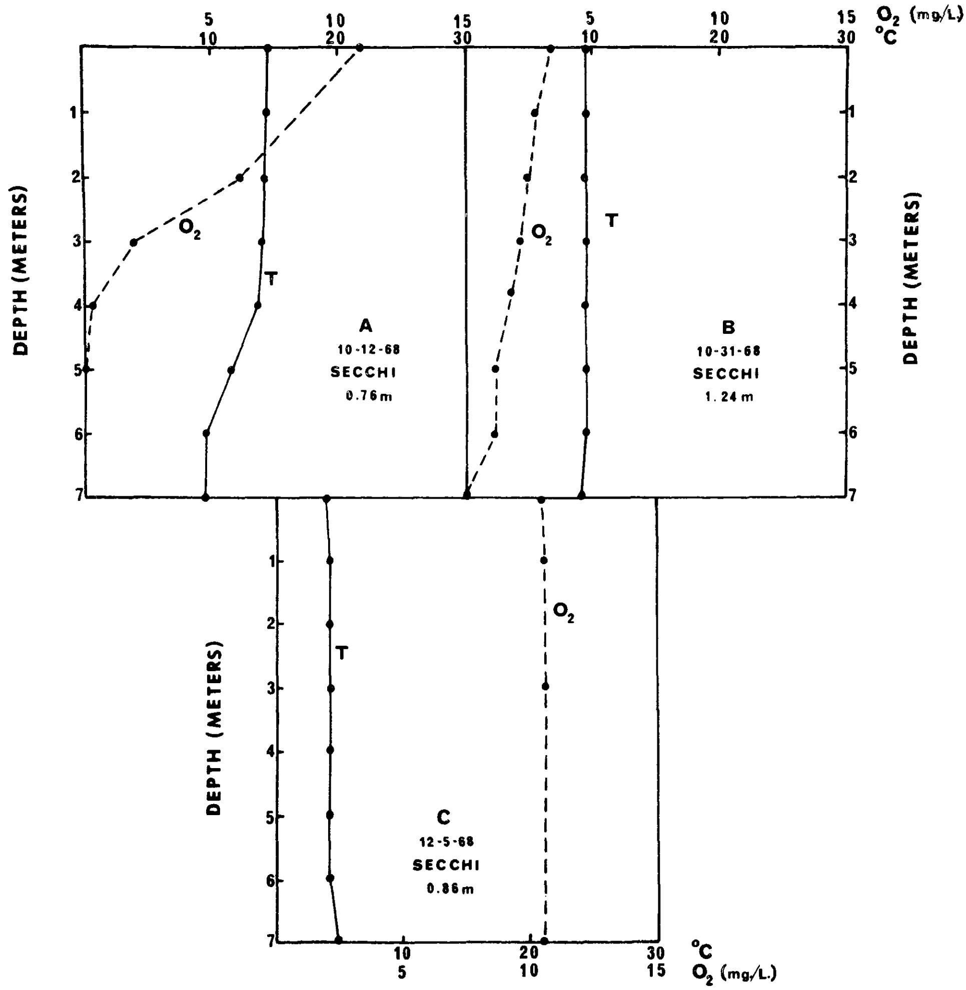

FIGURE 5. Representative dissolved oxygen, temperature, and transparency measurements of Dollar Lake, Fall, 1968.

On 2 November 1968, after a brief period of unseasonably warm, calm weather, the lake restratified and remained so for about one week. During this interval, dissolved oxygen was again depleted in strata below a depth of four meters. Stratification was subsequently eliminated by a period of cold, windy weather, and thereafter the lake mixed and cooled, and then froze on the night of 6 December.

Secchi Disc transparency varied. First it was low early in the fall, during a bloom of *Ceratium* sp. (Fig. 5, graph A), then it was higher as the lake cooled and the bloom decreased (graph B), and then it became low again late in the fall just before freezing.

Ice thickness varied from a few millimeters early in December, and during thaw periods in February and March, to a maximum of nine centimeters in January. The lake was often snow-covered.

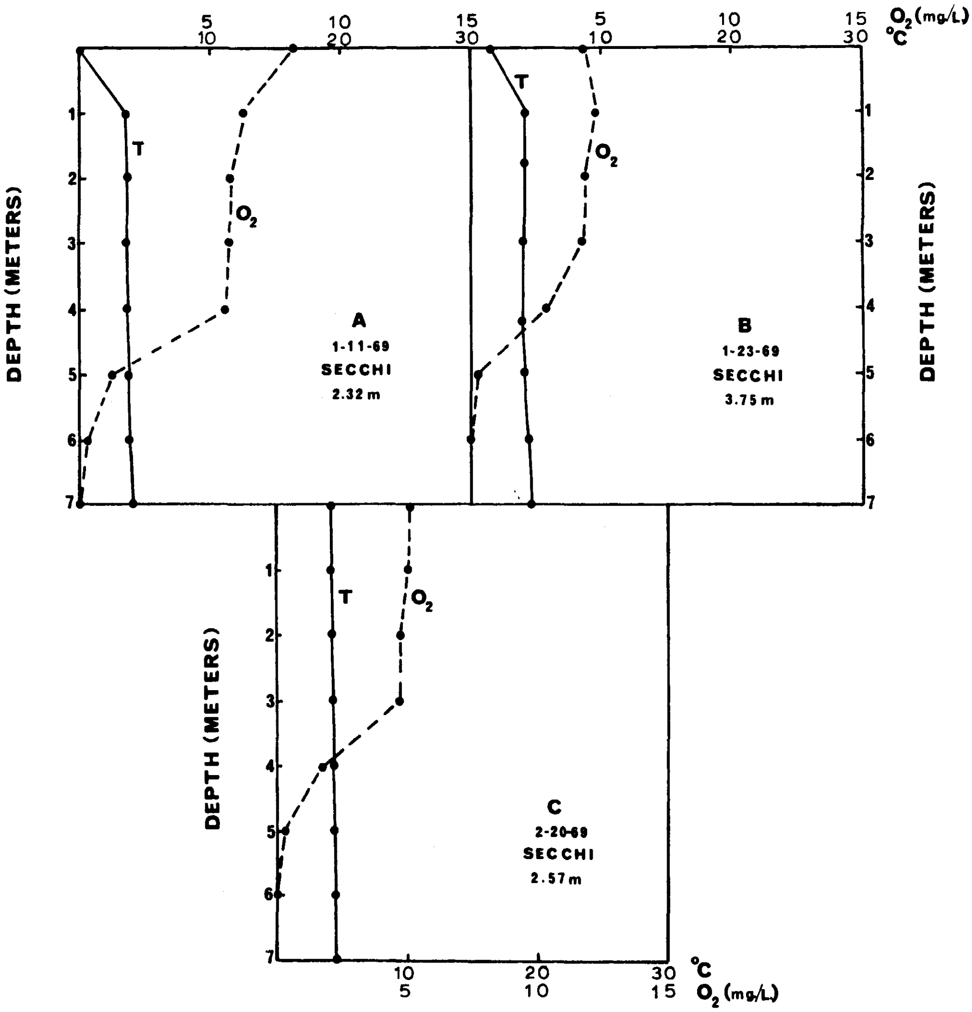

FIGURE 6. Representative dissolved oxygen, temperature, and transparency measurements of Dollar Lake, Winter, 1969.

Following ice formation, there was an inverse stratification of water temperature (fig. 6). Lighter, cooler, surface waters warmed during the winter, presumably from solar radiation and possibly from meltwater of terrestrial origin which drained onto the lake margin and ice-covered surface and may have seeped under the ice. By mid-February, water temperature was 4.2°C just below the ice and 4.65°C at seven meters. The ice broke up on 15 March, 1969. The lake water was most transparent during winter months (fig. 6) due to a low seston content of the water.

The amount of dissolved oxygen in the water just below the ice varied during the winter. Chlorophyll-pigment analysis suggested that there may have been a considerable amount of photosynthesis under the ice when snow cover was absent Dissolved oxygen was gradually depleted from deep waters during the period of ice cover.

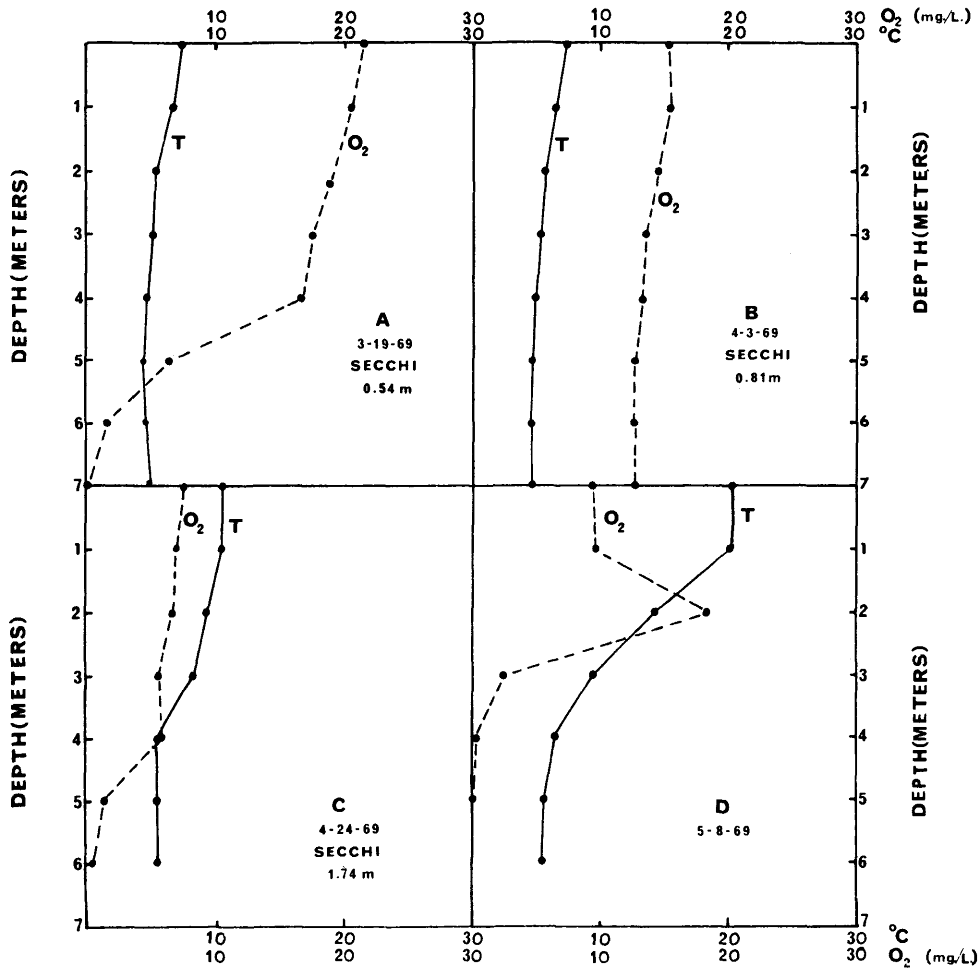

FIGURE 7. Representative dissolved oxygen, temperature, and transparency measurements of Dollar Lake, Spring, 1969.

In the spring, the lake circulated completely, warmed, and then stratified. The contrast in water temperature and dissolved oxygen between the lake just after ice-out (graph A), when the water was very cold and oxygen stratification was still present, and the lake during circulation (graph B) and stratification (graphs C, D) is shown in Figure 7. Temporary thermal stratification occurred during calm warm days in early April, but heavy winds were sufficient to break up these early stratifications. By mid-April the lake had a stable stratification, and oxygen depletion of the hypolimnion had begun.

Oxygen was quickly consumed in the deep strata in the spring. After 21 days of stratification, only a trace of dissolved oxygen was present at six meters, and one week later (graph D), no dissolved oxygen was present below the four-meter stratum. The metalimnetic-oxygen maximum in graph D was correlated with a large quantity of phytoplankton pigments at that depth, again suggesting that photosynthesis was often largely responsible for the observed amounts of dissolved oxygen.

Water transparency was most variable during spring months. Very rapid changes in both zooplankton and phytoplankton populations were observed and may have been related to the changes in Secchi Disc readings.

DISCUSSION

On the basis of the data presented here, and using the terminology of Hutchinson (1957), Dollar Lake is classified as a dimictic, second-class lake. Dimictic is a term used to describe those lakes which circulate twice per year, while a second-class lake is one which becomes "thermally stratified but with bottom temperatures sufficiently above 4°C for the extrapolation of the summer temperature curve to involve a significant increase in the heat entering the lake" (Hutchinson, 1957, p. 440). In contrast, first-class lakes are so large that an increase in either depth, or area, or both would not increase the uptake of heat per unit area.

Two important characteristics of eutrophic lakes are the depletion of dissolved oxygen during stratification and low transparency (Sawyer, 1966; Fruh, 1967). For example, Edmondson *et al.* (1956) describe a decrease in Secchi Disc transparency of Lake Washington (Seattle, Washington) from 4.1 meters in 1913 to a mean of 2.3 meters (range 1.7–2.8 meters) in 1955. Associated with the decrease was nutrient enrichment with sewage, and a large increase in the standing crop of phytoplankton. In this same lake, these authors also report a steady decline in dissolved oxygen in the hypolimnion over the same period, and attribute the decline to the large amount of oxidizable material which falls into the hypolimnion from nutrient-induced plankton blooms. To the extent that these two criteria are indicative of eutrophy, Dollar Lake is classified as a eutrophic lake.

The rapid depletion of dissolved oxygen in the hypolimnion of Dollar Lake appears to be related to three factors: 1) the heavy influx of nutrients from septic tanks, which induces large plankton blooms, 2) the small volume and low mean depth, and 3) the sheltering effect of the hills around the north and northeastern sides of the lake. Of these, the nutrient condition may be most important, because waters rich in these substances have large plankton blooms, from which materials eventually settle out and are oxidized in deep waters. These blooms also shade deeper portions of the lake so that net photosynthesis is confined to only the top few meters. Related to nutrients in effecting eutrophism are the lake's small volume and shallowness. These two factors appear to intensify eutrophy by reducing the dilution factor (amount of plant nutrients per unit volume of lake) and by reducing the distance between the heterotrophic recycling layer (bottom) and the productive layer (surface). If the lake were exposed to more wind, stratification would probably occur later in the spring, and short-term restratification in the fall would be far less likely.

This report has provided base-line morphometric and certain physico-chemical data on a small, dimictic, second-class, eutrophic lake in northeastern Ohio. The overall purpose of this research is to provide a comparative description of the structural and functional features of lakes in varying stages of eutrophication and disturbance, and ultimately to lead to discussions of questions concerning the pattern of succession and the relative ecological maturity of these lakes.

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