The Meromixis of Sunfish Lake, Southern Ontario

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In the meromictic Sunfish Lake the large populations of phytoplankton that are observed periodically were associated with circulation of the mixolimnion. Perhaps some organic dissimilation took place in the lower mixolimnion, recycling nutrients during spring and fall circulation. Phytoplankton was practically absent from the epilimnion during the summer but a population of *Oscillatoria agardhii* remained in the metalimnion, where it was responsible for a pronounced and persistent metalimnetic oxygen maximum. The monimolimnion contained about 5100 mg/liter of dissolved solids and the upper mixolimnion about 2200 mg/liter. Ventilation of the monimolimnion did not always coincide with circulation and subsurface springs may have been responsible. Circulation to the lake bottom was observed only once in 18 months.

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INTRODUCTION

IN A MEROMICTIC LAKE the efficiency of the exchange between the mixolimnion and the monimolimnion to a great extent controls the trophic level of the euphotic zone. Thus in a permanently meromictic lake the monimolimnion acts as a nutrient trap, and, particularly if the importation of nutrients from the watershed is low and the lake is small, sheltered, and relatively deep, primary productivity will be low. Examples of this condition include Krottensee, Austria (Findenegg, 1965), and Green Lake, New York (Jackson and Dence, 1958). In meromictic lakes in which circulation may be complete given favourable meteorological conditions, some return of nutrients to the euphotic zone is accomplished and the primary productivity is consequently higher. An example of this is Hall Lake, Washington (Edmondson, 1963; Edmondson quoted in Frey, MS, 1967). Another consideration, often overlooked, is the recycling of nutrients through circulation in the mixolimnion itself. The effectiveness of this in supplying nutrients to the euphotic zone would in large measure depend on the intensity of organic dissimilation in the lower mixolimnion, the degree of circulation achieved, and its frequency (Findenegg, 1937; Kuznetsov, 1968). This effect apparently would be more applicable to meromictic lakes that have occasional complete circulation. There is, however, little published information on meromictic lakes of this type.

The present study was undertaken to explain the occasional appearance of large algal blooms in the upper waters of Sunfish Lake, a small lake whose phytoplankton productivity is otherwise low. The lake is meromictic, full

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circulation being observed once during the 18 months of study but not subsequently. In the following description several aspects of the meromixis are examined, in particular the influence of the periods of partial or full circulation on the growth of the phytoplankton.

Sunfish Lake is situated at an altitude of 365 m about 8 km to the west of Waterloo in southern Ontario. The lake lies in a small depression surrounded by sandy kames over a Salina (upper Silurian) bedrock of shale, salt, and gypsum (P. F. Karrow, Department of Earth Sciences, University of Waterloo, personal communication). Sunfish Lake and the nearby Spongy and Hofstetter lakes form a series of kettles on the outskirts of the Waterloo Hills. The very small watershed is mostly farmland or mixed deciduous woodland with some hemlock (*Tsuga canadensis*) and cedar (*Thuja occidentalis*) in areas of poor drainage.

The morphometric data of Sunfish Lake is as follows: total area, 8.3 ha; maximum length, 577 m; maximum width, 189 m; maximum depth, 20 m; mean depth, 10.4 m; volume development ratio 1.56; relative depth, 6.15%; maximum depth (m)/$\sqrt{\text{area (ha)}}$, 6.94.

The maximum depth is remarkably deep for the small area of the lake. The relative depth, where the maximum depth is expressed as a percent of the mean diameter (Hutchinson, 1957), and the volume development are high, indicating the pronounced concavity of the lake basin. The main inlet flows only intermittently and a direct passage of water from it to the nearby outlet, bypassing the lake, has been observed on several occasions. There are one or two other very small temporary inflow streams and the presence of several subsurface springs has been reported by local residents. Whether or not these springs are rich in dissolved salts is not known. The littoral is very narrow and mostly free of aquatic plants, but patches of *Chara* sp. occur, the most extensive being around the outlet. The lake bottom is covered by a black sulfide sapropel.

METHODS

Systematic sampling was carried out weekly from February 1966 to July 1967 at a permanent buoy near the deepest point in the lake (Fig. 1).

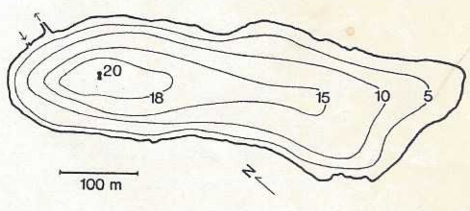

FIG. 1. Hydrographic map of Sunfish Lake showing the position of the sampling station (■). Depths in meters.

Samples of water for chemical analysis and phytoplankton enumeration were collected with a Kemerrer bottle at 1- or 2-m intervals from the surface to the bottom. At each sampling interval the temperature and the percent saturation of oxygen at the observed temperature were measured with an Electronic Instruments Limited Model 15A dissolved oxygen meter. All samples were kept in polyethylene bottles and the further chemical analyses were generally performed on the same day as collection. *p*H was measured in the laboratory with a Fisher Accumet *p*H meter. Alkalinity (corrected for sulfide), nitrate nitrogen, and silicate (monthly) were measured by the methods in Mackereth (1963). Total phosphate phosphorus and sulfide were measured by the methods of the American Public Health Association (1965). Sulfate was measured by the turbimetric method and iron by the 2,4,6-tripyridal-*S*-triazine method of the Hach Chemical Company (1965). In the comparison of chemical concentrations above and below the chemocline (Table 1) all the analyses except total dissolved solids (TDS) were performed by atomic absorption analysis. The TDS was estimated by evaporation and weighing.

TABLE 1. Some chemical concentrations (mg/liter) above and below the chemocline in Sunfish Lake.

		Depth	
		1 m	18 m
TDS[a]	June 6, 1968	2120	5160
TDS	Dec. 10, 1968	2235	5023
Mn	Oct. 25, 1968	0.01	2.50
Fe	"	Trace	0.03
Zn	"	Trace	0.02
Cu	"	Trace	Trace
Na	"	24.02	34.22
K	"	2.82	2.82
Mg	"	12.17	14.03
Ca	Feb. 10, 1969	55.0	105.0

[a]TDS = total dissolved solids.

The populations of phytoplankton were estimated by sedimentation of 100-ml samples with Lugol's iodine followed by enumeration over an inverted microscope. Units are a single cell, a colony, or a filament 450 μ long (i.e., the diameter of the field of the Whipple eyepiece used).

PHYSICAL AND CHEMICAL CHARACTERISTICS

TEMPERATURE

The isotherms of Sunfish Lake (Fig. 2) are indicative of meromixis. During February and March 1966 the 4 C isotherm was at a maximum of 14 m, the temperature increasing to 5.1 C near the bottom. During the winter of 1966–67 the 4 C isotherm, initially at 13 m in December, gradually rose to about 4 m by the end of February suggesting some process of heating. During the summers of 1966 and 1967 the temperature near the bottom was never less than 5.4 C and on several occasions there was an inverse stratification existing from about 15 m to the bottom. Only during the circulation period in November–December 1966 was there some suggestion of circulation to the bottom.

The thermal profile for November 23, 1966 (Fig. 3), shows a maximum at about 16 m and the profile for July 7, 1967, shows a slight but definite temperature inversion from about 14 m to the bottom.

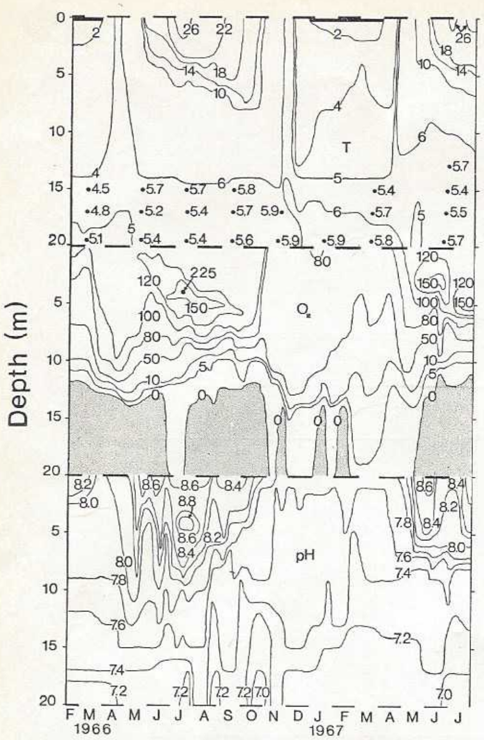

FIG. 2. Isotherms (C) and isopleths of percent saturation of dissolved oxygen and of *p*H in Sunfish Lake, February 1966 to July 1967. Heavy bars are ice cover and stippled areas are anaerobic.

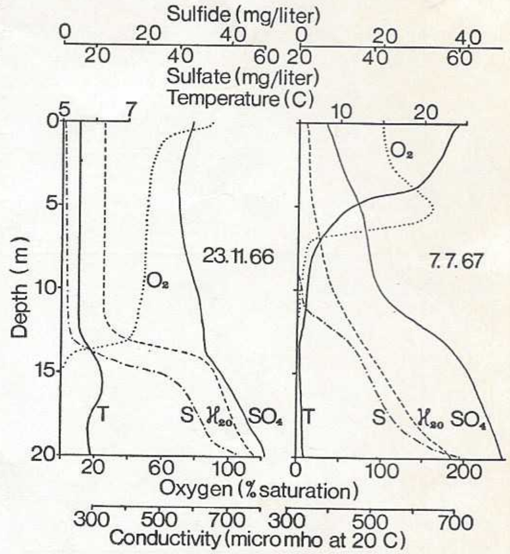

FIG. 3. Profiles of temperature (C), conductivity, dissolved oxygen, sulfide and sulfate on two dates in Sunfish Lake.

DISSOLVED OXYGEN

The isopleths of dissolved oxygen (Fig. 2) clearly indicate prolonged periods of anoxis below 11–12 m and the metalimnetic oxygen maximum during the summers. Although periods of circulation would account for the partial ventilation of the monimolimnion in November–December 1966 and April 1967 no such explanation can account for the oxygen present in July 1966 or under the ice during the winter of 1966–67.

During the prolonged circulation of November–December 1966 the percentage saturation of dissolved oxygen in the mixolimnion fell to less than 80 and, except for one brief interval associated with a brief growth of phytoplankton immediately under the ice, remained less than 80% until circulation the following spring. Very likely this demonstrates the high biochemical oxygen demand of the monimolimnion and lower mixolimnion. On occasions when the dissolved oxygen meter readings were checked against chemical analysis by the standard Winkler method the latter always gave negative results when the meter registered trace (less than 5% saturation) amounts.

Probably, in the presence of H_2S the oxygen electrode is more sensitive than the chemical method.

*p*H and Alkalinity

There was a marked decrease in *p*H with depth (Fig. 2). The highest values, 8.0–8.8, were recorded mainly in the epilimnion in the summers of both 1966 and 1967. From November 1966 to May 1967 the *p*H of the surface waters fell to between 7.4 and 7.8. There was little evidence of seasonal changes in the *p*H of the lower monimolimnion, the values being usually around neutrality.

The isopleths of alkalinity (Fig. 4) indicate a marked increase with depth, particularly near the bottom. The concentrations ranged from 75 mg/liter

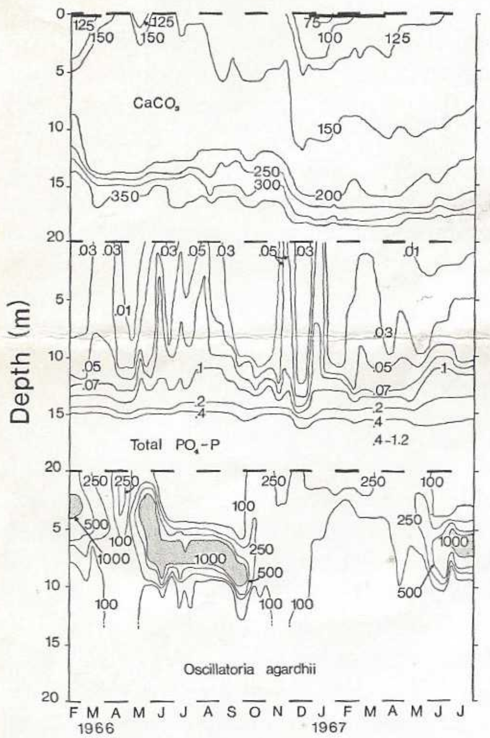

Fig. 4. Isopleths of alkalinity as mg/liter of $CaCO_3$, mg/liter of total phosphate phosphorus, and filaments/milliliter of *Oscillatoria agardhii* in Sunfish Lake, February 1966 to July 1967. Heavy bars are ice cover and stippled areas are 1000 filaments/milliliter or more of *O. agardhii*.

at the surface to over 350 mg/liter at the bottom. A decrease in alkalinity occurred at all depths during the circulation of November–December 1966. There was a partial recovery toward the end of the period of observations.

Phosphate, Nitrate, and Other Observations

There was a pronounced increase with depth of total phosphate phosphorus (Fig. 4) throughout the study period. Concentrations varied from about 0.01 mg/liter near the surface to over 1 mg/liter near the bottom. In general, the stratification with depth of total phosphate phosphorus in the mixolimnion was most evident during thermal stratification, the isopleths clearly indicating the periods of circulation. Organic dissimilation in the lower mixolimnion in the summer of 1966 is suggested by the general increase in total phosphate phosphorus. The deep circulation of November–December 1966 is clearly reflected in the isopleths yet surprisingly there was apparently little influence on the concentrations below about 15 m.

Amounts of nitrate nitrogen varied inconsistently with depth and time from a trace to 0.25 mg/liter. None was detected below 12 m by the method used. Concentrations of dissolved silicate varied from about 5 to 10 mg/liter.

There was more than twice the concentration of TDS above the chemocline as there was below (Table 1). The most abundant element analysed was calcium. Of the other elements analysed only potassium was more concentrated above than below the chemocline.

On November 23, 1966, the chemocline was evidently between 13 and 15 m (Fig. 3) with the lake circulating to about 15 m. The position of the chemocline was not nearly so evident on July 7, 1967, although a temperature minimum was at 14 m.

Amounts of sulfide near the bottom were usually around 40 mg/liter and sulfate between 60 and 72 mg/liter (Fig. 3). On November 23, 1966, trace amounts of sulfide were found at the surface. Sulfide was generally detectable at 9 or 10 m during thermal stratification of the mixolimnion.

Secchi disc transparency was generally between 4 and 5 m during the summer months but during the periods of circulation it decreased to $2–2\frac{1}{2}$ m.

PHYTOPLANKTON

Over the entire period of observation, by far the most abundant phytoplankter was a species of *Oscillatoria*, tentatively identified as *O. agardhii* Gomont but in some respects resembling the variety *O. agardhii isothrix* Skuja. When observations began in February 1966, a fairly large population existed under the ice and was particularly dense between 2 and 4 m (Fig. 4). During circulation of the mixolimnion in April 1966, the population declined to less than 250 filaments per milliliter. Coincident with the onset of thermal stratification in May the population increased rapidly and by the end of May was in excess of 1000 filaments per milliliter between 2 and 8 m. In June, July, and August the population was practically confined to the metalimnion and densest between 6 and 8 m. In September and early October, the center of the bloom descended further to between 8 and 10 m. With the onset of autumn circulation, the population became scattered fairly uniformly through the mixolimnion. Other phytoplankton were very sparse in the epilimnion during both summers and consisted chiefly of low numbers of several species of Chroococcales. During the winter of 1966–67, there was a small increase in *Oscillatoria* immediately under the ice to about 250 filaments per milliliter but a large population, such as was found in February 1966, did not develop. Also, unlike the previous year, a large population did not develop immediately after thermal stratification in May 1967. The increase was gradual and not until the 3rd week in June was there a population in excess of 1000 filaments per milliliter between 5.5 and 7.5 m.

Only four other species of phytoplankton formed persistent populations of appreciable abundance. These were *Asterionella formosa* Hass., *Stephanodiscus hantzschii* Grun., *Cryptomonas erosa* E., and *Cryptomonas curvata* E. (Fig. 5). All four species had periods of growth before and during the spring

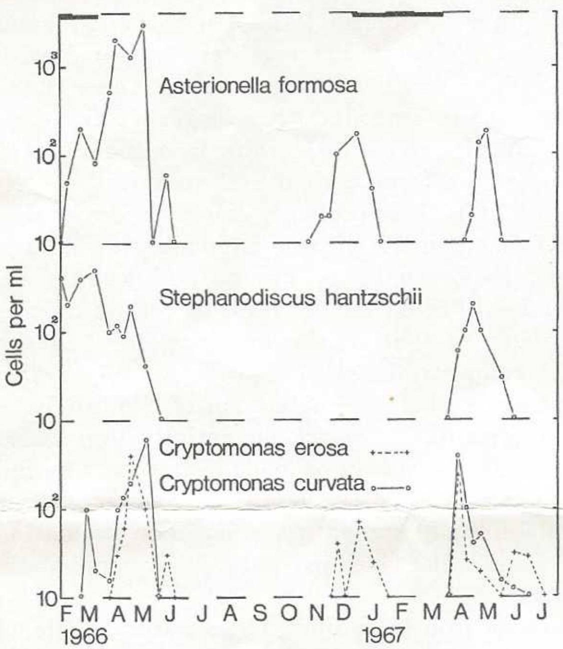

FIG. 5. Variations in populations of four species of phytoplankton in Sunfish Lake, February 1966 to July 1967. Heavy bars are ice cover.

overturn in both years and *A. formosa* and *C. erosa* also had minor blooms in early winter 1966–67. The spring increase in 1966 was greater in each instance than that in 1967, particularly so for *A. formosa.*

DISCUSSION

Of known meromictic lakes in North America, Sunfish Lake is chemically most similar to Green and Round lakes, New York (Likens, MS, 1967). However, Green Lake has high transparency, paucity of phytoplankton, and low productivity (Jackson and Dence, 1958) and in these respects is quite unlike Sunfish Lake. Green Lake is also deeper (50 m), and complete circulation has never been reported. Takahashi et al. (1968) concluded that the cause of permanent stratification of Green Lake is crenogenic, little contribution to the meromixis coming from biological activity within the lake. In Sunfish Lake, since the presence of saline subsurface springs has not been demonstrated, and considering the biological activity within the lake, meromixis is probably largely biogenic, its maintenance assisted by the morphometry of the lake basin and its sheltered situation. It is highly unlikely that meromixis can be attributed entirely to morphometric features as Northcote and Halsey (1969) postulated for Yellow Lake, B.C. The nature and antiquity of meromixis in Sunfish Lake is currently under investigation by microfossil and chemical analysis of the sediments.

The concentrations of sulfate and sulfide in Sunfish Lake (Fig. 3) are, however, too great to be entirely biogenic (cf. Hutchinson, 1957). In Green Lake the maximum amount of sulfide is about 56 mg/liter (Turano and Rand, MS, 1967) compared with 40 mg/liter in Sunfish Lake. On the other hand the sulfate content of Green Lake is about 1500 mg/liter compared with only 70 mg/liter in Sunfish Lake. The origin of the sulfate in Green Lake has been ascribed to leaching from the surrounding geological formations and possibly the sulfate in Sunfish Lake is derived by leaching from the bedrock, which is known to contain gypsum, or from agricultural runoff.

The decrease in *p*H with depth (Fig. 2) is probably caused by increasing amounts of carbon dioxide, which has a much greater influence on *p*H than the increasing alkalinity (Fig. 4). In Green Lake, Turano and Rand (MS, 1967) point out that the *p*H is more affected by the ratio of carbon dioxide concentration in the monimolimnion to that in the mixolimnion than the corresponding ratio of alkalinity concentrations.

The concentration of phosphate in the monimolimnion of Sunfish Lake is very large and its origin is uncertain. There are no entirely unpolluted waters in the vicinity with which comparisons may be made so the contribution from farming and domestic activities cannot be evaluated. The concentrations of total phosphate in the mixolimnion are dependent partially upon circulation and eddy diffusion across the chemocline and partially upon tropholytic processes in the mixolimnion itself.

The very low amount of soluble iron in Sunfish Lake water (Table 1) is unusual for an inland meromictic lake (cf. Hutchinson, 1957), although ferrous iron is completely absent in the monimolimnion of Lake Mary, Wisconsin, a biogenically meromictic lake (Hutchinson, 1957). In both cases iron is presumably deposited in the sediments as FeS. Conversely, the concentration of TDS (Table 1) is higher than in either Lake Mary or Stewart's Dark Lake and comparable to Round and Green lakes, New York (Likens, MS, 1967). The increase of total dissolved solids in the mixolimnion and the decrease in the monimolimnion between June 6 and December 5, 1968, is probably the result of partial autumn circulation into the monimolimnion.

The occurrence of oxygen in the monimolimnion did not always correspond to periods of deepest circulation. The oxygen may may have entered the lake via subsurface springs, but the irregular nature of the partial ventilation is unexplained. Turano and Rand (MS, 1967) found a concentration of about 1 mg/liter in the monimolimnion of Green Lake. The low concentrations of oxygen in Sunfish Lake were sometimes associated with H_2S. Sorokin (1966) described a similar occurrence in meromictic Lake Belovod and discussed the conditions under which it may occur.

The metalimnetic oxygen maximum (Fig. 2) generally extended from 3 or 4 m to the upper part of the *Oscillatoria* bloom, at about 7 m. In the summer of 1967 the uppermost limit of the oxygen maximum was shallow, averaging 3–6 m. In September 1966 the lower edge of the *Oscillatoria* bloom was in water of less than 10% oxygen saturation and in the presence of at least 1 mg/liter of hydrogen sulfide. In all important respects the behaviour of *O. agardhii* in Sunfish Lake is similar to that described in Myers Lake, Indiana (Eberly, 1959), and McLish Lake, Indiana (Eberly, 1964a), both of which have metalimnetic oxygen maxima. Eberly (1964a) uses the ratio maximum depth $(m)/\sqrt{\text{area (ha)}}$ and suggests that it has to exceed 3 before a metalimnetic oxygen maximum can develop. In Sunfish Lake this ratio is 6.94. Eberly (1964b) reviews the occurrence of metalimnetic oxygen maxima in lakes of the world and their morphometric characteristics. Ninety percent of the lakes had a volume development ratio of greater than 1.00; in Sunfish Lake the ratio is 1.56, indicating the pronounced concavity of the lake basin. Another ratio used by Eberly is relative depth. In Sunfish Lake it is 6.15, compared with 4.16 for McLish Lake and only 2.94 for Myers Lake (west basin). Included in Eberly's review are at least four lakes possessing metalimnetic oxygen maxima that are also meromictic. Their relative depth ratios vary from 1.53 to 10.21 and inversely with their area. Thus Sunfish Lake undoubtedly is related to the class of lakes found in Wisconsin and Indiana that show metalimnetic oxygen maxima or meromixis or both. They are all of glacial origin and have a significantly higher relative depth ratio than lakes in the same area without metalimnetic oxygen maxima or meromixis. Similarly the small size and high relative depth of Sunfish Lake make it comparable to a group of Japanese lakes with metalimnetic oxygen maxima (Eberly, 1964b).

The periods of growth of major species of phytoplankton other than *O. agardhii* in Sunfish Lake (Fig. 5) were associated with circulation of the mixolimnion. In every case the population declined upon, or shortly after, thermal stratification. In spite of the deep circulation and considerable exchange across the chemocline in November–December 1966 the populations in December 1966 and in the following spring were not so great as in the spring of 1966. However, the nature of the autumn 1965 circulation was not studied.

It is improbable that phosphate is limiting at any time, though nitrate might be. The isopleths indicate little association between the amounts of phosphate and the populations of *O. agardhii*. In the epilimnion in summer the concentration of total phosphate phosphorus never fell much below 0.01 mg/liter, yet the total population of phytoplankton from June to September in the upper 3 or 4 m rarely totalled more than 10 cells/ml at any time. Recently Rigler (1968) postulated that the concentration of inorganic phosphate in lake water is much lower than indicated by the molybdenum blue test. If this is so, lack of phosphate may perhaps limit growth in Sunfish Lake. It is equally possible that iron or some other substance is limiting. The meromixis of Sunfish Lake undoubtedly hinders the return of nutrients from the monimolimnion but this alone cannot explain the low productivity of phytoplankton in the epilimnion during the summer. The same features of morphometry that contribute to the meromixis of Sunfish Lake must also help maintain a very stable epilimnion, allowing little eddy diffusion across the thermocline and thus preventing any return of nutrients except during the spring and fall circulations.

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