Physical and Chemical Limnology of Two Mountain Lakes in Banff National Park, Alberta[1,2]

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Limnological investigations of an alpine and a lower subalpine lake in Banff National Park from 1966 to 1968 showed that vernal circulation may not extend to the bottom in either lake and that complete autumn circulation may persist for several weeks in both lakes. Winter heat incomes were similar in the lakes, but the summer heat income was much lower for the alpine lake due to heat lost through water renewal. Thermal stratification was more clearly defined in the subalpine lake each year than in the alpine lake. When well-defined chemical stratification occurred, it was short-lived in both lakes. With the exception of phosphate, which was highest in spring and early summer, most changes in chemical composition appeared related to dilution. Very low oxygen concentrations occurred in the bottom water strata of the subalpine lake, but depletion was never severe in the alpine lake. Of the incident visible light 16% penetrated ice and snow cover (1 m) on the alpine lake, but less light reached the water of the lower subalpine lake because of cloudy ice and deeper snow. The trophogenic zone extended to the bottoms of both lakes (about 13 m) for at least part of each year.

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INTRODUCTION

Although many detailed physical and chemical limnological investigations have been conducted in alpine lakes of other countries (e.g., Löffler, 1968; Pechlaner, 1966; Pennak, 1955, 1968; and others), there have been few studies of alpine and subalpine lakes in western Canada, especially in winter. Rawson (1942, 1953) surveyed some large mountain lakes in western Canada, and some unpublished studies of other lakes have been made.

Preliminary to ecological studies on some lakes in Banff National Park, investigations of water temperatures, snow and ice cover, light penetration, and several aspects of chemical limnology in Herbert and Snowflake lakes were conducted in 1966, 1967, and 1968. Herbert Lake was included in a survey study by Rawson (MS, 1939) and in a study of primary production in some mountain lakes by Fabris (MS, 1966), but no previous investigations had been carried out at Snowflake Lake.

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[2]Some of the Snowflake Lake data was taken from a thesis submitted by the author in partial fulfillment of the requirements for the degree of Doctor of Philosophy from the University of Calgary, Calgary, Alta.

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Snowflake Lake is 50 km north and Herbert Lake is 60 km northwest of the town of Banff, Alberta (inset, Fig. 1). Other lake data are summarized in Table 1.

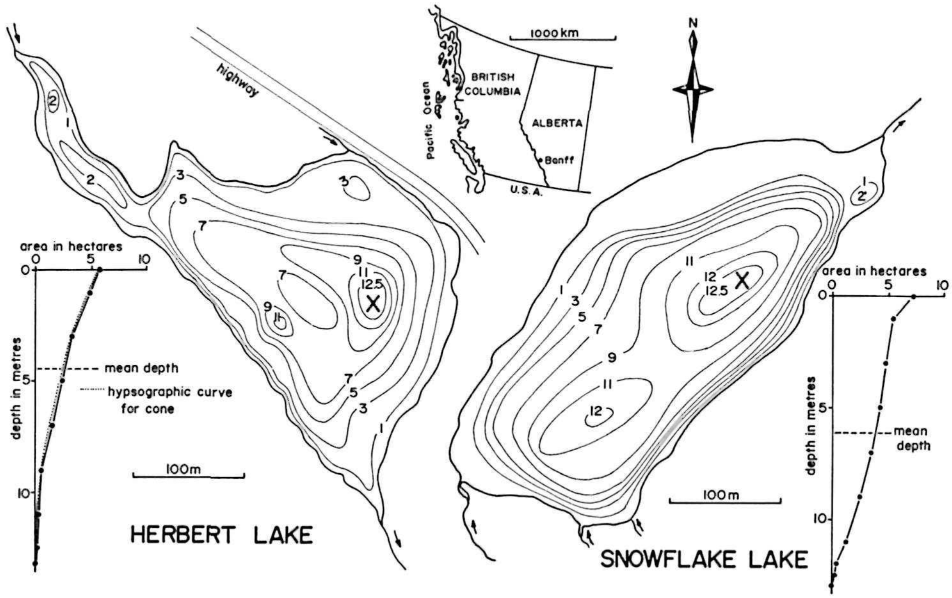

FIG. 1. Bathymetric maps and hypsographic curves for Snowflake and Herbert lakes, Banff National Park. All depths are in meters. The main sampling location at each lake is marked "X."

TABLE 1. Locations, elevations, and morphometric data for Snowflake and Herbert lakes.

	Snowflake Lake	Herbert Lake
Location	51°36′N; 115°50′W	21°28′N; 116°13′W
Grid reference	11U/809167/NH	11U/542010/NH
Elevation (*m*)	2320	1615
Surface area (*ha*)	7.1	5.7
Max depth (*m*)	13.0	13.3
Mean depth (*m*)	6.1	4.5
Approx volume ($\times 10^4 m^3$)	43.6	25.4

Situated in a cirque valley and bordered by a meadow, Snowflake Lake is near treeline in the "alpine zone" (Pechlaner, 1966). There is no higher emergent or benthic vegetation in the lake. Herbert Lake is in the lower "subalpine zone" (Rowe, 1959) and is bordered on three sides by stands of white spruce (*Picea glauca*) and lodgepole pine (*Pinus contorta*). There is a narrow band of emergent vegetation (*Carex* sp.) along part of the shoreline. Scattered clumps of *Chara* sp. and *Potamogeton* sp. occur in the shallow water (Fabris, MS, 1966). Most of the shallow areas of the lake are devoid of higher plant forms.

Although occasional air temperatures of 26 or 27 C were reached in July or August in the vicinity of Snowflake Lake from 1966 to 1968, mean daily air temperatures for the June to September period were in the 5–10 C range. Daily means for the winter period were usually in the –12 to –4 C range with records as low as –38 C in the January–March period (Baptie, MS, 1968). Although records for the cirque area are few and incomplete, it is estimated that the annual precipitation, expressed as the equivalent of rain, ranges between 50 and 70 cm, most of which falls as snow. The alpine zone in this region is subject to winds of up to 80 km hr^{-1} or more, most frequently in autumn and winter.

The forest shelters Herbert Lake from winds, which are usually lower in velocity in the lower subalpine than in the alpine zone. Thirty-five years of weather records for Lake Louise Junction near Herbert Lake indicate that air temperatures fluctuate greatly throughout the year and from year to year (unpublished Department of Transport records). Since 1935, the high and low air temperatures for the November to April period were 23.3 and –52.8 C and the high and low for the May to October period were 34.4 and –27.8 C. The mean daily winter air temperatures are usually in the –8 to +4 C range and the mean daily summer air temperatures are usually in the 10–20 C range. Temperatures well above freezing occur frequently during the winter. Expressed as the equivalent of rain, the total annual precipitation in the Herbert Lake vicinity is usually between 60 and 70 cm, about 60% of which falls as snow.

METHODS

Most samples and measurements were taken at one station at the deepest part of each lake (Fig. 1). Water samples were taken with a Van Dorn-style PVC sampler and stored in polyethylene bottles that were acid-washed and triple-rinsed in demineralized water. Field analyses of alkalinity, hardness, *p*H, and specific conductance were performed within half an hour of sampling whenever possible. Specific conductance was measured with a Dionic Series 3 Conductivity-Meter; *p*H was determined with an E.I.L. Model 308 *p*H Meter; total alkalinity and hardness were determined in the field with chemicals from the Hach Chemical Co., Ames, Iowa. Laboratory water analyses were performed by the Inland Waters Branch, Department of Energy, Mines and Resources of Canada according to standard methods (American Public Health Association, 1965). Dissolved oxygen was measured with a Lakes Instrument Co. Mark II oxygen sensor. Samples of bottom sediments, taken from the deepest parts of both lakes during the winter of 1967, were dried at 100 C for 24 hr and then ashed at 650 C for 2 hr. No corrections were made for the transformation of carbonates and bicarbonates into oxides.

Soundings were made with a Lowrance "Fish-Lo-k-tor" transistorized echo sounder that was checked against a leaded line. Lake volumes were calculated according to the method suggested by Welch (1948). The outlet stream flow from Snowflake Lake was estimated in 1967 on a sandy bottom stretch of uniform dimensions using a floating chip.

Temperatures were determined with a Yellow Springs Instrument Co. Model 425C thermistor thermometer calibrated against a mercury thermometer at each use. The heat incomes for both lakes were calculated according to Hutchinson (1957) and incorporated a 0.9 expansion factor for ice (Pechlaner, 1966). Heat required to melt snow was included for Herbert Lake, but not for Snowflake Lake because little snow remained on the ice at the time of the spring thaw. Nine cm of snow was taken to be equivalent to 1 cm of ice.

No sunshine recorder was available at the time of these investigations. Estimates of hours of daylight for the two lakes were based on field observations and on extrapolations from sunrise–

sunset tables from the Calgary International Airport. Incident light at the lakes was measured with a Sekonic photometer.

Light penetration into the water was measured with a modified underwater photometer and GKA 48-BO1 galvanometer supplied by The International Agency for ^{14}C Determination. The photometer was fitted with a selenium cell that is sensitive only to the short-wave radiation between 350 and 700 mμ (visible light). Filters used with the underwater photometer had the following specifications:

	Schott BG-7	Chance-Pilkington OGr-1	Schott RG-2
Max transmission (mμ)	475	530	660
Range (mμ)	300–600	450–600	590–835

Underwater readings were corrected in the manner outlined by Westlake (1965). In winter, a 15-cm hole was bored in the ice and efforts were made to minimize snow cover disturbance. Before light readings were taken, the ice-hole around the cable was packed with snow, a piece of opaque rubberized fabric was placed around the cable, and snow cover was restored as closely as possible to its undisturbed condition.

PHYSICAL CHARACTERISTICS

Morphometry, Water Renewal, Bottom Sediments

In general the basin of Snowflake Lake is shaped like a flanged bowl whereas that of Herbert Lake approximates an inverted cone (hypsographic curves, Fig. 1). The drainage basin for Snowflake Lake is only 150 ha, which is approximately 21 times the lake area and only about half the comparable figures (mean = 40.5 times) given for 32 Italian alpine and subalpine lakes by Ravera and Tonolli (1956).

The estimated annual water renewal (7.7 times, 1967), most of which occurs between mid-June and mid-August, was similar to the rates determined for the Austrian Finstertaler Seen (large = 2.8 times; small = 11.2 times) by Pechlaner (1966). Snowflake Lake has a volume similar to that of the smaller Austrian lake. Drainage basin area and water renewal rates for Herbert Lake were not determined, but the water renewal rate for this lake is probably in the order of once a year.

The bottom material in Snowflake Lake is mostly fine gravel on the steeper slopes, but the sediment in the deepest areas consists of black mud rather low in organic content. The upper strata of the deepwater sediments in Herbert Lake are medium to dark brown, flocculent, and higher in organic content. The average weight loss for the Snowflake samples was 20.1% of the dry weight; for Herbert samples, 65.4%.

Ice and Snow Cover

Snowflake Lake was usually frozen from about October 10 until late June or early July and Herbert Lake from about the end of October until mid-May (Fig. 2). Snowflake Lake remained blown free of most snow during much of each winter, but snow cover on Herbert persisted throughout the winter. Consequently, the ice layer tended to be somewhat thicker on Snowflake Lake. When ice holes were cut at Snowflake, the water level always

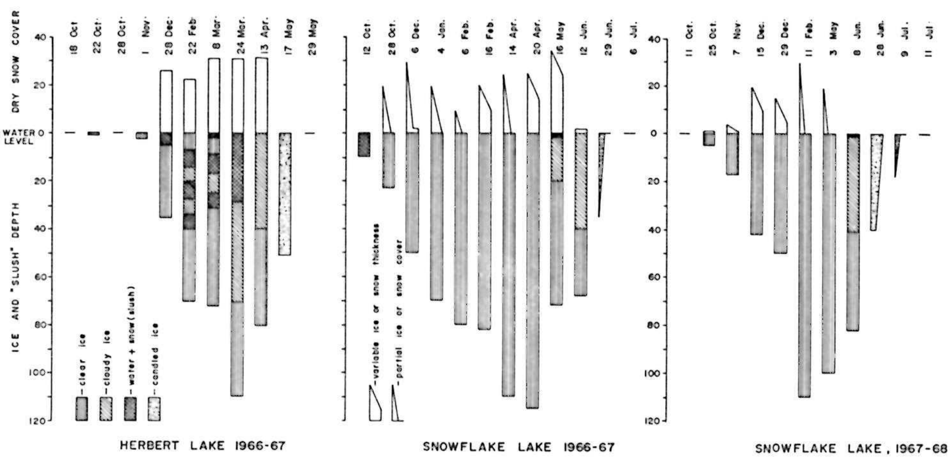

FIG. 2. Ice and snow cover on Herbert and Snowflake lakes. Depths are in centimeters.

remained a few centimeters below the upper ice surface, except in a small area on one side of the lake where deep snow accumulated.

In Herbert Lake, the weight of snow often pushed the ice downward and caused water to well up through cracks into the snow, where the upper layer froze if temperatures were sufficiently low. This resulted in the formation of alternate layers of ice and slush and hence a solid layer of cloudy ice during spells of very cold weather, in sharp contrast to the predominantly clear ice of Snowflake Lake. Because total ice thickness tended to remain constant on Herbert Lake from January to April, the lower surface of the ice layer must have melted off continuously. The lower half of the ice layer was usually fairly clear and rather soft, which suggests that the crystal structure of the ice changed as the temperature increased.

TEMPERATURE

In Snowflake Lake, a thermocline developed in 1967, but was poorly defined in 1966 and 1968 (Fig. 3). The 1967 thermocline was not greatly different from that in Vorderer Finstertaler See in 1961 (Pechlaner, 1966). Under the ice, lower water temperatures occurred in Snowflake Lake at all depths than were found in the Austrian lake, where the water temperature was virtually isothermal at 4 C. The isopleths for Snowflake Lake indicate a rather short period of true isothermy at ice breakup, the slow development of thermal stratification, and a long period of autumn isothermy. Wind velocities during autumn were influential in lengthening the autumn overturn and in producing the low water temperatures that persisted throughout the winter. The lower summer water temperatures in 1966 and 1968 were undoubtedly due to higher water renewal rates, heavier rainfall, and more overcast skies in those years than in 1967.

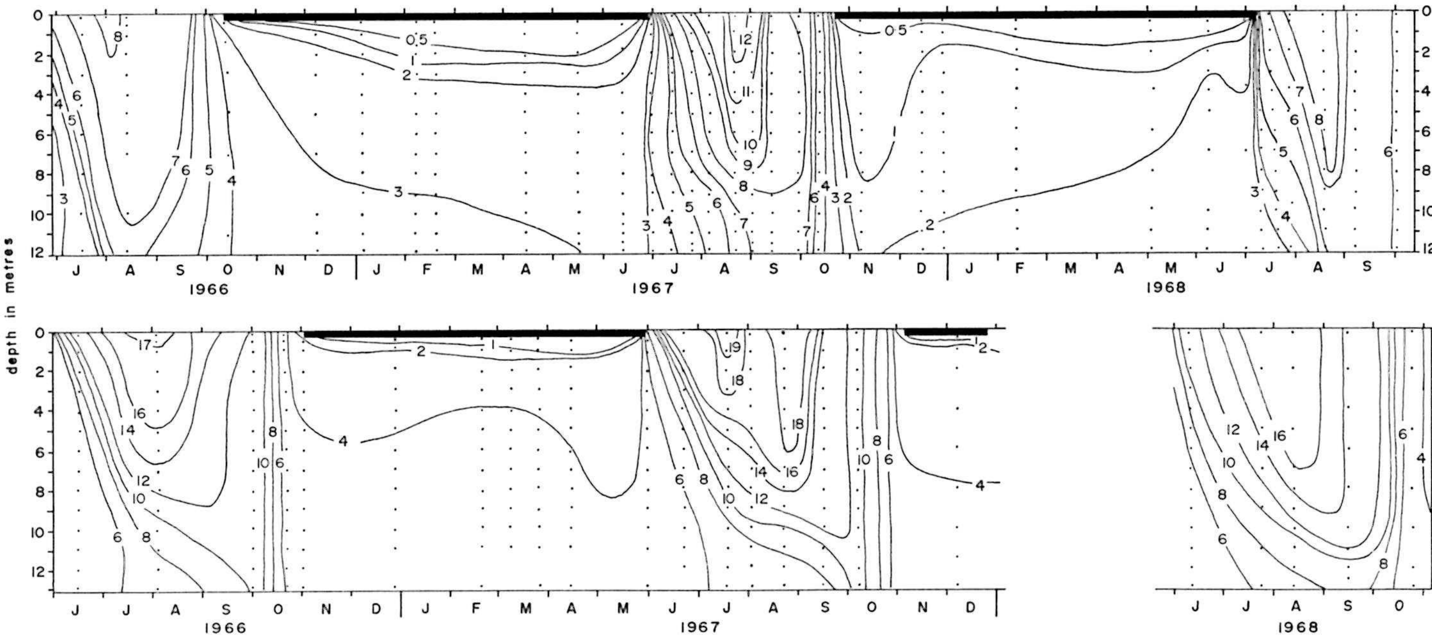

FIG. 3. Temperature (Celsius) isopleths for Snowflake Lake (*upper*) and Herbert Lake (*lower*) during 1966–68.

The higher surface temperatures and marked thermocline in Herbert Lake in 1967 were reflections of the warmer summer that year. Spring isothermy was short-lived, but autumn isothermy persisted about as long as in Snowflake Lake. Temperatures under the ice were higher than those in Snowflake Lake, where autumn winds were colder, more frequent, and higher in velocity. When Herbert Lake was frozen over, slightly higher temperatures at mid-depth than at bottom (usually 0.1–0.2 degrees C higher) suggested the presence of warm springs or limited heating from the bottom sediments between the 5 and 7 m depths.

The cold, wet summer of 1966 partly accounted for a lower summer heat income that year for Snowflake Lake (Table 2). Differences in lake inlet and outlet temperatures during the open-water season in 1967 indicated that a heat loss of up to 9000 cal cm^{-2} occurred through water renewal. The greatest actual heat loss from this source occurred during July, but the greatest difference between inlet and outlet temperatures occurred in September, a feature probably common to most north temperate zone lakes (see Rodgers and Anderson, 1961). Although water renewal rates and inlet–outlet temperatures are not available for Herbert Lake, the summer heat loss due to water renewal would be small compared with Snowflake Lake, where loss due to water renewal could amount to from two to four times the calculated summer heat income.

TABLE 2. Heat budgets for Snowflake Lake, 1966, 1967, and for Herbert Lake, 1967, 1968 (cal cm^{-2}).

	Winter heat income	Summer heat income	Annual heat budget
Snowflake Lake 1966	8,145	2,215	10,360
1967	8,135	4,345	12,480
Herbert Lake 1967			
Not including snow cover	7,577	6,004	13,581
Including snow cover	12,167	–	18,171
Herbert Lake 1968			
Not including snow cover	7,583	5,367	12,950
Including snow cover	10,263	–	15,630

If the heat required to melt the accumulated snow on the lake is included, then the winter heat income for Herbert Lake was much higher than that for Snowflake Lake. This may be due in part to higher air temperature at Herbert Lake and to warm inlet water or heating from the bottom. The higher winter heat income for Herbert Lake in 1967 than in 1968 was required to melt the nearly twice normal snowfall that winter. Incomplete data showed apparently direct relationships between total winter snowfall and ice breakup dates.

LIGHT

For both lakes, the sunrise-to-sunset period was estimated to range from about 6½ hr in December to 15½ hr in June. For Snowflake Lake, the screening effect of the mountains was less in summer than in winter because of the position of the mountains and the elevation angle of the sun. The percentage reduction of sunshine was calculated to be between 8 and 26%, about half the screening effect noted for the Austrian Finstertaler Seen (Pechlaner, 1966).

Midday surface light intensities for Snowflake Lake were usually between 64,000 and 87,000 lux on clear days. A maximum reading of 103,300 lux occurred in the forenoon of June 29, 1967, when the mountains were snow-covered and the sun was near the summer solstice. The next highest intensity was recorded April 20, 1967, a day of almost continuous hazy overcast, which indicates the diffusing effect of light cloud or haze. Similar light intensities were recorded for Herbert Lake at about the same time. A low sun angle together with partial white cloud cover can increase the total radiation on the earth's surface by 40% (Hutchinson, 1957). The shielding effect of heavily overcast skies was apparent on June 29 and November 7, 1967. Cloud cover can reduce the possible radiation by up to 50% in winter and 30% in summer (Rodgers and Anderson, 1961).

The extinction coefficients for Snowflake Lake were estimated from the nomograph given by Sauberer (1962), and fell between 0.32 and 0.47, indicating very little light-absorbing substance in the water and little change in the amount present during the open-water period. The sharp rise in light extinction below 9 m on June 29 (Fig. 4) was also found during July. This was the time of high surface runoff, when cold meltwater from the snow around the lake slid down the sides of the lake basin and created 2 or 3 m of turbid water at the bottom. Although the range of selective filters for the underwater photometer was incomplete at the time of these investigations, some readings were taken at Snowflake Lake. The increased attenuation of light in the different spectral ranges was greatest during the period of high water renewal (July) and blue was absorbed at a proportionately higher rate at this time (Fig. 5).

On Snowflake Lake, over 16% of the incident light penetrated more than 1 m of combined ice and snow cover; on Herbert Lake, up to 13% (Fig. 4).

CHEMICAL CHARACTERISTICS

Low oxygen concentrations in Snowflake Lake were confined to the bottom 2 m (Fig. 6). This and the marked gradient at 6 or 7 m throughout most of the year were indications of limited water circulation under the ice and during July and August. The absence of anaerobic conditions was likely due to the accumulation of only small amounts of organic matter. The increase in dissolved oxygen under the ice in mid-May coincided with spring phytoplankton development (Anderson, MS, 1968). Low oxygen concentrations and the absence of sharp dissolved-oxygen gradients under the ice in Herbert Lake were thought to have been due to more circulation and less photosynthesis

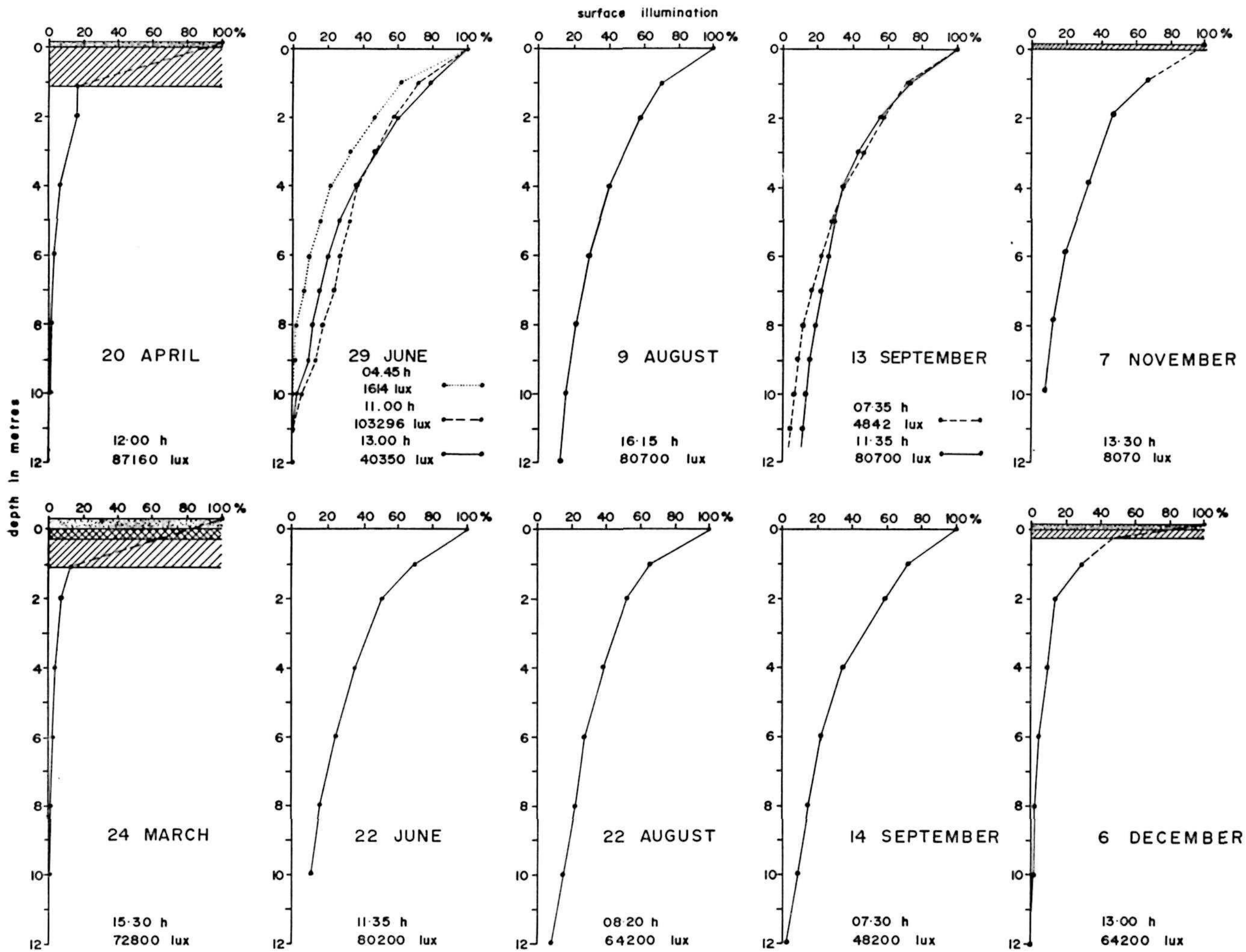

FIG. 4. Penetration of visible light in Snowflake (*upper*) and Herbert (*lower*) lakes as percentages of surface intensity.

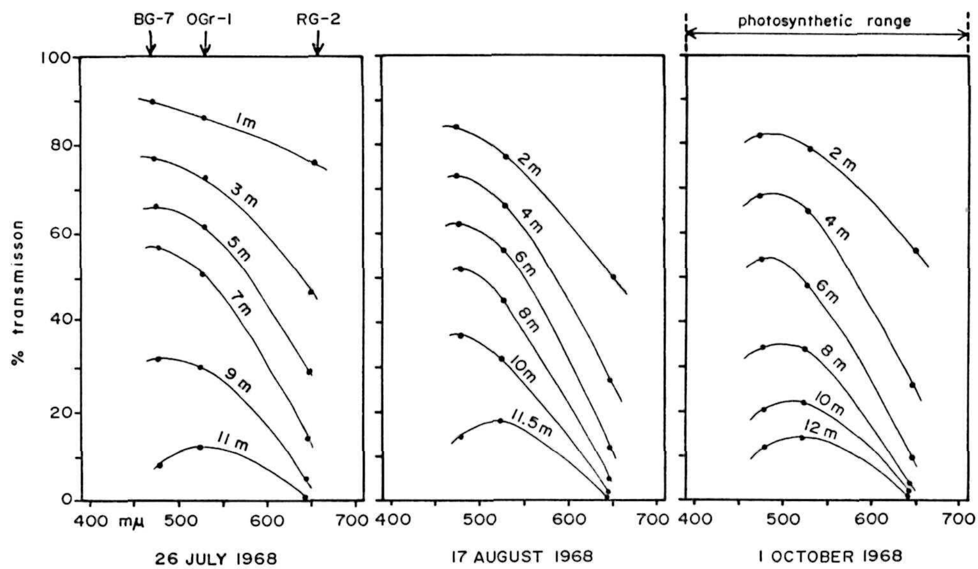

FIG. 5. Penetration of shortwave radiation in Snowflake Lake expressed as percentages of surface intensity.

(Anderson, unpublished data) than occurred in Snowflake Lake. The uniform vertical distribution of oxygen in autumn in both lakes coincided with the prolonged overturn.

Calcium, followed by magnesium, was the dominant cation and bicarbonate was the dominant anion in both lakes (Table 3). However, unlike Snowflake Lake and most lakes in the Banff, Jasper, and Yoho national parks where sulfate is the subdominant anion (Anderson, MS, 1969a, b), chloride was the subdominant anion in Herbert Lake. The order of dominance was not altered by expressing concentrations as milliequivalents per liter, although magnesium, sulfate, and chloride become more important in terms of reacting values.

The ratio of salinity (or sum of constituents as ppm) to the specific conductance as μmhos cm^{-1} at 25 C is between 0.55 and 0.70 for most waters (American Public Health Association, 1965). This ratio for Snowflake and Herbert lakes fell consistently between 0.47 and 0.56 with an approximate mean value of 0.53. Specific conductance and sum of constituents had similar seasonal patterns and reached lowest surface values in June, July, and August (Fig. 7, *c*, *d*, *g*, *h*), when water renewal and primary production rates were highest in Snowflake Lake. Concentration gradients were more striking in Herbert than in Snowflake Lake and were probably related to the more clearly defined thermocline and the lower summer circulation in Herbert Lake. The probability of incomplete overturn in both lakes in spring is suggested by the isopleths in Fig. 7, although vernal circulation may reach a greater depth in Snowflake than in Herbert Lake.

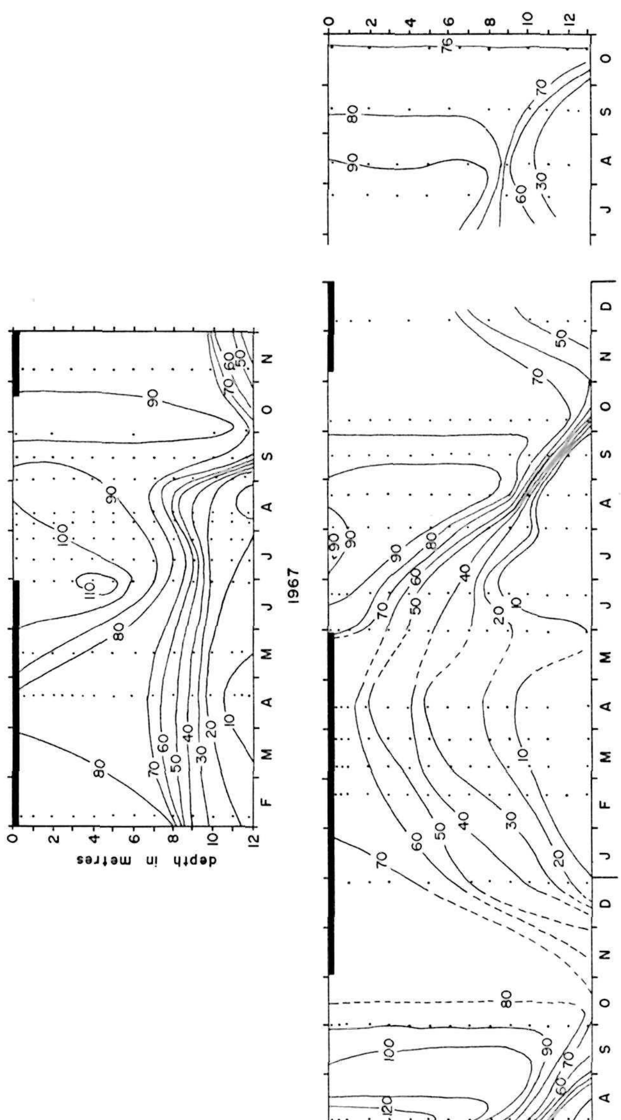

FIG. 6. Dissolved oxygen in Snowflake Lake (*upper*) and Herbert Lake (*lower*), expressed as percentage saturation corrected for temperature and altitude.

Two *p*H maxima in the surface waters of both lakes were found in 1967 (Fig. 7, *b*, *f*). The first occurred under the ice after the time of maximum ice thickness, and the second just after the period of highest water renewal.

In both lakes, the seasonal variations in the concentrations of sodium, potassium, magnesium, calcium, bicarbonate, sulfate, chloride, and silica

TABLE 3. Concentrations (in ppm) of some anions and cations from near surface and near bottom in Snowflake and Herbert lakes during spring and summer, 1967.

	Snowflake Lake				Herbert Lake			
	Apr. 14		Aug. 21		Mar. 8		Aug. 22	
Constituent	2 m	8 m	0.5 m	8 m	2 m	8 m	0.5 m	8 m
Hardness (*total as* $CaCO_3$)	127	122	89.2	92.7	168	169	161	178
Sum constituents	138	135	96.5	105	173	173	163	182
Calcium	32.5	31.7	24.9	21.6	41.0	41.3	40.0	42.0
Magnesium	11.1	10.4	6.6	9.6	15.9	16.0	14.8	17.7
Iron (dissolved)	0.02	0.02	0.01	0.01	<0.005	<0.005	0.01	0.01
Aluminum	0.17	0.10	0.10	0.04	0.01	<0.01	0.12	0.08
Manganese (total)	0.02	0.03	0.010	0.035	0.01	<0.01	0.010	0.020
Copper	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.007	0.006
Zinc	0.005	<0.005	<0.005	<0.005	<0.01	<0.01	<0.005	0.005
Sodium	4.7	4.8	1.8	4.5	2.5	2.0	1.8	1.9
Potassium	0.6	0.5	0.2	0.3	0.7	0.7	0.6	0.6
Ammonia	<0.1	<0.1	0.1	0.1	–	–	0.1	0.1
Bicarbonate	140	138	103	117	189	190	179	205
Sulfate	16.6	16.1	10.0	8.3	4.4	4.1	4.8	4.0
Chloride	0.5	0.4	0.1	0.2	8.5	8.4	6.5	8.3
Fluoride	0.05	0.04	0.04	0.04	0.18	0.08	0.08	0.07
Phosphate (diss.)	0.01	0.01	0.01	<0.01	0.02	–	0.02	0.01
Nitrate	0.10	0.22	<0.1	0.1	0.4	0.5	<0.1	<0.1
Silica	2.7	2.9	2.3	2.5	6.8	6.8	6.5	6.4

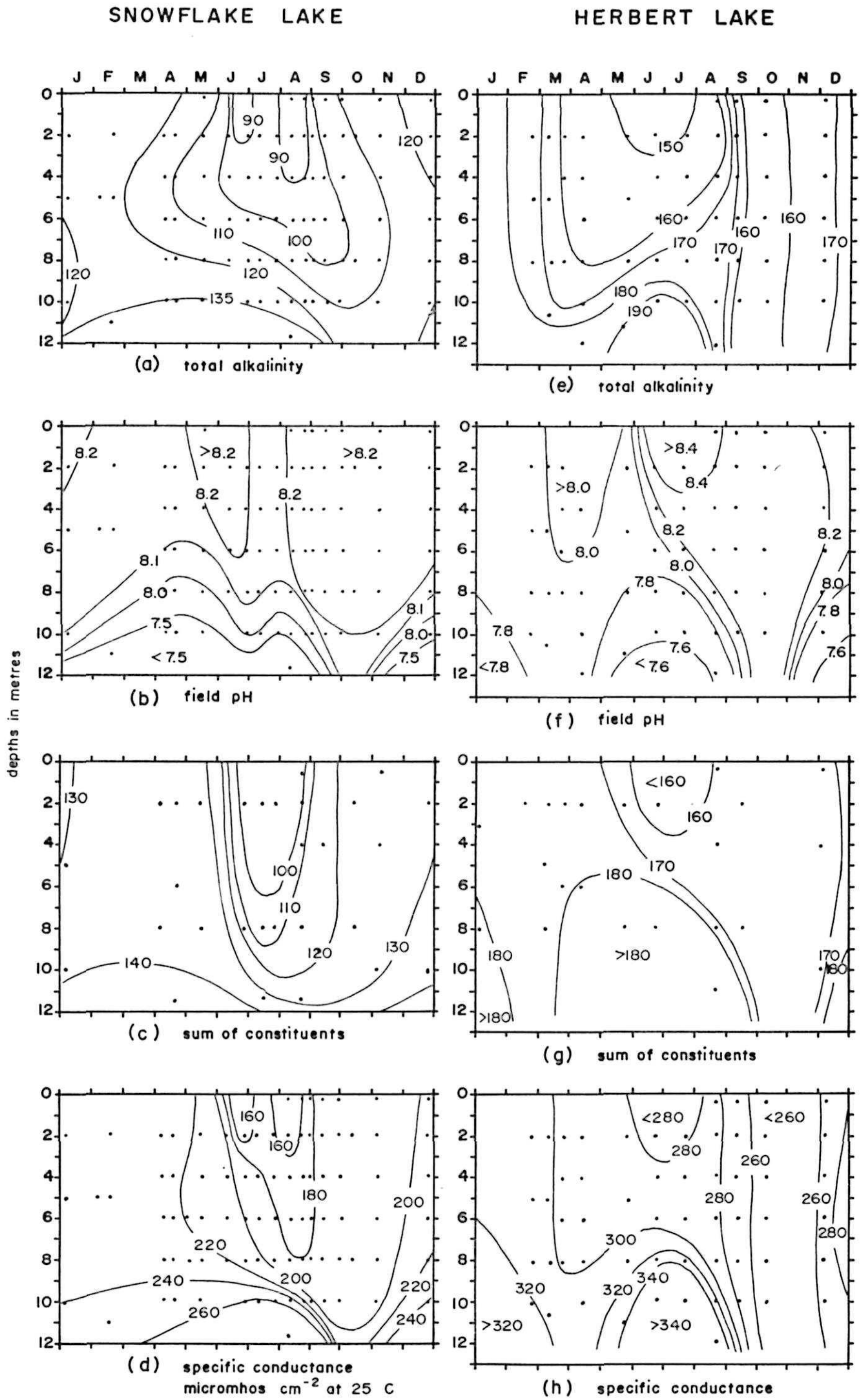

FIG. 7. Isopleths for *p*H, total alkalinity, specific conductance, and sum of constituents for Snowflake and Herbert lakes, 1967.

tended to follow closely the patterns for specific conductance and sum of constituents and to reflect the combined influence of flushing and photosynthetic activity. No clear pattern was exhibited by dissolved iron and manganese, but small increases were apparent during and immediately after the period of late winter and early spring stagnation, which would produce a weakly reducing environment in and near the sediments (Gorham, 1958).

No satisfactory methods for lakeside determination of nitrate or dissolved phosphate were available at the time of investigation, but laboratory analyses indicated that the total dissolved phosphate concentrations were very low (Table 3). Exceptions occurred at the time of highest water renewal, when concentrations occasionally doubled or tripled. Nitrate rarely exceeded 0.1 ppm in either lake.

DISCUSSION

With respect to physical and chemical limnology, Snowflake Lake is fairly typical of the alpine and upper subalpine lakes (other than glacial lakes) in the National Parks of Canada, and Herbert Lake is representative of the small, mesotrophic lower subalpine lakes (Anderson, MS, 1968, MS, 1969a, b).

Incomplete vernal circulation in both lakes (Fig. 6, 7) may have been due to low wind velocities, and in Herbert Lake to uniform 4 C temperatures under the ice at the time of ice breakup (Fig. 3). The lack of separation of winter and summer stagnation periods in Herbert Lake (Fig. 6) was probably due to incomplete spring overturn. Rawson (MS, 1939) stated that "adequate" circulation occurred in Herbert Lake, that oxygen saturation near bottom was not lower than 80%, and that stagnation was unlikely to occur. Measurements in the present study indicated that saturation below 50% is likely to occur in the lake in both summer and winter. Saturation levels below 5% were found in the bottom 2 m at both times in 1967 (Fig. 6). Circulation in the lake may be lower now than it once was and the processes of eutrophication, natural or artificial or both, may have accelerated somewhat in the past 30 years. Oxygen supersaturation did not commonly occur in the lakes, but near-saturation levels were common. The infrequent occurrence of supersaturation may have been due to the low photosynthetic production measured in the lakes (Anderson, MS, 1968, and other unpublished data). It is unlikely that oxygen saturation figures for alpine lakes are of value as indicators of production (Pechlaner, 1966).

It is likely that the low concentrations of dissolved iron in the two lakes was due to a combination of factors: to the small amount of dissolved organic matter present that could function as a chelator; to the iron-poor geological formations in which the lakes occur (Baird, 1967; McLaren, 1955); and to the infrequent occurrence of anaerobic conditions in the lakes. Seasonal *p*H maxima (Fig. 7, *b*, *f*) coincided with periods of low circulation and with peaks of photosynthetic activity (see Arnemo, 1964).

Although visible light constitutes only about half the total incoming irradiance as measured by a pyrheliometer (Strickland, 1958), it has been pointed out (Smith, 1968) that the total energy between 350 and 700 mμ characterizes the photosynthetically useful radiant energy in natural waters. Although the photometer output at each depth in this study was indicative of the total light energy at that depth, the relationship is complex because different wavelengths are selectively filtered out by the water and because the selenium cell varies in its sensitivity to wavelengths between 350 and 700 mμ (Westlake, 1965). The percentage of incident visible light that penetrated the ice and snow cover in Herbert and Snowflake lakes was much greater than that reported for some other lakes in winter (Chandler, 1942; Halsey, 1968; Pechlaner, 1964; Pennak, 1968; Rodhe, 1962; Wright, 1964). In Snowflake Lake, this was undoubtedly due to the high transparency of the ice, little snow or slush on the ice, and the high albido.

The depth at which light intensity is 1% of surface intensity is suggested as the lower limit of the trophogenic zone (Steemann-Nielsen and Aabye Jensen, cited by Arnemo and Nauwerck, 1965). During much of the year, this zone extended to the bottom of Snowflake Lake, and to the bottom of Herbert during some of the open-water season.

The winter heat income for Snowflake Lake (Table 2) was approximately the same as the 7830–8920 cal cm^{-2} calculated for Vorderer Finstertaler See by Pechlaner (1966). Although the ice was thicker and the water colder at Snowflake Lake, the Austrian Lake has a greater mean depth, which probably contributed to the similar heat income. The summer heat income figures for Snowflake Lake were much lower than Pechlaner's figures of 5690–6740 cal cm^{-2} for Vorderer Finstertaler See. This was undoubtedly due to the higher (nearly four times) water renewal rate for Snowflake Lake. The heat loss due to water renewal will be proportionately greater in small lakes having relatively high water renewal rates, and the calculation of summer heat income without considering this source of loss produces an inaccurate figure.

The summer heat income figures for Herbert Lake (Table 2) were much higher than those for Snowflake Lake but slightly lower than those for Vorderer Finstertaler See. The Herbert Lake summer value compared closely with the value of 5650 cal cm^{-2} for Amethyst Lake (Rawson, 1953), and the annual budget for Herbert Lake compares closely with the annual budget of 15,300 cal cm^{-2} determined for Lake Erken in Sweden (Nauwerck, 1963).

There is little positive evidence so far for either lake that enough heat exchange from the bottom sediments occurs to produce circulation as was reported for Tub Lake by Likens and Ragotzkie (1965, 1966). However, the gradual rise of the 2 C isotherm in Snowflake Lake (Fig. 3) in the winter of 1967–68 suggests that heat transfer to bottom waters from the sediments may occur some years.

Thermoclines are "not regularly developed in temperate alpine lakes" (Thomasson, 1956), a feature that is undoubtedly related to the short open-water season and to the prevalence of high velocity winds and low air temperatures at high altitudes. The weak summer thermal stratification in Snowflake Lake and the small zone of low oxygen saturation indicated that less than 10% of the lake volume was isolated by stratification (Fig. 3, 6, summer 1967). If this is the case, then the actual and estimated water renewal rates were nearly equal.

ACKNOWLEDGMENTS

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REFERENCES

AMERICAN PUBLIC HEALTH ASSOCIATION. 1965. Standard methods for the examination of water and wastewater. 12th ed. Amer. Public Health Ass., Inc., New York. 769 p.

ANDERSON, R. S. MS, 1968. The limnology of Snowflake Lake and other high altitude lakes in Banff National Park, Alberta. Ph.D. Thesis. University of Calgary, Calgary, Alta. 218 p.

MS, 1969a. Aspects of the physical and chemical limnology of a large number of lakes in Banff National Park. Can. Wildlife Serv. Rep. Ser. 82 p.

MS, 1969b. Aspects of the basic limnology of several alpine and subalpine lakes, Jasper National Park, Alberta. Can. Wildlife Serv. Rep. Ser. 56 p.

ARNEMO, R. 1964. Limnological studies in hyttödammen. 1. Physical and chemical conditions. Rep. Inst. Freshwater Res. Drottningholm 45: 5–93.

ARNEMO, R., AND A. NAUWERCK. 1965. Limnological studies in hyttödammen. 2. Phytoplankton and its production. Rep. Inst. Freshwater Res. Drottningholm 46: 141–166.

BAIRD, D. M. 1967. Banff National Park: how nature carved its splendor. Geol. Surv. Can. Misc. Rep. 13: 307 p.

BAPTIE, B. MS, 1968. Ecology of the alpine soils of Snow Creek Valley, Banff National Park, Alberta. M.Sc. Thesis. University of Calgary, Calgary, Alta. 135 p.

CHANDLER, D. C. 1942. Limnological studies of Western Lake Erie. II. Light penetration and its relation to turbidity. Ecology 23: 41–52.

FABRIS, G. L. MS, 1966. Productivity in four small mountain lakes. M.Sc. Thesis. University of Saskatchewan, Saskatoon, Sask. 91 p.

GORHAM, E. 1958. Observations of the formation and breakdown of the oxidized microzone at the mud surface in lakes. Limnol. Oceanogr. 3: 291–298.

HALSEY, T. G. 1968. Autumnal and over-winter limnology of three small eutrophic lakes with particular reference to experimental circulation and trout mortality. J. Fish. Res. Bd. Canada 25: 81–99.

HUTCHINSON G. E. 1957. A treatise on limnology. Vol. I. John Wiley and Sons, Inc., New York. 1015 p.

LIKENS, G. E., AND R. A. RAGOTZKIE. 1965. Vertical water motions in a small ice-covered lake. J. Geophys. Res. 70: 2333–2344.

1966. Rotary circulation of water in an ice-covered lake. Int. Ver. Theor. Angew. Limnol. Verh. 16: 125–133.

LÖFFLER, H. 1968. Die Hochgebirgsseen Ostafrikas. Hochgebirgsforschung 1: 1–68.

MCLAREN, D. J. 1955. Devonian formations in the Alberta Rocky Mountains between Bow and Athabasca Rivers. Geol. Surv. Can., Dep. Mines Tech. Surv. Bull. 35: 1–59.

NAUWERCK, A. 1963. Die Beziehungen zwischen Zooplankton und Phytoplankton im See Erken. Symb. Bot. Upsal. 17: 163 p.

PECHLANER, R. 1964. Plankton production in natural lakes and hydroelectric water-basins in the alpine region of the Austrian Alps. Int. Ver. Theor. Angew. Limnol. Verh. 15: 375–383.

1966. Die Finstertaler Seen (Kühtai, Österreich) 1. Morphometrie, Hydrographie, Limnophysik und Limnochemie. Arch. Hydrobiol. 62: 165–230.

PENNAK, R. W. 1955. Comparative limnology of eight Colorado mountain lakes. Univ. Colo. Stud. Ser. Biol. 2: 75 p.

1968. Field and experimental winter limnology of three Colorado mountain lakes. Ecology 49: 505–520.

RAVERA, O., AND V. TONOLLI. 1956. Body size and number of eggs in diaptomids, as related to water renewal in mountain lakes. Limnol. Oceanogr. 1: 118–122.

RAWSON, D. S. MS, 1939. A biological survey and recommendations for fisheries management in waters of the Banff National Park. Dep. Mines Resources Can., Unpubl. Rep., Nat. Parks Bur. 128 p.

1942. A comparison of some large alpine lakes in Western Canada. Ecology 23: 143–161.

1953. The limnology of Amethyst Lake, a high alpine type near Jasper Lake, Alberta. Can. J. Zool. 31: 193–210.

RODGERS, G. K., AND D. V. ANDERSON. 1961. A preliminary study of the energy budget of Lake Ontario. J. Fish. Res. Bd. Canada 18: 617–636.

RODHE, W. 1962. Sulla produzione di fitoplancton in laghi transparenti di alta montagna. Mem. Ist. Ital. Idrobiol. Dott Marco de Marchi Pallanza, Italy 15: 21–28.

ROWE, J. S. 1959. Forest regions of Canada. Can. Dep. Northern Affairs Natur. Resources, Forestry Branch Bull. 123: 71 p.

SAUBERER, F. 1962. Empfehlungen für die Durchführung von Strahlungsmessungen an und in Gewässern. Int. Ver. Theor. Angew. Limnol. Mitt. 11: 1–77.

SMITH, R. C. 1968. The optical characterization of natural waters by means of an "extinction coefficient". Limnol. Oceanogr. 13: 423–429.

STRICKLAND, J. D. H. 1958. Solar radiation penetrating the ocean. A review of requirements, data, and methods of measurements, with particular reference to photosynthetic productivity. J. Fish. Res. Bd. Canada 15: 453–493.

THOMASSON, K. 1956. Reflections on arctic and alpine lakes. Oikos 7: 117–143.

WELCH, P. S. 1948. Limnological methods. McGraw-Hill Book Co., Inc., Toronto, Ont. 381 p.

WESTLAKE, D. F. 1965. Some problems in the measurement of radiation under water: a review. Photochem. Photobiol. 4: 849–868.

WRIGHT, R. T. 1964. Dynamics of a phytoplankton community in an ice-covered lake. Limnol. Oceanogr. 9: 163–178.