

Limnological contrasts and anomalies in two adjacent saline lakes

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Abstract

Differences in physical, chemical, and biological conditions in two small (<20 ha) saline lakes less than 1 km apart in south-central British Columbia are examined. Although the lake basins are morphometrically similar, differences in their watershed geology and topography in large part may be responsible for the more saline lake showing severe and anomalous meromictic features while the less saline lake exhibits normal dimictic characteristics. Bacterial and phytoplankton population densities and production profiles of the lakes are compared along with some aspects of their zooplankton populations.

Introduction

Although closely situated saline lakes and ponds may show considerable variation in their physical-chemical and biological characteristics (Scudder 1969; Blinn 1971a, b; Topping & Scudder 1977), few exhibit such striking differences as those found in two small permanent water bodies less than a kilometre apart in the southern Okanagan Valley of British Columbia (Fig. 1). One of the lakes (Mahoney) is strongly meromictic and seasonal changes in various limnological features have been described previously (Northcote & Halsey 1969). The other (Green) is a more typical temperate dimictic lake and while many aspects of its limnology have been known for some time (Northcote unpub.), these have not been reported previously.

Of the several possible causes for marked local differences in lake conditions, those most frequently implicated are geological and morphological features of the lake basins. In our case, however, these lakes seemed reasonably similar (at least in comparison of the more usual parameters), which prompted us to make a detailed investigation of conditions associated with the period between early spring and

summer in each of the lakes to see if this might reveal causal mechanisms for their widely disparate characteristics.

Methodology

Lake surfaces and watershed morphometry were taken from B.C. Ministry of Environment, Surveys and Mapping Branch topographic maps 82E.023.3.3 and 82E.033.1.1 (scale: 1/5000) compiled from August 1972 air photography. Lake depth contours were obtained from B.C. Fish and Wildlife Branch surveys based on echo-sounder transects. All other observations were recorded at midlake stations on each lake (Fig. 1).

Vertical temperature and conductivity readings were made with a regularly calibrated (standard 0.01 M KCl) YSI Model 33 meter, taking care to clean the probe after each immersion in the monimolimnion of Mahoney Lake. Because of the marked vertical differences in chemical composition and concentration in this lake, it was necessary to determine separate temperature-conductivity relationships for a series of depths in order to make

appropriate corrections for expressing conductivity at a standard temperature of 25 °C. Details of this correction will be reported elsewhere (Hall & Northcote, in prep.). Vertical dissolved oxygen readings were taken with a YSI Model 57 meter calibrated by air saturation as well as Winkler determinations of surface water. Water transparency was measured with a standard Secchi disc and percent transmission of light with a Beckman EV 3 light meter.

The pH was measured with a Fisher Accumet pH meter (Model 210), fitted with a combination electrode. Alkalinity was determined on 5 or 10 ml samples diluted to 100 ml with distilled water and titrated with 0.02 N H₂SO₄ to pH 8.3 and 4.5 using a pH meter (A.P.H.A. *et al.* 1980). Sulphide samples were preserved with 2 N zinc acetate and 6 N NaOH in glass stoppered bottles and quantified by the iodometric titration procedure (A.P.H.A. *et al.* 1980).

For carbon determination, triplicate 20 µl samples were injected into the total and inorganic carbon channels of a Beckman total carbon analyzer (Model 915) and compared to standard curves made with potassium acid phthalate (TC channel) and sodium bicarbonate (IC channel). Organic carbon was determined by difference. Kjeldhal nitrogen (organic N + NH₃ - N) was measured by acid digestion of 200 ml samples, distillation into borate buffer and titration with standard acid (A.P.H.A. *et al.* 1980). Nitrate and nitrite nitrogen were determined by a Technicon autoanalyzer technique using a cadmium reduction column (Willis 1980). Total phosphorus was measured by acid digestion (H₂SO₄ + K₂SO₄) of 10 ml samples on a programmed Technicon block digester followed by colorimetric measurement on a Technicon autoanalyzer II using the ammonium molybdate-potassium antimonyl tartrate-ascorbic acid reduction (a modification of the Technicon industrial technique no. 327-74W).

Phytoplankton biomass was estimated from chlorophyll a measurements with a Perkin Elmer Hitachi spectrophotometer on 90 percent acetone extracts of samples filtered on 0.45 µm membrane filters (A.P.H.A. *et al.* 1980). Phytoplankton production was measured by the ¹⁴C radioisotope method. Vertical samples collected with a van Dorn bottle were placed in duplicate light and dark BOD bottles to which 1 µCi of ¹⁴C-sodium bicarbonate

solution (8.4 mCi mmol⁻¹ - New England Nuclear) was added. The bottles were incubated *in situ* in a horizontal position on plexiglass holders for 8 hours. Subsamples were filtered on 0.45 µm membrane filters (Sartorius) which were acid treated, dissolved in PCS scintillation solution (Amersham-Searle) and counted on a Nuclear Chicago Isocap scintillation counter using an external standard for quench correction (A.P.H.A. *et al.* 1980).

Heterotrophic activity and bacterial productivity measurements were made on samples incubated *in situ* in 20 ml disposable plastic syringes. Net heterotrophic activity was measured using uniformly labelled ¹⁴C-glucose (255 mCi mmol⁻¹) and ¹⁴C-acetate (57.6 mCi mmol⁻¹) representing 5.11 µgC l⁻¹ and 7.03 µgC l⁻¹ respectively of added carbon (New England Nuclear). One ml of isotope was added to 9 ml of water in the syringe using two active and one blank sample (0.2 ml formaldehyde) for each depth. Samples were incubated for 4 hours, filtered through Nucleopore 25 mm filter assemblies containing 0.22 µm membrane filters (Sartorius) which were counted in a manner similar to algal productivity samples. Bacterial productivity was estimated by the incorporation of ³H-thymidine where 10 µCi of isotope (69.4 Ci mmol⁻¹) was added to 10 ml samples in duplicate live and formalized syringes followed by incubation for 2 hours (Fuhrman & Azam 1980). Samples were filtered, the filters washed with trichloroacetic acid solution, hydrolyzed with HCl, followed by scintillation counting. Thymidine incorporation (mol l⁻¹ day⁻¹) was converted to give a productivity rate of cells l⁻¹ day⁻¹ by multiplying by 0.2 10¹⁸ to 1.3 10¹⁸ to reflect the range of DNA levels in cells and finally by 3.564 10⁻⁸ µgC cell⁻¹ for conversion to µgC l⁻¹ h⁻¹ (D. Stroh, pers. commun.).

Bacterial numbers and biomass were determined by direct counting of formalized samples using epifluorescence microscopy and the DAPI staining technique (Porter & Feig 1980). All samples for chemical, bacterial and phytoplankton measurements were collected on April 28 and 29, 1982.

Samples (60 ml) for phytoplankton identification and enumeration were taken from a well-mixed 3.5-l van Dorn bottle and preserved in Lugol solution. Subsamples were transferred to 27 ml settling chambers for 24 hours and counts of taxa were made under a phase contrast inverted microscope at 750× magnification, usually across 3-6 randomly selected fields (Utermohl 1958).

Table 1. General characteristics of the geological formations associated with Green and Mahoney Lake drainage basins (summarized from Church 1973, 1979).

Age	Formation	Member	Description	Chemical features
Pre-tertiary (Triassic or older)	Vaseaux		Metasedimentary and metavolcanic rocks, mainly siliceous and phyllitic gneiss and some schist	Relatively low alkali composition
Tertiary (Eocene)	Marron	Yellow Lake 1a	Mostly pyroxene-rich mafic phonolite lava; rhomb porphyry and augite crystal-bearing lavas with abundant zeolite fillings in cracks and fissures	Relatively high alkali composition, high alumina to silica ratios
		Kitley Lake 3	'Clot-lath' and other porphyrys with fractures commonly filled with calcite	Alkali-rich
		Kearns Creek 4	Vasicular pyroxene-rich basaltic andesite lava	Moderate total alkalis, low alumina to silica ratios
		Nimpit Lake 5	Trachyte and trachyandesite lavas	Alkali-rich, intermediate alumina to silica ratios, potash-rich
	Park Rill 6	Merocrystalline andesite lava	Moderate total alkalis, low alumina to silica ratios, soda-rich	
	Skaha	10	Mostly chert and green-stone breccia, some tephrite lava, polymictic fanglomerate and granite boulder conglomerate	Relatively low to intermediate alkali composition

Two replicate zooplankton samples were obtained from selected depths with a PAR Model 34 600-0 000 electric pump using a weighted 24 mm ID clear plastic hose. The pump delivered an average volume of 34.9 l minute⁻¹ and was operated for 2 minutes at each depth, straining the discharge through a 102 µm Nitex mesh plankton net. The samples were preserved in 4% sugared formalin. Three 1-ml subsamples were taken from suitable well-mixed concentrations of each replicate sample for identification and counting under a stereobinocular microscope, usually at 25-100 power, although all species identifications were checked with a compound microscope at appropriate higher magnifications.

General geology and morphometry

During Pleistocene glaciation, the southerly moving Wisconsin ice sheet covered the southern Okanagan to an elevation of over 2 000 m, with the

most recent ice advance stopping near Mahoney Lake (Church 1973). The watersheds of Green and Mahoney lakes are situated close to areas of pitted outwash deposits (Nasmith 1962) and the lakes probably occupy kettle basins.

The two lakes lie astride a major north-easterly oriented fault separating Triassic or older metasedimentary and metavolcanic rocks of the Vaseaux Formation from the Tertiary (Eocene) rocks of the Marron and Skaha formations (Fig. 1, Table 1). Thus, both their watersheds drain roughly equal portions of the harder pre-Tertiary metamorphics and the softer Tertiary rocks although the latter in the Green Lake watershed are almost entirely of the Shaka Formation in contrast to those of the Mahoney Lake watershed which are mainly highly fractured lavas of the Marron Formation (Fig. 1, Table 1).

Major morphometric characteristics of the two lakes seem reasonably similar (Fig. 1, Table 2). There is less than 20 m difference in their elevations and although the drainage area of Mahoney Lake is

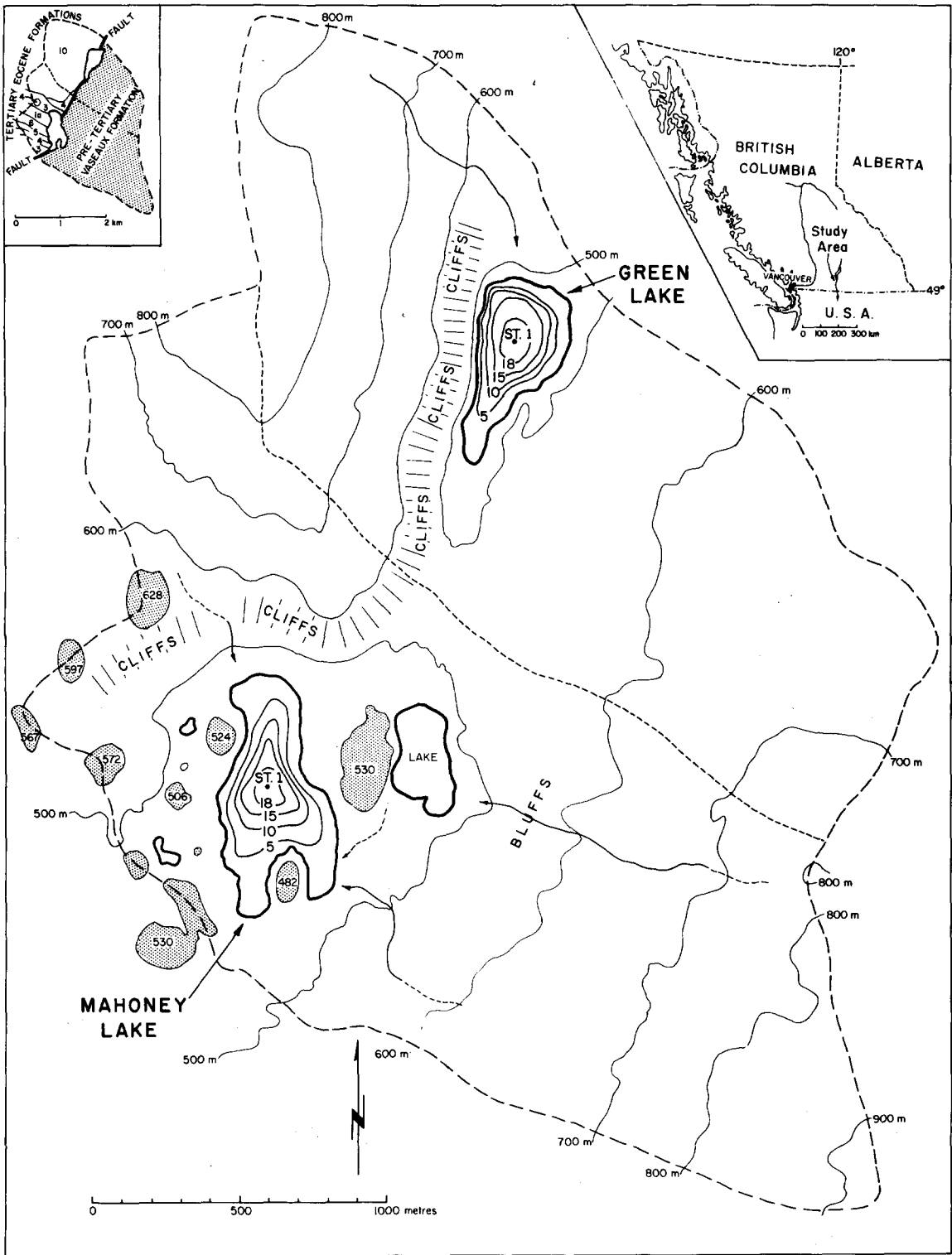


Fig. 1. Generalized geological and morphometric features of Green and Mahoney lakes in south-central British Columbia. Upper right inset shows location of the study area; upper left inset shows geology of the lake drainage basins adapted from Church (1979); see Table 1 for details; main map shows topographic contours (100 m intervals) of drainage basins (---), location and maximum elevation of hills within the basins, and approximate depth contours (m) of lakes.

slightly larger, it includes three small internal sub-basins associated with two ponds near its west shoreline and a small lake just over 200 m to the east (Fig. 1). Mahoney Lake does have over 1.5 times the surface area of Green Lake, but its maximum effective length and width are only 1.27 times larger. The more sinuous shoreline of Mahoney Lake gives it a slightly higher shoreline development compared to that of Green Lake. Maximum and mean depths of Mahoney are about 2 m less than those of Green, but because of its somewhat larger size, Mahoney has about 1.2 times the volume of Green.

Physical-chemical conditions

Temperature, oxygen and conductivity

Striking differences were evident between Green and Mahoney lakes in temperature, oxygen and conductivity profiles (Fig. 2). By mid-April, only a few days after breakup of ice cover, considerable heating of their surface waters already had occurred so that surface temperatures of both lakes were close to 8 °C. Thermal stratification proceeded normally throughout spring to summer in Green Lake with thermocline formation at about 6 m

clearly distinguishing a well-mixed epilimnion and a hypolimnion whose lowermost waters were strongly depleted of dissolved oxygen. Indeed the lake may not have circulated completely after ice breakup so that the depletion could have been a result of overwinter decomposition. There was little vertical change in conductivity in Green Lake, surface values ranging between 2 730–2 870 $\mu\text{S cm}^{-1}$ and near-bottom values between 3 035–3 520 $\mu\text{S cm}^{-1}$ over the spring period.

The thermal stratification that developed in Mahoney Lake after ice melt was completely different to that in nearby Green Lake (Fig. 2). Although the surface temperatures of the two lakes were similar in mid-April, the thermal profile of Mahoney rose sharply to a peak at about 1.5 m and then declined again to a minimum at a depth of 6 m. In late April, there was a maximum differential of 10 °C between the surface temperature and the thermal peak at 1.5 m. The depth of this maximum descended to 2 m in mid-May and to 3 m by early June (Fig. 2), reaching a temperature of 24 °C. Concomitantly the thermal minimum at the upper surface of the monimolimnion remained at 6 m from April to June but increased in temperature from 4.6 to 9.8 °C over this period. The maximum temperature of the monimolimnion (ca 15 °C) was reached at about 15 m, close to the bottom and the present maximum depth.

Dissolved oxygen profiles of Mahoney Lake also contrasted sharply with those of Green Lake. As with temperature, the surface oxygen concentrations in the two lakes were similar, but just below 0.5 m, the values in Mahoney decreased rapidly to a minimum of less than 0.5 mg l^{-1} at least until mid-May. The depth of the first oxygen minimum descended from about 1.5 m in mid-April to 3.0 m in early June. Surprisingly, dissolved oxygen concentrations *increased* again to reach a second peak at 5–6 m with maximum values of almost 4 mg l^{-1} in mid-April increasing to almost 8 mg l^{-1} in early June. Below 6 m, oxygen decreased rapidly to virtually zero by 8 m.

The conductivity of near-surface (0–0.5 m) water of Mahoney Lake was several fold higher than that of Green and increased from about 12 500 $\mu\text{S cm}^{-1}$ in mid-April to 16 800 in early June. Between 0.5 and 1.5 m, conductivity increased rapidly to over 25 000 at 2 m and then showed only a slight increase between 2 and 6 m. A second sharp chemocline was

Table 2. Major morphometric characteristics of Green and Mahoney lakes.

Characteristic	Green	Mahoney
Maximum elevation (m)	490.7	471.5
Drainage area (ha)	306.2	385.4 ^a
Surface area ^b (ha)	12.6	19.8
Maximum effective length (m)	648	820
and direction (°)	24.5	9.0
Maximum effective width (m)	320	407
Shoreline length (m)	1 884	2 691
Shoreline development	1.5	1.7
Maximum depth ^b (m)	20.1	18.3
Mean depth ^b (m)	9.0	6.9
Relative depth ^c (%)	5.0	3.6
Volume (10 ⁴ m ³)	113.6	136.2

^a Includes internal sub-basins around the 3 small adjacent lakes (Fig. 1).

^b At maximum elevation evident from long-term high water marks.

^c $Z_r = \frac{50 Z_m \sqrt{\Pi}}{\sqrt{A}}$ (Walker & Likens 1975).

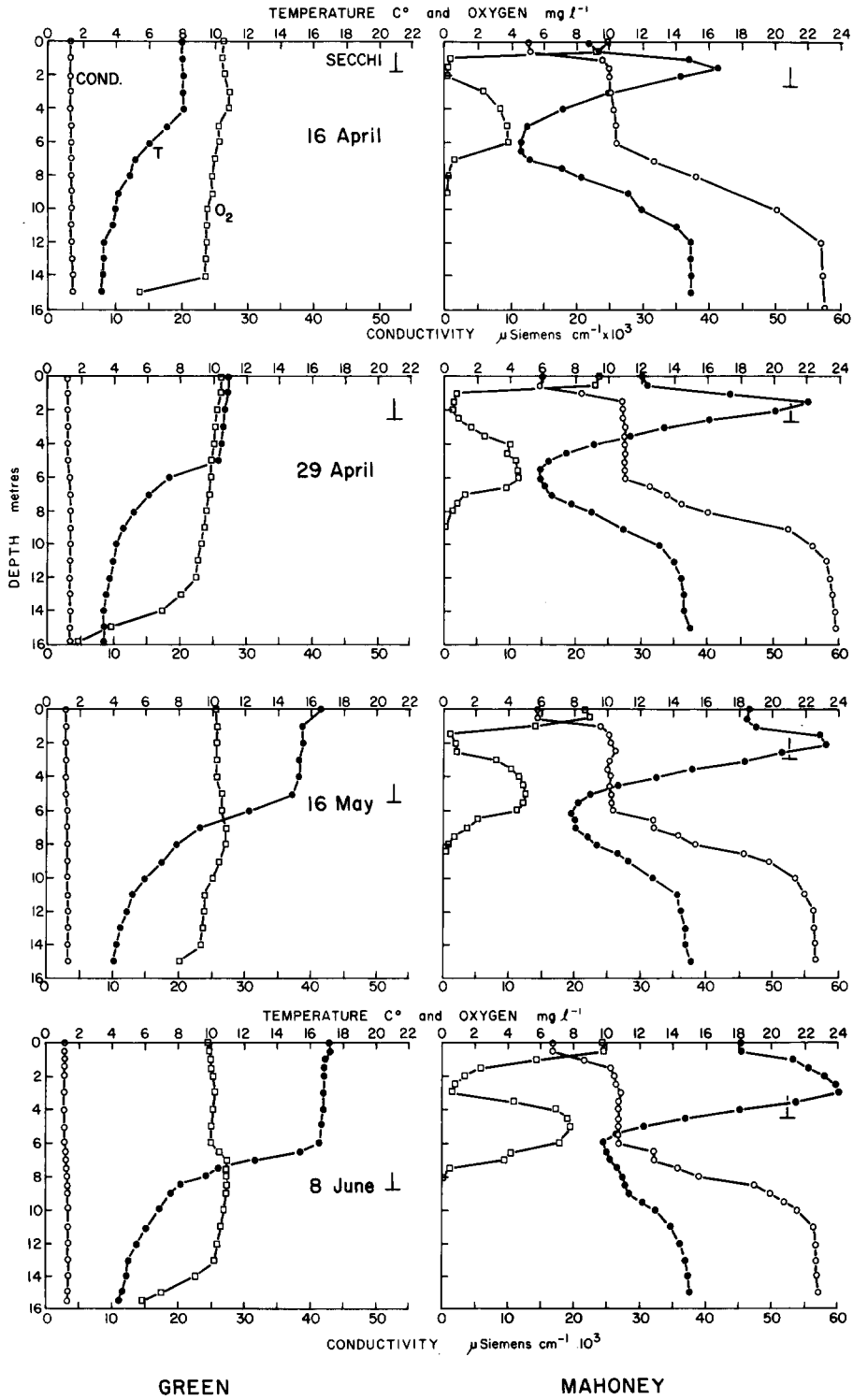


Fig. 2. Temperature, dissolved oxygen and specific conductivity profiles for Green and Mahoney lakes during spring to summer, 1982. Secchi disc transparency also indicated (⊥).

Table 3. Selected water quality parameters for Green and Mahoney lakes, April 28, 1982.

Lake	Depth (m)	pH	Alkalinity ^a		Sulphide (mg l ⁻¹)
			CO ₃ ²⁻	HCO ₃ ⁻	
Green	0	9.20	12	10.5	0
	1.5	9.23	12.1	11.2	0
	5	9.20	9.2	14.8	0
	7	9.20	10.4	15.8	0
	16	9.12	10.4	16.0	2.1
Mahoney	0	8.85	6.4	11.2	0
	1.5	8.99	13.0	18.9	0.7
	5	8.97	14.0	18.2	0.1
	7	8.10	0	49.6	256.0
	9	7.45	0	132.8	384.2
	14	7.35	0	183.6	458.7

^a Alkalinity components expressed as meq l⁻¹.

evident by the conductivity increase below 6 m, reaching a maximum of over 55 000 $\mu\text{S cm}^{-1}$ near the bottom of the monimolimnion at 15 m.

Nutrients and other chemical characteristics

Differences in the vertical distribution of selected chemical characteristics are evident between Green and Mahoney lakes (Table 3). The pH of Green Lake did not show much vertical variation and was always greater than pH 9 while Mahoney Lake showed a maximum pH of 8.99 at 1.5 m and a rapid decrease in the monimolimnion to a low value of 7.35. Total alkalinity (CO₃²⁻ + HCO₃⁻) in Green Lake showed a slight increase with depth with a

gradual increase in the bicarbonate alkalinity component attributable to the slight decrease in pH. In Mahoney Lake, there was almost a ten fold increase in total alkalinity between the surface and bottom waters coincident with an increase in conductivity (Fig. 2). The lower pH in the monimolimnion resulted in a disappearance of the carbonate component of alkalinity. Sulphide was only detected in Green Lake just above the sediment. In Mahoney Lake the sulphide showed a slight increase in the oxygen depleted zone at 1.5 m and a very rapid increase to over 400 mg l⁻¹ in the near-bottom waters of the monimolimnion.

The vertical distribution of nutrients (Table 4) in the two lakes is related to vertical conductivity and oxygen conditions which regulate the form of nitrogen in the two lakes. Inorganic carbon in Green Lake is quite uniform with a slight increase in the lower waters which appears to be at the expense of organic carbon depletion. Both inorganic and organic carbon profiles reflect the salt-stratified conditions in Mahoney Lake with a significant accumulation of carbon in the lower waters. The slight increase in organic carbon at 7 m is coincident with the presence of a plate of purple photosynthetic sulphur bacteria near this depth. Kjeldhal nitrogen (org N + NH₃) shows a slight increase in the bottom waters of Green Lake but very rapidly increases in Mahoney Lake in its lower anoxic zone. As expected nitrate and nitrite levels were highest in the surface waters and reached lowest values in the areas low or depleted in oxygen. Total phosphorus was uniformly low at all depths in Green Lake and the

Table 4. Vertical distribution of nutrients^a in Green and Mahoney lakes, April 28, 1982.

Lake	Depth (m)	Inorganic carbon	Organic carbon	Kjeldhal nitrogen	Nitrate and nitrite-N	Total phosphorus
Green	0	204	36	1.6	0.06	0.017
	1.5	214	23	1.6	0.05	<0.010
	5	204	39	1.7	0.04	0.015
	7	245	<1	1.8	<0.01	0.015
	16	246	4	2.4	<0.01	0.017
Mahoney	0	159	45	2.0	0.06	<0.010
	1.5	266	62	4.0	<0.01	0.010
	5	264	64	4.2	0.03	0.050
	7	490	110	22.6	0.05	0.100
	9	1190	90	99.5	0.02	4.75
	14	1400	100	151.3	-	9.20

^a All values expressed as mg l⁻¹.

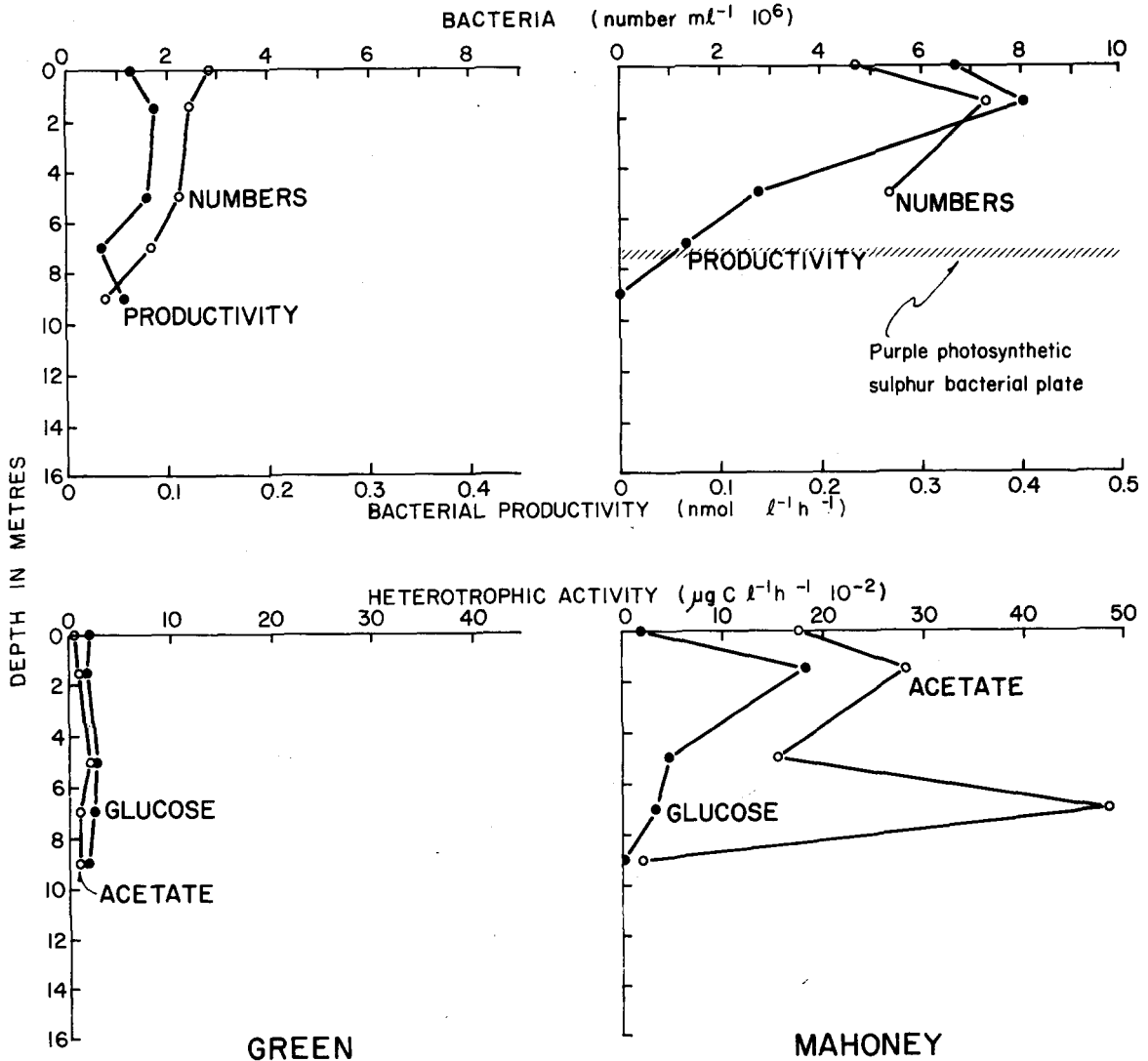


Fig. 3. Bacterial numbers, production (in terms of ^3H -thymidine incorporation), and heterotrophic activity profiles for Green and Mahoney lakes, 28-29 April 1982.

surface waters of Mahoney, but increased by almost three orders of magnitude in its bottom waters.

Biological conditions

Microbial numbers, productivity and heterotrophy

In late April, bacterial numbers were much higher in Mahoney Lake than in Green (Fig. 3). There was a gradual decrease in numbers with an

increase in depth in Green Lake. In Mahoney, a peak in bacterial numbers occurred in the oxygen depleted zone at 1.5 m. Samples collected at 7 and 9 m could not be enumerated as the addition of formaldehyde for preservation resulted in the formation of a finely divided white precipitate, probably sulphur. Nevertheless, in the middle of the bacterial plate, slightly below 7 m at this time, numbers must have been several orders of magnitude higher than at any other depth in the lake. A very dense plate of purple sulphur bacteria (Fig. 4), apparently in large part *Thiocapsa* sp. (Northcote & Halsey



Fig. 4. The purple sulphur bacterial plate of Mahoney Lake entrapped in a 3.75 l van Dorn bottle (68 cm long) taken from about 7 m at Station 1, 4 October 1980.

1969), has been recorded at or near 7 m in Mahoney Lake at various times of the year for over two decades. In terms of bacterial biomass, Green Lake contained 0.102 mgC l^{-1} in the surface water which decreased to 0.026 mgC l^{-1} at 9 m. For comparison, Mahoney Lake contained 0.168 mgC l^{-1} at the surface and increased to 0.261 mgC l^{-1} in the 1.5 m oxygen depleted zone.

Bacterial productivity reflects the bacterial biomass profiles with low levels in Green Lake. However, there is no gradual uniform decrease with depth as numbers showed. Mahoney Lake had a much higher productivity in the mixolimnion,

dropping to values of Green Lake or lower in the monimolimnion. The peak productivity is coincident with numbers in the shallow oxygen depleted chemocline at 1.5 m (Fig. 3). The purple photosynthetic sulphur bacterial plate at about 7 m did not show a very high incorporation of thymidine even though a high biomass was clearly indicated by dense clumps of magenta colored cell material. Bacterial productivity in terms of carbon fixation shows a range between 0.4 to $4.1 \mu\text{gC l}^{-1} \text{ h}^{-1}$ in Green Lake and 0.9 to $18.6 \mu\text{gC l}^{-1} \text{ h}^{-1}$ in the top 5 m of Mahoney, dropping to $3.0 \mu\text{gC l}^{-1} \text{ h}^{-1}$ in the bacterial plate and to a negligible value in the deeper monimolimnion.

The net heterotrophic activity (radioactivity incorporated into cell material without a respiration correction) was much higher in Mahoney Lake than in Green (Fig. 3). There was very little vertical change in the heterotrophic uptake of either glucose or acetate in Green Lake with the uptake of glucose slightly higher than acetate. In contrast, Mahoney Lake showed a large vertical change with the glucose uptake profile similar to that for bacterial productivity and numbers. The acetate uptake in Mahoney was much larger than glucose uptake and showed areas of maximum activity in the two chemoclines. The highest uptake rate for acetate at 7.0 m was coincident with the plate of purple photosynthetic sulphur bacteria.

Phytoplankton

Marked differences were evident in the phytoplankton communities present in the two lakes in late April (Table 5, Fig. 5). In Green Lake the community was much more diverse with Chlorophyta, Cyanophyta, Cryptophyta and Chrysophyta all represented at most depths sampled by one or more common species, and the latter group by at least 10 species of diatoms (Table 5). In Mahoney Lake no Chlorophyta were found and two species of Cyanophyta dominated the community at least in the upper 5 m with virtually no phytoplankton occurring at depths of 7 m or deeper (Fig. 5). Although total cell numbers were much higher in surface samples from both lakes on 8 June (averages 638 and 3779 ml^{-1} in Green and Mahoney respectively), cyanophytes still composed over 99% of the population present in Mahoney whereas in Green Lake chlorophytes, chrysophytes and crypto-

Table 5. Relative abundance^a by depth of major phytoplankters in Green and Mahoney Lake samples, 28 April 1982.

Group	Genus/species	Green					Mahoney				
		Sample depth (m)					Sample depth (m)				
		0	1.5	5	7	9	0	1.5	5	7	9
Chlorophyta	<i>Chlamydomonas</i> sp.			x							
	<i>Oocystis</i> sp.	C	C	C	C	x					
Cyanophyta	<i>Chroococcus</i> sp.					C	A	A	A		
	<i>Gloeocapsa</i> sp.						C	C			
	<i>Spirulina</i> sp.	C	A	A	A	A					
Chrysophyta	<i>Achnanthes minutissima</i>	x	x	x	x		x				
	<i>Amphiprora alata</i>	x	x	x	x	x					
	<i>Amphora coffeaeformis</i>						x				
	<i>Campylodiscus</i> sp.						x	x	x		
	<i>Cymbella caespitosa</i>	x		x	x						
	<i>Cymbella</i> sp.			x							
	<i>Denticula elegans</i>			x				C		_b	
	<i>Diatoma hiemale</i>		x								
	<i>Frustulia rhomboides</i>	x	x	x	x						
	<i>Gomphonema olivaceum</i>						x				
	<i>Hannaea arcus</i>						x				
	<i>Navicula</i> sp.	x	x	x			C				
	<i>Nitzschia acicularis</i>	x		x							
<i>Nitzschia palea</i>	x	x	C	C	x				_b		
<i>Tabellaria fenestrata</i>									_b		
Cryptophyta	<i>Chroomonas acuta</i>	C	C	C	C		x				

^a x = present (<10 cells ml⁻¹); C = common (10–100 cells ml⁻¹); A = Abundant (>100 cells ml⁻¹).

^b A few cells found, presumably dead.

phytes also were represented in moderate numbers.

Light penetration was far greater in Green than Mahoney Lake so that the depth of 1% surface intensity was well below 12 m in the former lake but only just below 7 m in the latter lake, no doubt a result of shading by the dense bacterial plate. Correspondingly phytoplankton production in Green Lake did not decrease sharply with depth whereas that in Mahoney Lake fell to zero at 9 m (Fig. 5). Overall, phytoplankton production in Green Lake was at least an order of magnitude higher than in Mahoney Lake. Neither the abundance, biomass nor production of phytoplankton in Mahoney Lake appeared to be affected greatly by the severely anoxic conditions present in the uppermost (ca 1.5 m) stagnation zone.

Zooplankton

A single species of rotifer and calanoid copepod dominated the early spring zooplankton community in each lake although late instar larvae of *Chao-*

borus americanus were found at depths of 5 m and lower in Green Lake (Fig. 6) along with a few *Daphnia schødleri*. *Keratella* reached a maximum abundance of over 200 individuals l⁻¹ at 7 m in Green Lake and the predatory rotifer *Asplanchna* occurred in much lower numbers in Mahoney Lake in surface waters as well as at depths of 3 and 6–7 m. Copepod nauplii, copepodites and adults of *Diaptomus tyrrelli* occurred in moderate abundance in Green Lake to depths of 5 m. In Mahoney Lake the surface waters contained many copepod nauplii as well as some copepodites and adult *Diaptomus connexus*. Virtually no copepods were found in the deoxygenated waters at 1.5 m but the population reappeared at 3 m with adults reaching maximal numbers (7 140 l⁻¹) there and intermediate numbers at 5 and 6.5 m before dropping sharply to very low levels at 7.5 m. In contrast to its phytoplankton population, zooplankton in Mahoney Lake were greatly reduced by the upper zone of low oxygen water between 1 and 3 m. No major change was evident in the zooplankton communities of the two

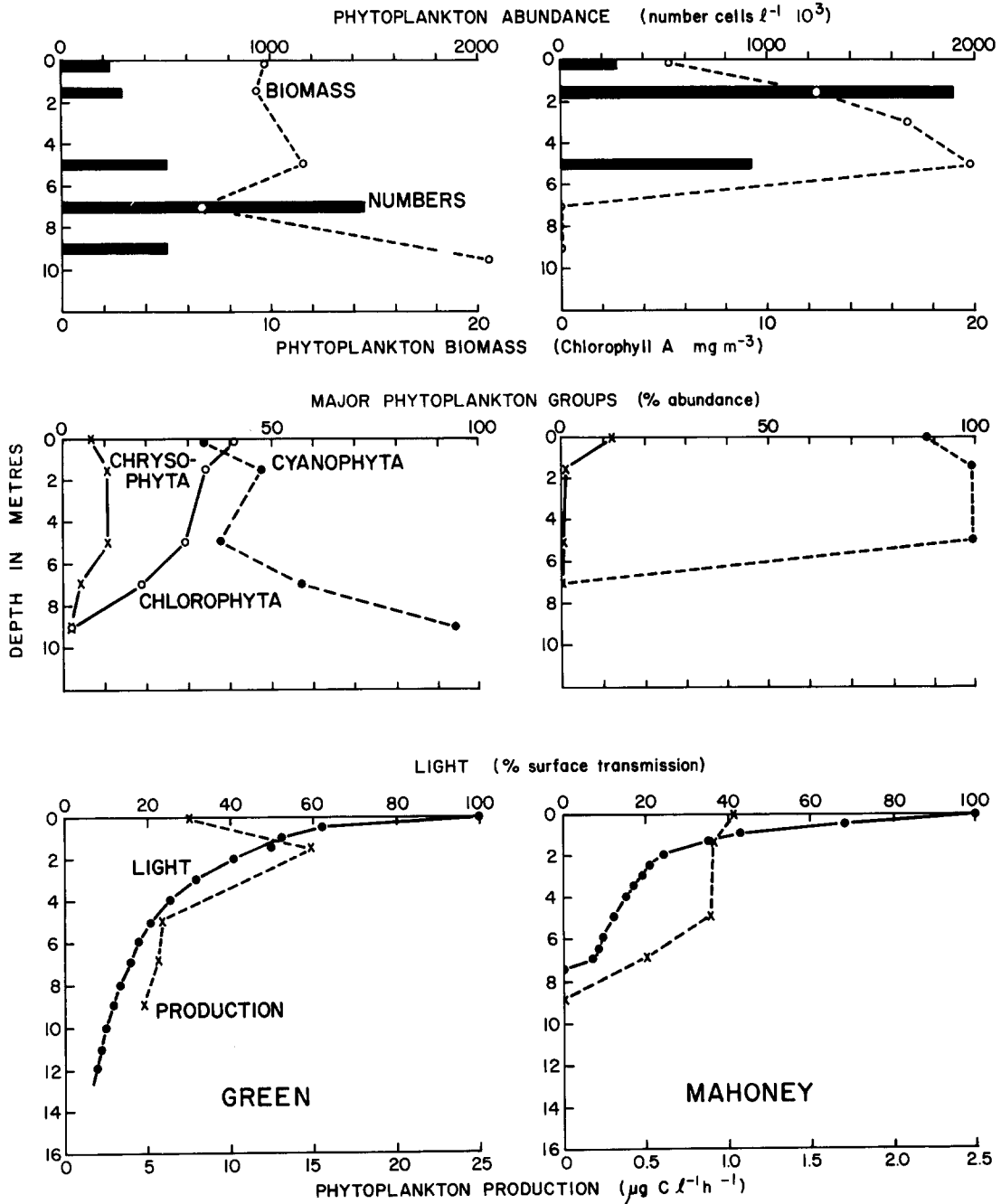


Fig. 5. Phytoplankton abundance, biomass, and production profiles along with mid-day light transmission for Green and Mahoney lakes on 28 April 1982.

lakes when sampled in early June although a few *Ceriodaphnia* were present then at least in the near-surface waters of Mahoney Lake and early instars

of *Chaoborus* larvae also were found in Green Lake.

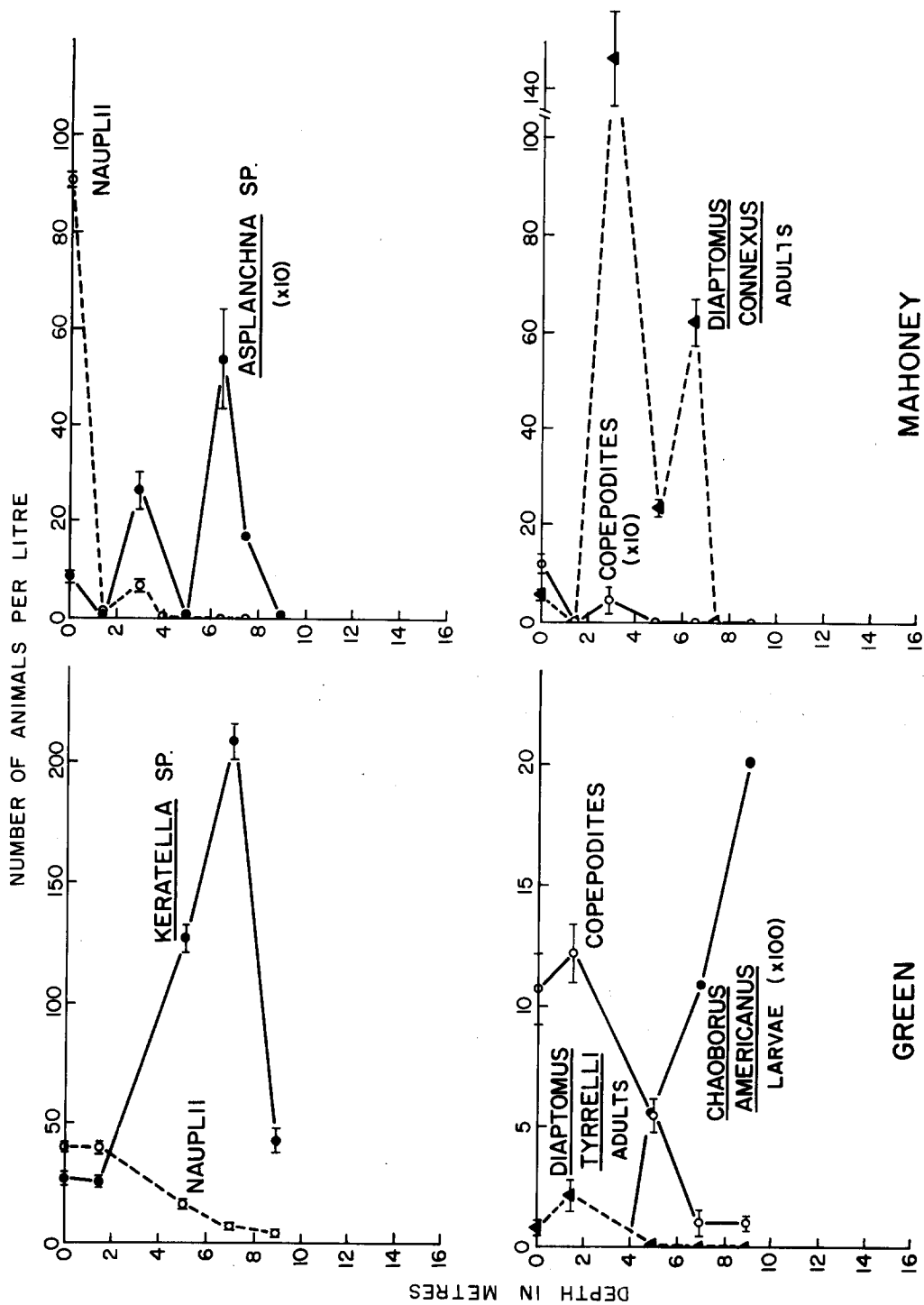


Fig. 6. Zooplankton abundance and distribution in Green and Mahoney lakes on 28 April 1982. Horizontal lines on data points (averages) give 1 S.E.; where absent points represent total counts.

Discussion

For the purposes of this presentation, there are two striking contrasts between Green and Mahoney lakes as well as the anomalous pattern of vertical stratification (physical, chemical and biological) in Mahoney Lake which need explanation. Firstly, why should these two lakes both lying astride the same geological systems have such markedly different total ionic composition? Secondly, why should two lakes of such similar morphometry react so differently with respect to circulation, one being dimictic and the other strongly meromictic? Finally, how can the severe microstratification of the upper few metres of Mahoney Lake be established *and* maintained and what are its biological consequences?

Surface waters of Mahoney Lake shortly after ice-out are over 4 times the conductivity of Green and by mid-June, almost 6 times higher. The differential in bottom water conductivity between the lakes is very much greater – Mahoney being 17 to 18 times that of Green. These differences in total electrolyte content are of course borne out in specific ionic contents of the lakes.

The accumulation of inorganic carbon (bicarbonate) and high sulphide in the lower waters during this investigation, as well as a comparison of the major cations (K^+ , Na^+ , Ca^{++} and Mg^{++}) and other anions (SO_4^{2-}) in the mixolimnion and monimolimnion (Northcote & Halsey 1969) support the vertical salt stratification evident in Mahoney. The small variation in vertical distribution of alkalinity and the presence of low levels of sulphide only in the bottom waters of Green support the well mixed dimictic character of this lake. The high levels of organic carbon, Kjeldhal nitrogen and total phosphorus in the bottom waters of Mahoney provide further evidence of the stability of the monimolimnion and its sink-like nature.

The high alkalinity and a pH above 8.5 favour the formation of carbonate and precipitation of calcite ($CaCO_3$) in the water column of Green Lake and the surface waters of Mahoney. The green to turquoise colour of Green Lake is most likely attributed to the suspended calcite and is reminiscent of the colour of some alpine lakes which receive fine suspended sediments from glacial meltwater. The re-solution of

some calcite in the monimolimnion of Mahoney could be caused by the lower pH and is evident from the higher calcium and bicarbonate levels (Northcote & Halsey 1969). This precipitation most likely causes the low levels of phosphorus observed through adsorption or coprecipitation processes with the calcite which has been observed in another lake in the area (Murphy *et al.*, in press) and could explain the high phosphorus levels in the lower waters of Mahoney.

A probable explanation for the differences in conductivity between the two lakes can be obtained by detailed comparison of the geological formations underlying their watersheds (Fig. 1, Table 1), particularly the Tertiary Eocene formations on the western portions of their drainage basins. Almost all of this side of the Green Lake watershed lies in the Skaha formation composed of harder rocks with relatively low alkali composition. On the other hand most of this part of the Mahoney Lake watershed lies in the softer highly fractured lavas of the Marron formation characterized by a higher alkali composition. Presumably these local differences in geology of the lake watersheds have played a major role in determining their disparate salinities. These conclusions are further supported by the salinity of the small lake which lies directly east of Mahoney (Fig. 1) but completely within the Skaha formation. Its surface water had a conductivity of $1\ 050\ \mu S\ cm^{-1}$ ($25\ ^\circ C$) on 16 May 1982, which was even lower than that of Green Lake.

But having a high salt content does not confer meromixis on a lake. Indeed it still is puzzling why these two adjacent lakes of such similar general morphometry (Fig. 1, Table 2) should be so different in circulation characteristics even though one is more saline than the other. However, there are some topographic differences between the watersheds of the lakes which we believe have been instrumental in establishing and maintaining their contrasting circulatory patterns. Mahoney Lake is almost ringed by a series of hills and is faced at its northern end by steep cliffs set at right angles to its major north-south axis (Fig. 1) and also to that of the prevailing wind direction in the Okanagan Valley. In contrast, there are few hills of any consequence in the Green Lake watershed, except for the gentle slopes on its eastern flank and the steep cliffs on its western side, both of which are more or less

parallel to its major axis and to main valley wind flow. Consequently Green Lake should receive much more frequent and effective wind action than Mahoney Lake. In our experience over several years this certainly seems to be the case although unfortunately we have yet to quantify these observations. Local aircraft pilots also have told us that Green is a much more 'windy' lake than Mahoney. Once again we see the important effect of local topography in limnological processes, in this case apparently producing an example of 'morphometric meromixis' (Northcote & Halsey 1969; Northcote 1980) arising from morphometry of the drainage basin rather than that of the lake basin itself. As pointed out by Walker & Likens (1975) local catchment topography may be an important factor in meromixis but one for which unfortunately we still seem to lack quantitative means of assessment. Obviously in the case of Mahoney Lake not only are the presence of local hills and cliffs important but also their orientation in relation to the effective length of the lakes and to that of the prevailing wind direction must be considered.

That saline and meromictic lakes may exhibit very sharp vertical stratification of temperature, conductivity or other features of course is well known (Anderson 1958a; Walker 1974; Hammer *et al.* 1978) and extreme examples have been reported for small, highly saline waters such as Hot Lake (Anderson 1958b) and Lyons Lake (Northcote & Halsey 1969). What makes the Mahoney Lake example of particular interest in our opinion is that the 'normal' seasonal pattern of mixing which usually occurs in the mixolimnion does not seem to take place but instead a secondary near-surface chemocline (along with associated extreme changes in temperature and oxygen) is superimposed on the system for at least a several month period after ice cover leaves. Presumably the low salinity surface layer of less than 1 m depth is formed by ice and snow meltwater producing a lower density layer in early spring. Such a phenomenon has been clearly described for Waldsea Lake (Hammer *et al.* 1978) although in this case no unusually sharp thermal maximum was associated with the secondary chemocline nor was severe oxygen depletion mentioned in that region. In Mahoney, the density differential produced by the near-surface chemocline is weakened somewhat by the marked temperature increase which develops shortly after ice melt, but

nevertheless the high stability layer between 0.5 and 1.5 m is very resistant to wind mixing. This shallow but significant layer must strongly inhibit wind-driven vertical mixing as is evidenced by the severe oxygen depletion occurring at its lower boundary as well as the marked build up in temperature from direct solar heating (Fig. 2). Later in the summer the salinity and temperature differential between this layer and the underlying 'mixolimnion' probably decreases as suggested in Figure 2 so that density differences eventually become too small to prevent complete mixolimnial circulation. Then the normal associated processes (re-oxygenation, etc.) should prevail. In the interim however a most unusual four layered system is established – a very shallow (<1 m) true mixolimnion, bounded on its lower surface by a sharp secondary chemocline, an almost anoxic layer nearly 1 m deep, another partially oxygenated layer of intermediate salinity bounded on its lower surface by the primary year-round chemocline, and finally the deep, permanently anoxic monimolimnion with maximum salinity. The biological ramifications of this complex, if perhaps in part temporary system, would seem to be far from inconsequential although we have not yet explored many of the fascinating possibilities.

The bacterial and phytoplankton biomass and productivity information suggest that Green Lake is dominated by phytoplankton carbon fixation while Mahoney is mainly dominated by a bacterial-detritus based system at least during late April. Green Lake showed phytoplankton productivity of 5–15 $\mu\text{gC l}^{-1} \text{h}^{-1}$ compared to bacterial productivity of 0.4–4.1 $\mu\text{gC l}^{-1} \text{h}^{-1}$ while in contrast Mahoney Lake had a phytoplankton productivity of 0–1 $\mu\text{gC l}^{-1} \text{h}^{-1}$ and bacterial productivity in the range of 0.9–18.6 $\mu\text{gC l}^{-1} \text{h}^{-1}$. The bacterial productivity found in Sannich Inlet B.C. (Fuhram & Azam 1980) was similar to the range of values found in Green Lake but considerably lower than productivity estimates made for Mahoney. There is a possibility that phytoplankton could take up thymidine which would result in an over-estimation of bacterial productivity. This error is probably very small. Fuhram & Azam (1980) could find no differences in light or dark uptake of thymidine; at nanomolar thymidine concentrations size fractionation studies demonstrated that more than 90 percent of the thymidine was incorporated into <1.0 μm particles; and growth rate studies comparing bacterial

abundance through direct counts and thymidine uptake were well correlated.

Photosynthetic carbon fixation by the purple sulphur bacteria in late April appeared to be low in Mahoney Lake. Possibly the BOD bottles actually were suspended at a lower level in or slightly below the bacterial plate where light limitation could occur (Fig. 5). Other research (Kuznetsov 1958; van Niel 1963; Sorokin 1966; Takahashi & Ichimura 1968) provides excellent information on the importance of bacterial photosynthetic processes in systems where the oxidation and reduction processes in the sulphur cycle are important. This photosynthetic bacterial plate obviously needs more investigation in Mahoney Lake.

The much higher heterotrophic uptake of acetate and glucose further supports the importance of bacterial processes in Mahoney and illustrates the significance of boundary areas, such as the two chemoclines, as a focus for high microbial activity. These areas represent potential traps where detritus can be mineralized and in the case of the 'temporary' chemocline at 1.5 m provide for further utilization of mineralized nutrients in the photic zone when this structure breaks down.

With the exception of acetate uptake at 5 m, the heterotrophic uptake rate in terms of carbon cell⁻¹ h⁻¹, or bacterial specific activity (Wright 1978) showed a gradual increase with depth in Green Lake for both glucose and acetate. This indicates that the bacteria in the deeper water were more efficient in scavenging organic solutes from the water or there was a greater respiratory requirement in the warmer surface waters. Respiration of the labelled solutes was not measured in this investigation. In the top 5 m of Mahoney, the bacterial specific activity was highest in the secondary chemocline at 1.5 m. The specific uptake rate for acetate was between 3–25 times higher for acetate in Mahoney Lake than in Green. This higher preference for acetate probably reflects the more favorable environment for facultative and anaerobic microorganisms in Mahoney since acetate is one of the common intermediates of anaerobic fermentation processes (McCarty 1964).

Phytoplankton abundance, biomass or production did not seem to be inhibited by the nearly anoxic upper stagnation layer although the community was composed almost entirely of blue-greens. If respiratory processes are not reduced by

low oxygen then with the concurrence of the high light and temperature conditions these algae may be able to attain high population levels there, if not high production rates, as is suggested in Figure 4. The phytoplankton population living at depths between 3 and 7 m must be photosynthetically active although cut off from any possibility of circulation into over or underlying waters. Production rates observed there are not much lower than at the surface (Fig. 5) and the total amount of oxygen present in this layer increased considerably from mid April to early June (Fig. 2), probably as a result of photosynthetic addition.

Zooplankton abundance was greatly reduced in the upper anoxic layer with only a few rotifers, copepod nauplii and adults (averages of 15, 37 and 9 per 100 l respectively) occurring in the samples from 1.5 m. Some of these individuals may make temporary excursions in and out of this layer while others perhaps migrate vertically through it. Nevertheless there would seem to be two distinct concentration zones of zooplankton, one in the uppermost metre and another between about 2 and 7 m, that are at least in part segregated by a region of very distinctive water quality condition. It will be of interest to determine whether or not the two zones are indeed separate and to what extent their different environmental conditions affect key population parameters.

These two adjacent and superficially similar saline lakes demonstrate once more how subtle differences in drainage basin characteristics (localized geology and topography) may profoundly influence major limnological processes and give further support to the view that lakes in many ways are products of their watersheds.

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