Some Limnological Features of a Shallow Saline Meromictic Lake

G. C. ANDERSON

Department of Zoology, University of Washington, Seattle, Washington

ABSTRACT

Seasonal variations of some physical, chemical, and biological features were studied from December 1954 to October 1956 in Hot Lake, a shallow saline body of water occupying a former epsom salt excavation in north central Washington. The lake is meromictic and during the period of study had an average salt gradient of approximately 100 g/liter at the surface to 400 g/liter at the bottom, the major salt being magnesium sulfate. The mixolimnion was thin enough that the monimolimnion was heated directly by the sun, with the result that temperatures in excess of 50°C were recorded in the monimolimnion during summer. Much of this heat was retained during the winter. The calculated value of heat gain in the monimolimnion agreed reasonably well with the observed value. The flora consisted mainly of *Chara*, a bottom mat of blue-green algae, and a dense population of green sulfur bacteria in the upper part of the monimolimnion. *Artemia salina* was the dominant zooplankter, and some features of its life history as affected by the unusual thermal properties of the lake are described.

INTRODUCTION

The purpose of this paper is to report some physical, chemical, and biological features of an unusual meromictic saline lake located near Oroville in north central Washington. The region is semi-arid and has a moisture index value of −20 (Thornthwaite 1948). The paper is a contribution from a project directed by Dr. W. T. Edmondson, on Limnology of Arid Lands, currently being carried out at this institution under the sponsorship of the State of Washington Research Fund in Biology and Medicine and the National Science Foundation. Although the major portion of the project has been concerned with lakes in a somewhat more arid region, the Columbia Basin, the present lake was included in the investigation because of its unusual qualities.

There have been two separate investigations of Hot Lake in the past. St. John and Courtney (1924) investigated the flora of the lake and drainage region but confined their studies to the vascular plants. Only one species of vascular plant inhabited the lake, *Distichlis spicata* (L.) Greene.

Jenkins (1918) described the geology of the region and advanced an explanation for the origin of salts in the lake. The lake bed lies close to rock consisting of metamorphic rocks, dolomites, and shales, and in the drainage area surrounding the lake are numerous mineral deposits consisting mostly of pyrite and pyrrhotite bodies which were largely oxidized to a mixture of iron oxides, quartz, clay, and gypsum. Whitish drainage streaks led from the deposits to the lake, and from this evidence Jenkins postulated the following:

"These facts suggest the possibility that the sulphates and sulphuric acid, known to form from the oxidation of pyrite and pyrrhotite through the action of meteoric water and air, acted upon the dolomite and other magnesian rocks, forming magnesium sulphate, which is soluble, and calcium sulphate, which is much less soluble. The result was that the magnesium sulphate was carried to the lake in solution. What little calcium sulphate came with it was precipitated first, being less soluble, as a thin layer of gypsum over the sediment already deposited on the bottom of the lake."

The dominant mineral, epsomite ($MgSO_4 \cdot 7H_2O$), was in great enough quantity that during and for a short time after the first World War, epsom salt mining operations took place in the lake. These operations revealed a solid 15-foot layer of epsomite beneath the lake bottom. Between the layer of epsomite and bed rock was a thin layer of gypsum ($CaSO_4$) followed by a thin layer of clay-like material. The morphometry of the lake was changed somewhat by the mining activities which gave rise to the channeled depression now present.

The stimulus for beginning the present investigation was provided by Dr. Phil Church of the University of Washington, Department of Meteorology, who, after a trip to the Oroville area, returned with a water sample and local reports of unusually high temperatures at subsurface depths of the lake. A trip was immediately made to the region, and periodic samplings took place from December 1954 to December 1955, and infrequently during 1956. It is a pleasure to acknowledge the cooperation and courtesies extended by W. Ripley and H. Payne, the owners of the lake, and the Oroville Chamber of Commerce, especially Messrs. C. Wilder and Stafford Lewis. The helpful criticisms and advice of Dr. W. T. Edmondson, University of Washington, in the planning of field work and the assembly and interpretation of the data are particularly acknowledged. Thanks are also due the following people for generous assistance in various ways: Dr. Franz Ruttner, Lunz Biological Station, references to the Hungarian lake studies; Dr. W. T. Edmondson, identification of rotifers; Dr. Francis Drouet, Chicago Museum of Natural History, identification of blue-green algae; Dr. Ralph W. Dexter, Kent State University, identification of the brine-shrimp; U. S. Bureau of Reclamation, Ephrata, Washington, mineral analyses of lake waters.

MATERIALS AND METHODS

The outline of the shore of Hot Lake was obtained from aerial photographs, and depth contours were added after measurements were made with a brass sounding chain. The sounding program was carried out during maximum water elevation in 1955, and records of seasonal fluctuations were kept.

For the most part, routine sampling was done at a single station in the approximate mid-point of the lake which is also located at maximum depth. Water samples were taken with a Kemmerer water sampler and transported to the laboratory. Analyses included pH (Beckman pH meter), alkalinity titrations with 0.02N H_2SO_4 (American Public Health Association 1946), and total dissolved solids. Samples for oxygen determination were fixed in the field and titrated in the laboratory according to the unmodified Winkler method.

Temperature was measured with a direct reading Whitney resistance thermometer. Dr. L. V. Whitney kindly reconstructed the apparatus so that the high temperatures encountered could be recorded. Transparency was measured with a Secchi disc, and light penetration with a Clarke-type apparatus as recommended by the International Council for the Exploration of the Sea (Atkins *et al.* 1938).

The Clarke-Bumpus plankton sampler was used in sampling the zooplankton population, and a #10 bolting silk net was used throughout. The sampler was towed by rowing at maximum speed as it was impracticable to use an outboard motor due to the small size of the lake. The samples were preserved in formalin and later counted in a plastic tray. When samples were large, aliquots were taken with a wide-mouthed pipette and counted. Otherwise, the entire sample was counted.

LIMNOLOGICAL NATURE OF THE LAKE

Hot Lake lies in a glacial, wind-protected depression atop Kruger mountain (48°58′N, 119°29′W), part of a low mountain range bordering the Okanogan Valley of north central Washington. The elevation is approximately 2000 feet. Morphometric features include an area of 1.27 ha, maximum depth 3.25 m, mean depth 1.06 m, a channeled depression running most of the length of the lake, and the absence of an inlet or outlet (Fig. 1, Table 1). Investigations have failed to reveal any subsurface flow to the lake. Hence the only apparent source of water is from surface runoff which occurs mainly in early spring. Water loss occurs only by evaporation, and as a result the lake has become extremely saline. Wide variations in surface level and salinity occur

TABLE 1. *Area and volume at different depths in Hot Lake*
Values computed at time when surface level of lake was at the seasonal maximum, May 17, 1955.

Depth m	Area m²	Volume m³
0	12,720	
		7940
1	3,982	
		3369
2	2,792	
		2093
3	1,465	
		122
3.5		
Total Volume		13,524

depending upon rates of inflow and evaporation.

Apparently after the lake was re-flooded after mining operations in the early part of the century, a highly saline body of water resulted. As fresh water entered from surface runoff, the lake became stratified and meromixis was established. Because of the protection from the wind, the steep gradient in salinity from top to bottom, and the small surface area, there is a very stable stratification of the monimolimnion. It is not known if the lake was meromictic previous to mining operations or if this condition has been due to the basins formed by the mining establishment.

The nature of meromixis is somewhat different from that generally known in that separation into mixolimnion and monimolimnion is not distinct. Rather, there is at most times a sharp gradient in density from top to bottom with the gradient being somewhat more abrupt (chemocline) at the middle level of the lake. The major difference from meromictic lakes previously described is in the structure of the upper layer or mixolimnion. Most meromictic lakes (Findenegg 1935, Hutchinson 1937, Anderson 1958) have mixolimnia of uniform density throughout and are freely circulating except during times of temperature stratification. In Hot Lake that portion of the water mass which can best be described as the mixolimnion is at most times stratified due to differences in salt concentration, and wide seasonal variation

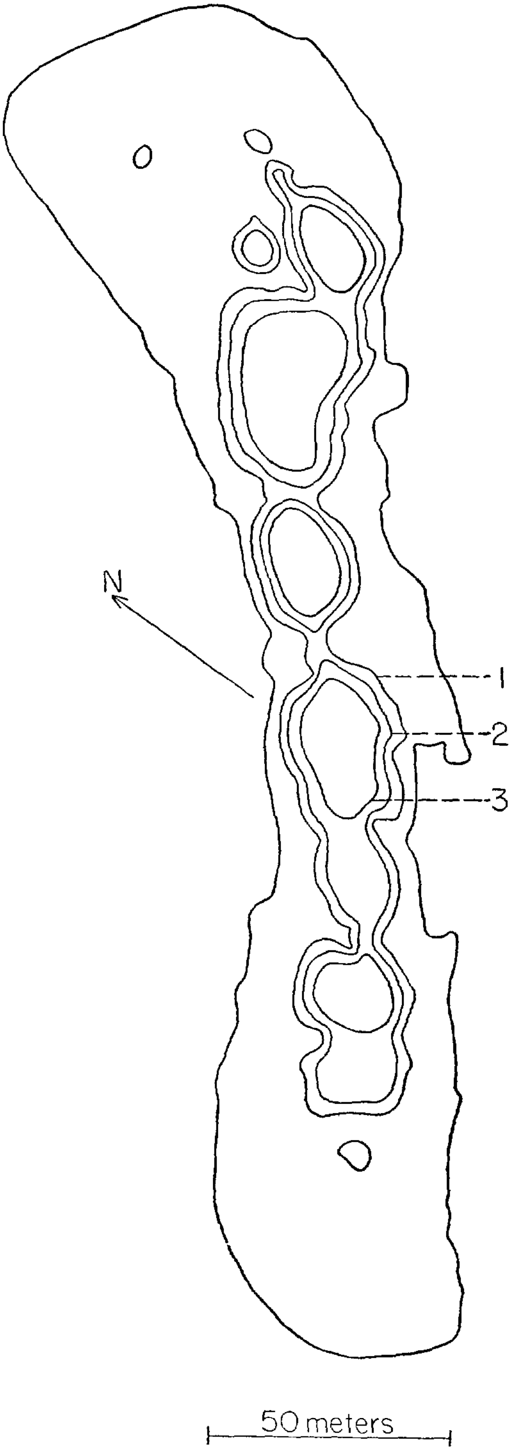

FIG. 1. Bathymetric map of Hot Lake, Washington, with depth contours in meters.

in characteristics occur. This is especially evident during the spring season after the lake has gained considerable fresh water from runoff. At this time the upper water, as distinct from the monimolimnion, is a two-layered stratum, the top layer of which is relatively fresh. Due to the marked wind protection mixing takes place slowly, and gradually the two-layered upper stratum loses its identity. As a result a mass of water with a density gradient from surface to the top of the monimolimnion is established, which in this paper is referred to as the mixolimnion. Because of mixing, evaporation, and addition of water each spring, the surface waters are subject to great changes in salt content with the trend being that of increase from spring to fall.

The problem of maintenance of meromixis is an interesting one. It might appear that stratification would break down eventually in meromictic lakes with a small volume and depth such as Hot Lake because of diffusion and other mixing processes. However, it must be remembered that not only is mixing kept at a minimum by protection from wind, but also the addition of a stratum of fresh water to the lake by spring runoff each year adds to the stability. In addition, and probably a most important factor, salt solutions in freezing precipitate a portion of their dissolved materials (Thompson and Nelson 1956). In this manner, seasonal losses of salt from the monimolimnion due to diffusion into the mixolimnion could be renewed during the winter period of ice cover.

PHYSICAL CONDITIONS

Temperature

The type of temperature stratification found in Hot Lake is unusual (Table 2). The temperature profile shown in Figure 2 (May 17, 1955) is typical of summer thermal conditions. Temperature at the surface was approximately 18°C and increased sharply with depth to the 1.5-m zone. A middle region, 1.5–2.2 m, represented a layer of maximum temperature (40°C), and from this region to the bottom the temperature decreased steadily to slightly less than 29°C.

TABLE 2. *Seasonal and vertical variation of temperature (°C) and seasonal variation of transparency (m) in Hot Lake, December 1954 to October 1956*

Depth (m)	1954	1955													1956		
	Dec. 7	Mar. 12	Apr. 16	May 17			May 18	May 29	June 25	Jul. 23	Aug. 22	Sept. 28	Oct. 18	Dec. 9	May 1	May 18	Oct. 24
				4:30 a.m.	12:40 p.m.	4:25 a.m.	5:25 a.m.										
0.0	Ice	Ice	14.40	11.00	17.92	17.53	13.29	20.31	21.00	26.77	21.92	13.73	11.70	Ice	13.61	23.12	6.48
0.25															13.66	22.48	
0.5		2.20	18.90	25.55	26.95	27.14	26.40	22.61	20.29	26.38	21.83	13.54	11.57	0.00	13.67	26.80	8.10
0.75	5.20														24.58	31.81	18.45
1.0	6.00	4.85	23.60	31.25	31.90	32.00	31.40	36.20	26.10	28.43	21.58	13.39	11.47	0.00	25.90	34.37	25.17
1.25															20.42	28.98	
1.5	16.00	11.18	27.50	37.20	38.10	39.70	39.20	44.50	45.75	42.68	32.17	13.70	11.47	0.00	16.45	22.21	29.48
1.75															12.60	17.62	
2.0	23.80	18.85	30.30	38.90	40.00	41.10	40.30	45.30	49.72	50.53	43.65	27.64	21.38	8.00	10.25	13.99	27.18
2.25		20.61													8.29	11.39	
2.3		21.10															
2.5	29.00		28.60	35.30	35.30	35.60	35.60	37.84	42.38	43.88	40.93	33.36	27.43	16.48	7.49	10.22	23.52
2.75												33.85	29.73	20.00	6.67	9.03	
3.0			26.90	31.80	31.72	31.70	31.67	32.05	34.65	36.19	36.67				6.83	8.63	20.70
3.1										35.68	35.72						
3.2						29.90			32.88								
3.25			26.90	28.30	28.71			29.70							7.48	8.82	
3.3							29.09										
3.5						28.78									8.33	9.30	18.20
3.75															9.98	10.32	
4.0															10.60		
Transparency		2.0	2.3				2.2		2.0	2.0	1.8	1.7	1.3		1	1.1	1.3

The water to a depth of 2 m is clear, whereas the monimolimnion is characterized by a dark brown, stagnant water containing hydrogen sulfide. Slightly below the 2-m level a thin layer of opaque green colored water was present. This was due to a large population of what appeared to be green sulfur bacteria, possibly *Chlorobium*. Light is readily transmitted through the transparent mixolimnion, but is absorbed rapidly in the bacterial zone and darkly colored monimolimnion. The heat gained in the monimolimnion from absorption of light energy cannot readily escape because of lack of circulation between the upper and lower layers. The mixolimnion, on the other hand, can gain a greater amount of heat from light energy and from atmospheric transfer on warm days, but can also lose this heat rapidly during periods of low atmospheric temperature such as during nights and during the cold season. Apparently, the major means of escape of heat from the monimolimnion is by conduction to the bottom and to the mixolimnion, but this is a slow process, as is evidenced by the gradual loss of heat during the period December 1954 to March 1955 (Fig. 3).

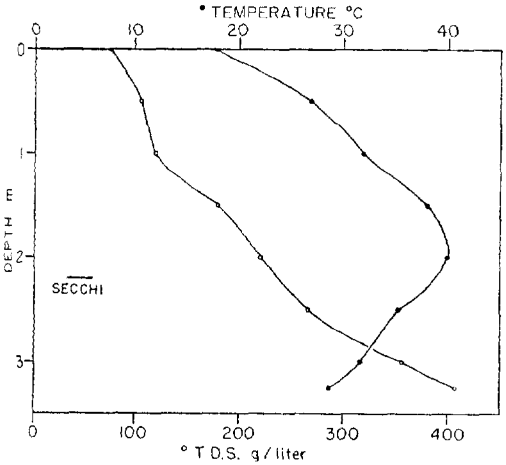

Fig. 2. Vertical distribution of temperature and salt concentration in Hot Lake, May 17, 1955.

Other bodies of water with similar therma

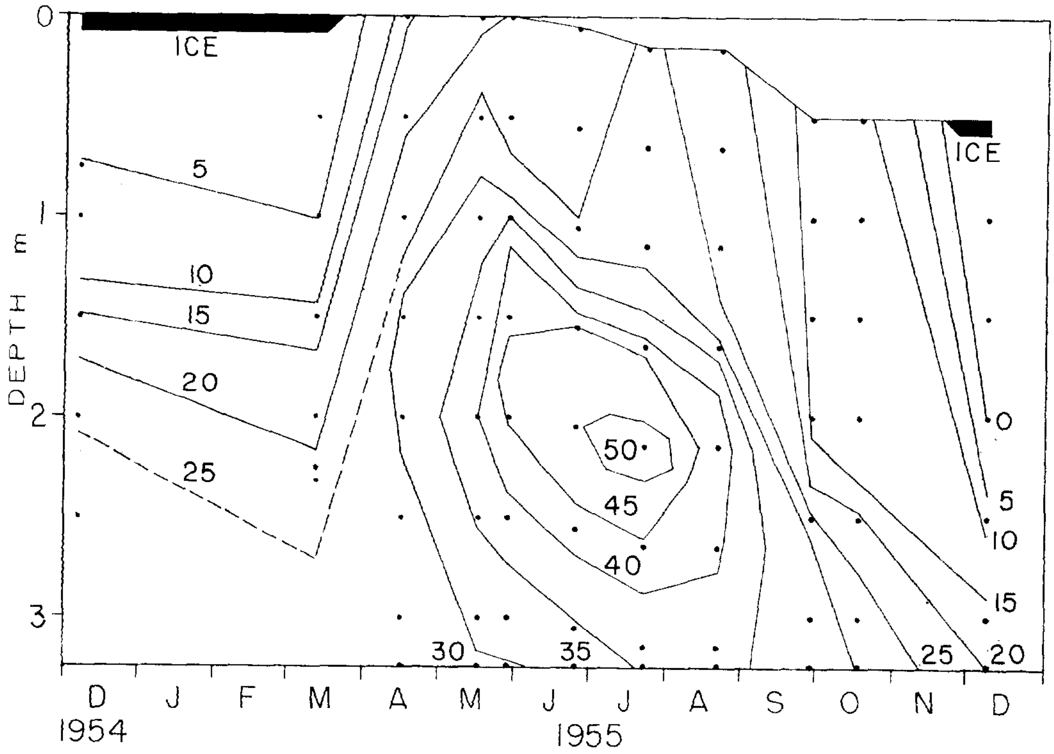

Fig. 3. Seasonal and vertical variations of temperature (°C) in Hot Lake, December 1954 to December 1955.

characteristics have been reported in the literature. Beadle (1943) reported similar small bodies of water in Algeria, the most striking being 0.3 m deep with a specific gravity of 1033 at the top and 1172 at the bottom. The surface temperature was 19.0°C and the bottom temperature 31.0°C. Kalecsinsky (1901) reported on some saline wind-protected lakes in Hungary which were overlain by shallow sheets of fresh water. The major part of his study was concerned with Medve See, which had a concentration of 24 per cent sodium chloride, a depth of 20 m, and an area of 4.3 ha. He found a maximum temperature of 56.0°C at 1.32 m, but earlier workers had found temperatures up to 71.0°C at depths below the surface. Schafarzik (1908), in a later study, reported a maximum temperature of 45.6°C at 2.0 m in Medve See, and Halbfass (1923) reports still another study of the same lake in which the maximum temperature occurred at 2.5 m. Since none of the lakes studied had a hot spring source and the rise in temperature was too great to explain by chemical oxidation of organic materials, the several investigators concluded that the radiant energy of the sun was stored in the saline waters immediately below the upper less concentrated zone, since release of heat is not possible due to lack of circulation. Similar thermal characteristics are also found in some oyster polls on the west coast of Norway (Gaarder and Spärck 1932). These polls are located in fjords which are connected to the open ocean by narrow and shallow entrances. Temperatures up to 28.0°C were recorded at subsurface depths after rain water had covered the surface during spring.

On December 7, 1954, the first sampling date, the lake had just frozen over and had less than 1 cm of ice cover. There was an almost uniform gradient in temperature with a maximum of 33°C at the bottom (Fig. 3). The next sampling data, March 12, 1955, after a winter of heavy ice cover, was at a time just before the ice left the lake. About 13 cm of slushy ice remained on the surface. Some heat had been lost from the monimolimnion, and the maximum temperature observed at the bottom of this stratum was 21°C. A steeper temperature gradient between 1.5 and 2.0 m was noted which indicated a discontinuity layer at the same level as shown by measurements of total dissolved salt. The lake gained heat rapidly after the disappearance of ice, and by April 16 the temperature profile had changed considerably. The maximum gain of heat occurred at the 2 m level. The surface temperature was 14°C, at 2 m 30°C, and a slight decrease to 27°C was noted at the bottom.

During most of the summer the gain in heat of the lake followed the same trend. The surface temperature reached a maximum of 27°C, the same magnitude as would be expected in most lakes of comparable size in the region. However, the temperature of the water in the 2 m region rose steadily and was always higher than that of the surface or the bottom. The bottom waters showed a steady gain during the summer, but the magnitude was small in comparison with the surface and middle waters.

The observed date of maximum heat was July 23, 1955. The series taken August 22, 1955, showed an overall loss of heat. The surface temperature had decreased to 21.7°C and the 2 m level to 43.6°C. The bottom waters remained relatively constant in temperature.

There are three factors which contributed to the loss of heat during August. The first factor is the lessening of solar energy input as the days became progressively shorter. The second factor, reduction in the thickness of the mixolimnion due to evaporation, decreased the insulation protecting the middle layer of maximum heat. Thus, the process of conduction of heat from the middle depth of the lake to the surface could occur over a shorter distance and become of greater significance. Also, disturbances in the upper water from wind would then more readily affect the lower waters by mixing. During the summer a health resort was established near the lake, and pumping of sub-surface waters for hot baths took place. Because figures are not available on the amount of water removed, it is not known if pumping contributed significantly to the loss of heat noted.

The lake lost heat rapidly during the fall

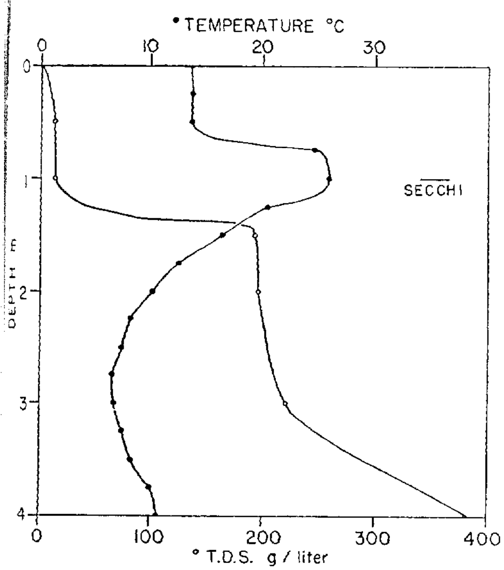

FIG. 4. Vertical distribution of temperature and salt concentration in Hot Lake, May 1, 1956.

and winter of 1955–56. The amount of heat retained in the preceding winter was much greater, which was presumably due to a lesser amount of mixing in that winter. In December 1955, the lake level was 0.5 m lower than in December 1954, and mixing, as indicated by temperature measurements, extended to approximately 0.5 m in 1954 and 1.5 m in 1955.

In 1956 the lake received more than 1 m of fresh water on the surface from heavy snowfall during the preceding winter. Only three series of measurements were taken during this year, but it is interesting to compare thermal conditions with 1955 (Table 2, Fig. 4). On May 1, 1956, the mixolimnion was nearly uniform in salinity to a depth of 1.0 m. The average transparency was 1.0 m. In accordance with these measurements, the region of maximum temperature was at 1.0 m in 1956, whereas in 1955 transparency was usually about 2.0 m, the depth of maximum heat. In both years the mixolimnion was relatively transparent, and directly beneath it a layer of highly colored water occurred, which accounted for the increase in temperature due to light absorption. Another feature of conditions in 1956 was the presence of a layer of water directly on the bottom which was warmer than that immediately above it. This apparently represents that portion of the lake which had remained relatively undisturbed since 1955.

Transparency

Transparency as indicated by Secchi disc observations varied with the depth of the mixolimnion (Table 2). Waters of the mixolimnion were of a clear relatively colorless nature, whereas the monimolimnion was highly colored. The Secchi disc could at any time be seen clearly at any depth in the upper water, but after entrance into the monimolimnion immediately disappeared from sight. By autumn of 1955, after considerable evaporation and mixing had occurred, the upper water became slightly colored, presumably due to the intrusion of the colored monimolimnion water. In 1955 the maximum value was 2.3 m in April, the minimum value 1.3 m in October. Transparency in 1956 was reduced, with a maximum of 1.3 m in October and a minimum of 1.0 m in May.

Light penetration and heating

Because of the unusual thermal properties of Hot Lake it seemed advisable to acquire information on the penetration of different wavelengths of light and to relate the absorption of light to heating at different depths. On August 23, 1955, measurements of light penetration were made in the visible spectrum (3800–7200 Å), roughly the range of the photoelectric cell used (2700–7500 Å). Measurement of ultra-violet and infra-red was not possible with the available equipment, but it is known that both components are absorbed rapidly by pure water and their effect on subsurface water is negligible (Clarke 1939). The five wavelengths investigated were 4500, 5250, 5750, 6150, and 6800 Å. Their transmission is illustrated on a semi-logarithmic scale as percentages of illumination measured just beneath the surface (Fig. 5). Maximum transmission occurred in the yellow region, and absorption at each end of the visible spectrum was great.

With the data at hand it is possible to compute the amount of heat the lake could gain at a given depth. Light was trans-

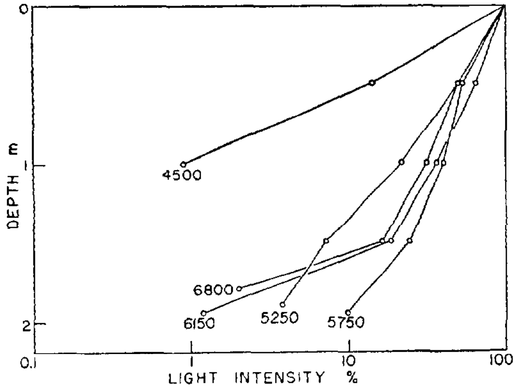

FIG. 5. Intensity of different wavelengths of light (Å) in the visible spectrum at various depths in Hot Lake, August 23, 1955.

mitted through the upper water fairly readily, but at 1.8 m there was a sharp break, beyond which light was scarcely measurable due to the beginning of the highly colored monimolimnion. The calculated intensity of light at 1.8 m was 3.62 per cent of surface illumination, and for purposes of the present discussion it is assumed that complete absorption occurred in the 10-cm depth zone directly below 1.8 m. If an average summer value of 600 g-cal/cm^2/day is arbitrarily assigned as the amount of light energy falling on the lake surface, then 21.72 g-cal/cm^2 would reach 1.8 m in one day and would be completely absorbed within the next 10 cm. This would allow the average temperature of that zone to rise 2.17°C/day if it were pure water. However, a 25 per cent solution of $MgSO_4$ at 25°C has a specific heat of 0.743 (National Research Council 1928) which would increase the above value to 2.92°C/day.

On May 17 and 18, 1955, the actual amount of heat gained in the lake at different depths was measured (Table 3). Vertical temperature series were taken at dawn and late afternoon on the first day and at dawn on the following day. In this manner the heat gain in daylight hours and the net gain in a 24-hour period was measured. The heat gain from 4:30 a.m. to 4:25 p.m. was considerable and occurred only above 2.5 m. Apart from the surface, the heat gain was the greatest in intermediate waters (1.5–2.0 m). At 2.0 m the gain was 2.20°C, which is in reasonably close agreement with the computed value of 2.92°C at 1.8–1.9 m in view of the assumptions necessarily made. Since the heat gained in the intermediate waters would not be expected to be completely retained due to conduction and other mixing processes, a lower actual value than that calculated seems reasonable. This is evidenced by the heat loss of 0.80°C at 2.0 m during the night, leaving a net gain of 1.40°C/day.

TABLE 3. *Diurnal temperature variations at different depths in Hot Lake, May 17 and 18, 1955 (°C)*

Depth m	May 17 4:30 a.m.	May 17 4:25 p.m.	Heat gain	May18 5:25 a.m.	Heat loss	Net gain
0	11.00	17.53	6.53	13.29	4.24	2.29
1	31.25	32.00	0.75	31.40	0.60	0.15
2	38.90	41.10	2.20	40.30	0.80	1.40
3	31.80	31.70	−0.10	31.70	0.00	−0.10

CHEMICAL CONDITIONS

As stated previously, the lake contains predominantly the mineral, magnesium sulfate (Table 4). Other ions are present, the most conspicuous being chloride, bicarbonate, and sodium. Qualitatively the mixolimnion and monimolimnion were similar, although the latter was characterized by having a much greater salt content and a noticeable amount of H_2S as revealed by the strong odor.

Large fluctuations occurred in salt concentration of surface waters. After the spring runoff in 1955 a minimum of 40 g/liter was recorded (April 16), and by late summer, evaporation and mixing accounted for an increase to a maximum value of almost 200 g/liter. A typical profile of salt distribution in 1955 is shown in Figure 2. In 1956 the runoff was great, and as a result the surface waters contained relatively little dissolved materials (0.37 g/liter) (Fig. 4).

The pH was generally alkaline. The maximum was 8.72 at the surface on December 7, 1954, and the minimum was 6.98 at the bottom on the same date.

TABLE 4. *Mineral analyses of Hot Lake waters, August 22, 1955*

Ion concentration expressed as mg/liter, conductivity as micromhos at 25°C. Analysis by Bureau of Reclamation, Engineering Laboratories Branch, Denver, Colorado.

	Surface	3 m
Conductivity	57,910	60,440
pH	8.2	7.8
T.D.S.	161,200	391,800
Ca	640	720
Mg	22,838	53,619
Na	7,237	16,790
K	891	1,564
HCO_3	3,148	3,062
CO_3	0	0
SO_4	103,680	243,552
Cl	1,668	1,882
NO_3	0	0

There was usually an abundance of dissolved oxygen in the surface waters maximum 12.9 mg O_2/liter, April 10, 1955) except in the autumn of 1955 when none was detectable. Oxygen was never found below 1.5 m. Because of the abundance of H_2S in the monimolimnion and probable diffusion of it into the mixolimnion, especially during the period of low lake level, the unmodified Winkler method is probably not suitable, and the information obtained thereby should be viewed with some scepticism. It is possible that oxygen extended somewhat below 1.5 m at times, but because of increasing H_2S interference with depth, apparent zero values could be encountered in depths shallower than the actual zero point. H_2S interference must surely be the explanation for the apparent zero value recorded in surface waters during autumn 1955, judging by the presence of *Artemia* in these waters.

BIOLOGICAL CONDITIONS

Flora

Two conspicuous constituents made up the bottom dwelling flora. *Chara* sp. was abundant in the shallow waters around shore, and beginning at a depth of approximately 1.0 m there was a thick mat of blue-green algae. The mat was made up of four species: *Plectonema nostocorum* Gom., *Oscillatoria chlorina* Gom., *Anacystis thermalis* (Menegh.) Drouet & Dailey, and *Gomphosphaeria aponina* Kuetz. Dr. Francis Drouet commented that these forms are sometimes found in hot springs but are not the common species of such habitats. However, they belong to a limited group of blue-green algae, which not only survive but grow vigorously in a wide range of environmental and physiological conditions. Evidence of this is seen in Hot Lake where the mat extends into the lower regions of the anaerobic monimolimnion, a factor which suggests hydrogen sulfide metabolism.

The presence of a rich population of green sulfur bacteria, possibly *Chlorobium*, was mentioned previously. The population was found in the upper part of the monimolimnion, slightly below 2.0 m. Its influence upon the absorption of light and resultant heating of the surrounding water has been discussed.

Fauna

The zooplankton in 1954 and 1955 consisted predominantly of the brine-shrimp, *Artemia salina* (Linnaeus). The rotifer, *Brachionus angularis* Gosse, was the only other zooplankter of note, but there were also occasional records of the rotifer *Keratella quadrata* (Müller), calanoid and cyclopoid copepods, and an ostracod.

Some features of the seasonal life history of *Artemia* are apparent from investigation of the fluctuations in numbers of eggs floating free in the water, immature forms, and adults (Fig. 6). Events occurring during the winter are not clear because few samples were collected then. Adult and immature forms were found in December of 1954 accompanied by relatively large numbers of free-floating eggs. Just prior to the disappearance of ice on the lake in March a large population of immature stages had developed, but there was little change in the populations of adults and eggs. The peak population of adults which occurred in July was accompanied by the maximum number of eggs. Shortly after this time the adult and egg numbers dropped, but a resurgence of immature forms occurred, probably due to reproduction of adults from the prior maximum. By Oc-

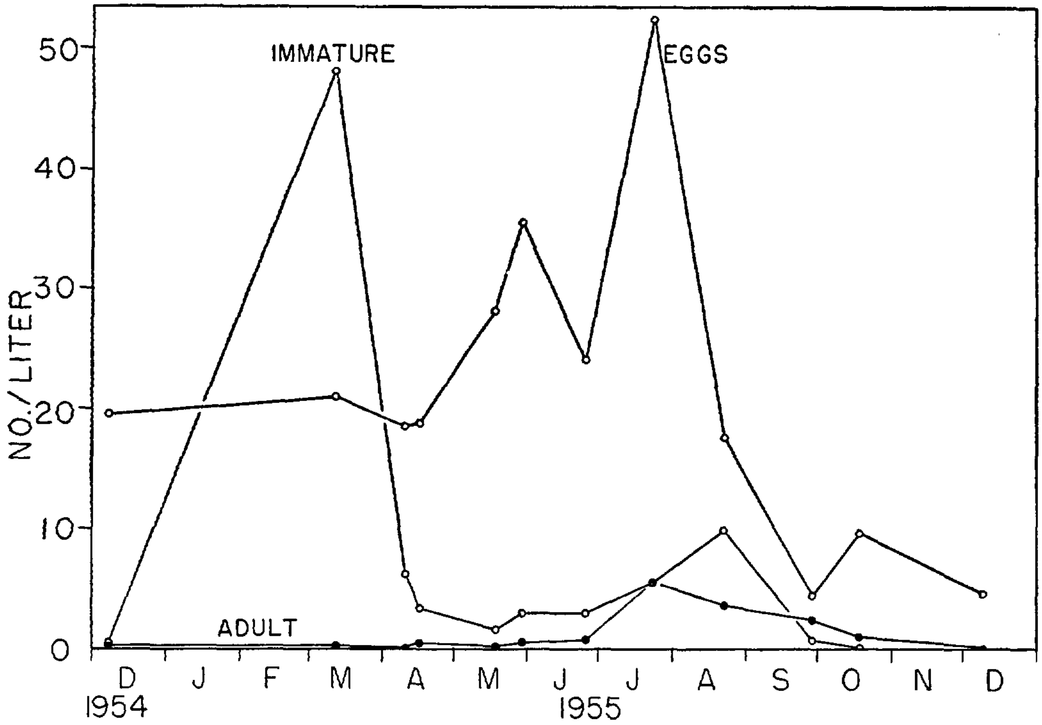

FIG. 6. Seasonal fluctuations of the egg, immature, and adult populations of *Artemia salina* in Hot Lake, December 1954 to December 1955.

tober the total population had dropped to low numbers, and in December only a few free-floating eggs were found.

The large crop of immature stages present in March, 1955, was apparently not successful, because it would be expected that under favorable conditions a large crop of adults soon would have resulted, assuming that the adult stage is long lived relative to the period of immaturity. The lake still had a fairly heavy ice cover at this time, and it may have been that the zone between the upper cold water and the lower warmer anaerobic zone was too restricted for such a large population.

It has been observed at times that *Artemia* shows a preference for certain depths of the lake at different times of the year. In December 1954 and early spring of 1955, it was noted from visual observations that the major portion of the population gathered in the lower reaches of the mixolimnion, presumably due to a temperature preference for the lower warmer waters. As summer progressed the population migrated to the surface waters. Apparently *Artemia* was excluded from the lower part of the mixolimnion after the temperature rose above 30°C. Because of the presence of warm and presumably oxygenated waters in some part of the mixolimnion during the winter of 1954–55, it was possible for reproduction to occur throughout most of the year. Copulating pairs were found on all sampling dates except December 9, 1955. It was reported in the discussion of temperature variation in the lake that the mixolimnion was much reduced in volume by evaporation throughout the latter part of 1955, and that by the time of ice cover in the winter the temperature of the entire mixolimnion had been reduced to slightly below 0°C, thus eliminating chances of survival of the adult population.

In 1956 conditions were different, but due to the infrequency of sampling, seasonal events cannot be described. However, there was one observation worthy of note. Much of the water added to the lake from melting snow remained relatively fresh and supported a large population of an undescribed species of *Branchinecta* (Dr. James E. Lynch, University of Washington, personal communication). *Artemia* inhabited the original upper layer of the lake, immediately beneath the "fresh" zone. The green sulfur bacteria were again found in the upper region of the monimolimnion. Transparency was such that one could readily see each of these regions with its inhabitants. Apparently *Branchinecta* and *Artemia* were confined to different regions by salinity requirements, whereas anaerobic conditions in the bacterial zone excluded the animals but were necessary for the growth of the bacteria.

SUMMARY

1. Seasonal variations of some physical, chemical, and biological features were investigated in Hot Lake, a meromictic saline lake occupying a former epsom salt excavation in north central Washington.

2. Because the lake has neither an inlet nor outlet, evaporation is important, and wide variations in salt concentration of the mixolimnion were common. The mixolimnion was never completely isohaline, and during the spring of 1956 a sufficient amount of melt water was received to establish temporarily a three-layered lake.

3. Thermal stratification was marked. The mixolimnion was thin enough that the monimolimnion was heated directly by the sun and developed a persistent high temperature—in excess of 50°C in July 1955. Much of the heat was retained through the winter, with temperatures higher than 20°C recorded in the bottom at the time of ice melt in spring.

4. The mixolimnion was transparent, the monimolimnion opaque. Maximum transmission of light occurred in the yellow region of the spectrum. Absorption of light at the top of the monimolimnion was great enough that the computed amount of heat the lake could gain at this depth from light absorption alone was 2.92°C/day. An observed value was 2.20°C/day.

5. The major mineral in the lake was epsomite ($MgSO_4 \cdot 7H_2O$). The pH was mostly alkaline, dissolved oxygen was never recorded below a depth of 1.5 m, and large quantities of H_2S were present in the monimolimnion.

6. The flora consisted principally of *Chara* sp. and a bottom mat of blue-green algae. Water at the top of the monimolimnion contained a dense population of green sulfur bacteria. The dominant zooplankter, *Artemia salina*, occurred at most times of the year, presumably due to the retention of heat at intermediate levels during winter. Copulating individuals were found at all sampling dates with the exception of the winter of 1955–56 when the temperature of the entire mixolimnion dropped below 0°C and the population disappeared. After the spring runoff in 1956 *Branchinecta* sp. inhabited the upper "fresh" zone, whereas *Artemia* was confined to lower more saline waters.

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