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An Experiment in the Artificial Circulation of a Small Michigan Lake[1]

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Abstract

The water of the hypolimnion of West Lost Lake, Otsego County, Michigan (T. 32 N., R. 1 W., Sec. 3), was pumped to the surface with a centrifugal pump and discharged into the epilimnion between July 29 and August 8, 1952. The volume of water displaced was 20.7 percent of the lake volume. As pumping progressed there was a steady lowering of the thermocline and decrease in thickness of the hypolimnion. At the conclusion of pumping, the volume of the

epilimnion had increased by 49.9 percent and the water of the hypolimnion had been displaced to the surface. The mean water temperature of the lake remained essentially constant during the experiment. In a three-week period following pumping, thermal conditions of the lake did not change appreciably. During pumping, conductivity and alkalinity increased in the epilimnion and in the bottom water, and the dissolved oxygen of the bottom water increased rapidly. The addition of bottom water increased the total phosphorus of the epilimnion by 2.8 micrograms per liter during the first 48 hours of pumping. Thereafter, phosphorus decreased to approximately the level encountered before pumping. An eightfold to tenfold increase in the volume of phytoplankton of the epilimnion took place during the period of pumping. The volume of phytoplankton and the weight of seston remained high for a three-week period following the experiment.

The experiment demonstrates that it is possible to bring about partial circulation of small trout lakes in midsummer. The procedure appears to be somewhat less effective in stimulating phytoplankton growth than artificial fertilization. However, the method has the advantage of increasing rather than decreasing the available trout habitat during midsummer, and also it offers a method of stimulating plankton production which would not be likely to cause a winter mortality of fish.

Introduction

During the past two decades, the Michigan Department of Conservation has sponsored a research program aimed at providing trout fishing in inland lakes. The results of field surveys have indicated there are a comparatively large number of lakes suitable in temperature and in the amount of dissolved oxygen for trout. Certain of these lakes are small, rather unproductive, stratified lakes ranging in size from 3 to 25 acres. Removal of warm-water fish by chemical treatment and subsequent stocking with trout have made many of these lakes very attractive to sportsmen. Attempts to improve this fish harvest by fertilization have shown that the addition of fertilizer may lead to serious oxygen depletion during the winter months (Ball, 1950) and also may decrease the volume of water suitable for trout by raising the level of the thermocline (Tanner, 1952).

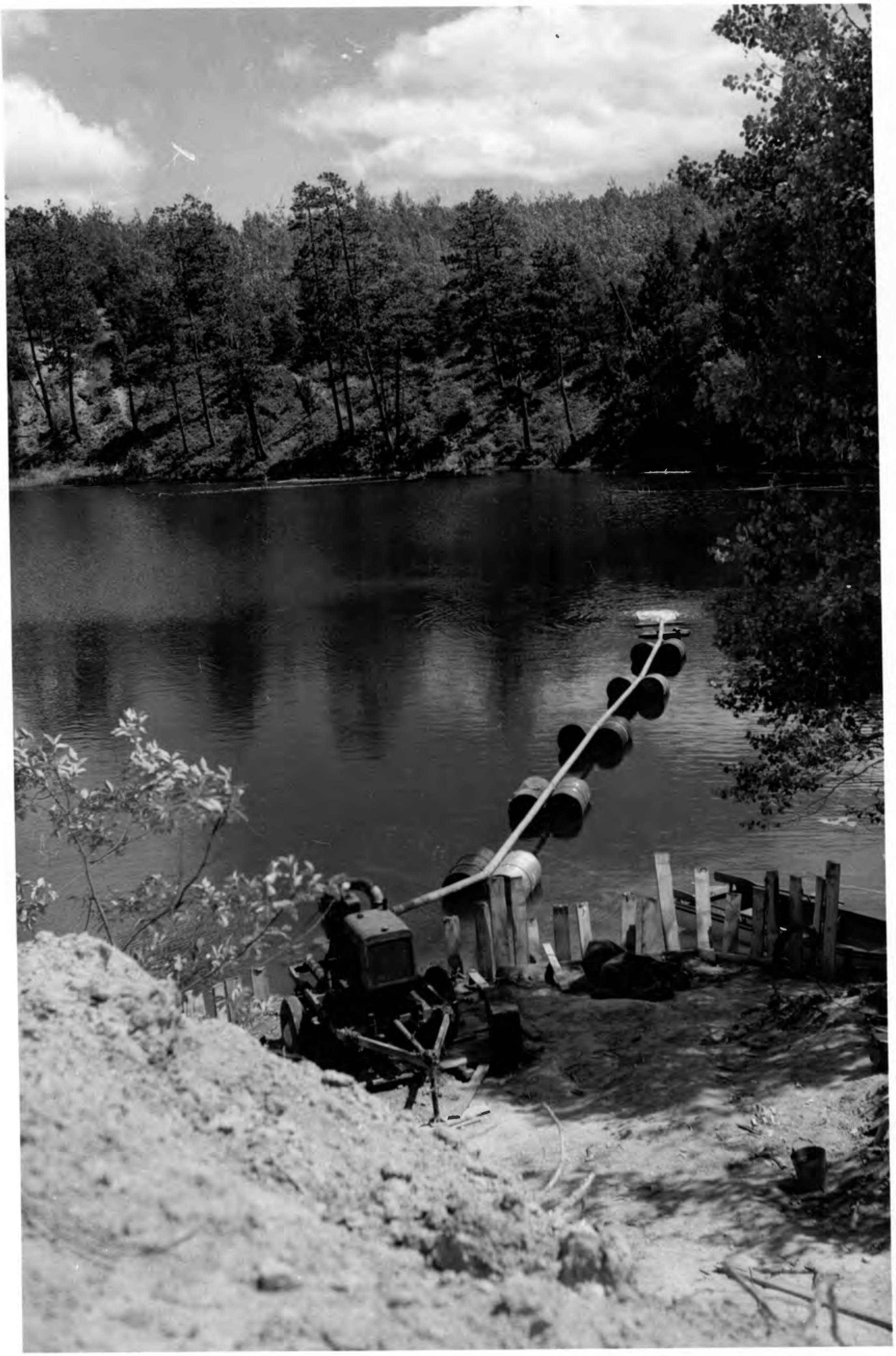
The present study was undertaken to determine: (1) if artificial circulation of the water of such small lakes could be achieved by pumping the bottom water to the surface, and (2) what influence, if any, the addition of the stagnant water of the hypolimnion to the photosynthetic zone in midsummer would have on the production of plankton. Such a procedure appears to have an advantage over fertilization in that it should increase rather than decrease the trout habitat by cooling and deepening the epilimnion. It is also apparent that there should be little risk of winter oxygen depletion since no nutrient material would be added to increase the potential production of the lake; the object being to more efficiently utilize nutrient already present but which under normal conditions is not made available in the photosynthetic zone until late fall.

The influence that vertical mixing of water masses has upon the distribution of nutrients and upon plankton production of the sea has been recognized for many years (Nathansen, 1906). Spring and fall maxima of plankton in the sea are correlated with water movements which enrich the photosynthetic zone with nitrogen and phosphorus (Harvey, 1945). Spring and fall maxima in plankton are also known in fresh-water lakes (Birge and Juday, 1922). The occurrence of such spring and fall maxima in stratified inland lakes has been frequently noted (Welch, 1952; Allee, Emerson, Park, Park and Schmidt, 1949). There are, however, few data indicating that well defined spring and fall maxima occur in small inland lakes. Pennak (1946) could find little evidence in the literature for spring and fall maxima, except in large and relatively deep lakes and rivers. Spring plankton pulses frequently consist of diatoms and may be related more to the quantity of silica available than to the availability of other nutrients (Lund, 1950). Midsummer blooms of the Cyanophyceae are characteristic of many of the small inland lakes (Hutchinson, 1944). Autumnal maxima are reported less frequently. Strøm (1930) suggested that the nutritive salts of the hypolimnion brought into the trophogenic waters at the fall overturn are not used by plankton in lakes at high latitudes because of temperature and light conditions at this season.

Unquestionably a variety of conditions exists in small inland lakes which modifies or destroys seasonal rhythms characteristic of the sea and large inland waters. Yoshimura (1932) found a midsummer plankton maximum in Takasuka Pond, a shallow eutrophic lake, which he believed was sustained in part by nutrients brought into the epilimnion from the hypolimnion by wind action. He also noted a relationship between the quantity of plankton and the inflow of stream water. Unstratified lakes may or may not show fall and spring maxima. It is frequently stated that a large littoral area in which vertical circulation to a major portion of the bottom is possible throughout summer stagnation favors high production (Strom, 1930). Many of the Michigan trout lakes are lakes whose depth is large as compared with surface area. Thus a large percentage of the water volume is below the upper limit of the thermocline. This restricts circulation of nutrients during summer stagnation and creates a condition of morphometric oligotrophy. It is of interest therefore to determine whether or not artificially created water movements during summer will to any degree counteract this inherent morphometric influence.

After the field work of the present study was underway, Grim (1952) published an account of an attempt to circulate the water of a small German lake in midsummer by pumping the warm surface water to the bottom of the hypolimnion. After 180 hours of pumping, the temperature of the bottom water had increased 5°C. During this period, the temperature of the surface water increased from 22°C. to 26°C. as a result of solar heating. Water movements initiated within the hypolimnion by pumping brought about an increase in thickness of the hypolimnion, and produced a sharp temperature gradient within the thermocline, but apparently had little influence upon the water of the epilimnion.

Figure 1.--Pumping equipment in operation at West Lost Lake

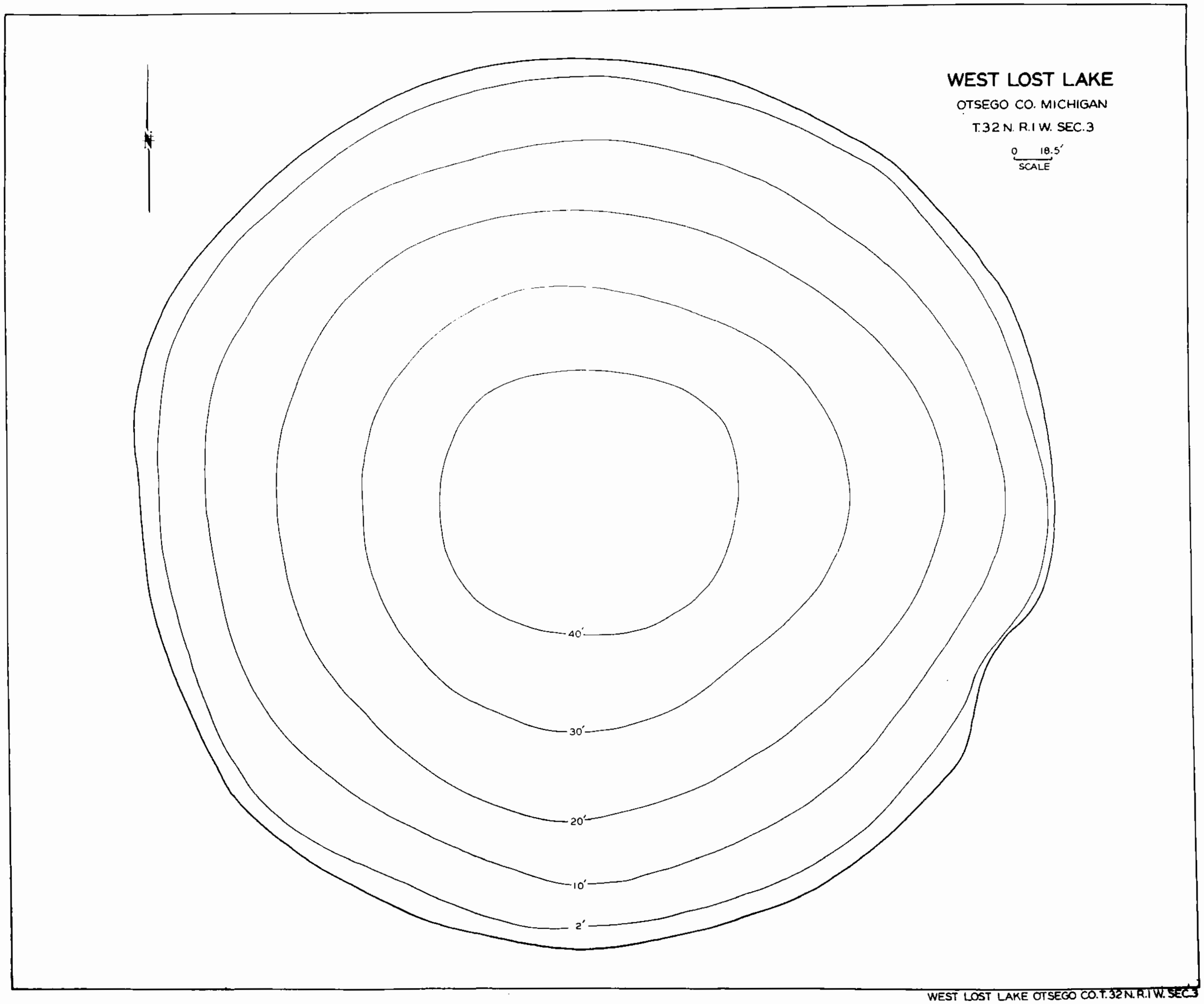


The lake selected for the experiment was West Lost Lake, one of a group of six trout lakes located in Otsego and Cheboygan counties, Michigan. These lakes lie within the Pigeon River Trout Research Area, administered by the Institute for Fisheries Research, and have been used extensively during the past 20 years as experimental lakes for fisheries investigations (cf. Eschmeyer, 1938; Ball, 1950). In 1948, West Lost Lake was poisoned to remove fish. In 1949, it was stocked with trout and fertilized with commercial fertilizer containing 10 percent nitrogen, 6 percent phosphoric acid, and 4 percent potassium. In 1949, 400 pounds of fertilizer were added during the summer, and in 1950 an additional 300 pounds were applied (Tanner, 1952). In the fall of 1950, the lake was again poisoned and the fish removed. At the time of our experiment the lake did not contain fish. However, the plankton and bottom fauna apparently had recovered from the effects of the poisoning in 1950.

West Lost and four of the other Pigeon River lakes lie in basins possessing an unusual degree of radial symmetry. All of the lakes are landlocked. The water surface is approximately 40 feet below the surrounding terrain, and the slope to the water is very abrupt (Figure 1). A recent collapse of a section of shore of one of the lakes (Section 4 Lake) has led to the belief that the lakes are limestone sinks (Tanner, 1952), although the sedimentary rock of the area apparently is covered by several hundred feet of glacial outwash and drift.

The lake has an area of 3.57 acres and a volume of 3,151,130 cubic feet. It has a mean depth of 20.3 feet and a maximum depth

Figure 2.--Hydrographic map of West Lost Lake.



WEST LOST LAKE
OTSEGO CO. MICHIGAN
T.32 N. R.I W. SEC.3

WEST LOST LAKE OTSEGO CO. T.32 N. R.I W. SEC.3

of 42 feet. The shoreline and subsurface contours are almost circular in outline and are spaced very uniformly down the entire slope of the basin (Figure 2). Features of the aquatic vegetation and bottom fauna have been discussed by Tanner (1952). Barrett (1952) discussed the bottom soils of the lake and their relationship to the alkalinity of the water, and the adsorption and regeneration of phosphorus during the fertilization experiment described above.

Methods

The equipment used in the pumping was a self-contained unit consisting of a centrifugal pump with a rated capacity of 25,000 gallons per hour powered by a four-cylinder industrial motor (Figure 1). The unit was mounted on a trailer. The surface of the lake was considerably below the surrounding terrain and the slope to the lake edge very steep. This necessitated the construction of an access ramp from the higher land to the water's edge with a bulldozer. Irrigation pipe, 4 inches in diameter, was used for both intake and discharge pipe. The intake end was first placed near the center of the lake in 36 feet of water. After 24 hours of pumping the pipe was lowered to the bottom of the lake, which at the intake end was 39 feet. No screen was used on the intake end since the lake bottom was free of trash. With the intake in this position, the discharged water showed traces of bottom sediments for about 5 minutes of operation. Thereafter it was equally as clear as the water collected in other parts of the lake at the 39 foot depth. The discharge pipe was suspended on floats constructed of oil drums, and the terminal end emptied into a floating barge. This served to break up the force of the flow and spread out the discharge water in a thin sheet at the lake surface. The discharge was at the south end of the lake, located approximately 60 feet from shore at a point where the water was 14 feet deep.

At the start of pumping on July 29, temperature observations were made in the vicinity of the discharge in an effort to determine the fate of the bottom water at the lake surface. At this time, water leaving the discharge was 51.0°F., and the temperature of the surface water was 75.9°F. With the Foxboro thermometer, it was possible to trace the cold bottom water as a well defined current moving horizontally just below the surface for a distance of from 2 to 5 feet from the discharge barge. At greater distances, the horizontal velocity of the cold current decreased and vertical mixing increased. Lenses of colder water 1 to 2 feet in thickness and 2 to 4 feet below the surface were encountered sporadically around the outflow at a distance of from 6 to 10 feet. Here the temperature varied between 67° and 72°F. At a greater horizontal distance, it became increasingly difficult to detect temperature differences in the water mass, indicating that the outflow was rapidly losing thermal identity. The temperature measurements gave no indication of density currents returning water to the deeper parts of the lake but suggested that the water was mixed rather thoroughly within 4 or 5 feet of the surface.

Pumping was started on July 29 and continued until August 8. The pump was in operation continuously except for shutdowns for refueling and motor maintenance. The total actual running time was 244 hours. The calibrated capacity of the pump was 20,000 gallons per hour. The calculated volume of water pumped is 652,400 cubic feet. Temperature of the water at the discharge was consistently 5°F. higher than the temperatures of the lake at the intake level, indicating that some water was entering the pipe through leaks at the joints above the intake. Efficiency could therefore have been improved slightly be securing better seals at the pipe joints.

Temperatures were taken at 1-foot intervals using 2 Foxboro resistance thermometers. The underwater photometer described by Greenbank (1945) was used to measure light penetration. Subsurface readings were made at 3-foot intervals and a surface reading was usually made after 2 successive subsurface readings. A Klett-Summerson photoelectric colorimeter was used for turbidity measurements and for phosphorus and iron determinations. Conductivity was measured with a portable battery-operated conductivity bridge. Oxygen, CO_2, inorganic and total phosphorus were determined using the methods outlined by Ellis, Westfall and Ellis (1946). To determine the percentage of dissolved organic phosphorus, samples were first filtered through 3 layers of No. 50 Whatman filter paper with a filter pump. All phosphorus determinations were made in duplicate. In most cases duplicates agreed within 1 or 2 scale divisions of the colorimeter. In case of greater discrepancies contamination was suspected and additional determinations were made. Inorganic iron was determined by the Dipyridyl method as outlined in Standard Methods of Water Analysis (American Public Health Association, 1949). Samples for chemical analysis were collected at the surface and at depths of 6, 13, 20, 36, 39 and 41 feet. The 20-foot depth was omitted on July 27 and July 31 but was added thereafter because of the increase in depth of the epilimnion.

Net plankton collections were made with a 10-liter plankton trap. Samples for seston determinations were collected with a Juday bottle. Two 1-gallon samples collected at each depth were centrifuged in a Foerst centrifuge at a flow rate of 1 gallon every 40 minutes. Ash-free dry weight of seston was determined by drying the centrifuged seston at 60°C., weighing on a sensitive balance, ashing in a muffle furnace at 600°C., and reweighing. Plankton counts were made from a modified Sedgwick-Rafter cell which could be used under a 4-mm. microscope objective. Estimates of the mean number of the predominant species within the cell were made using the procedure recommended by Serfling (1949). A 95 percent confidence interval was calculated for each mean. The average volume of colonies of each species was calculated by measuring approximately 50 randomly selected colonies.

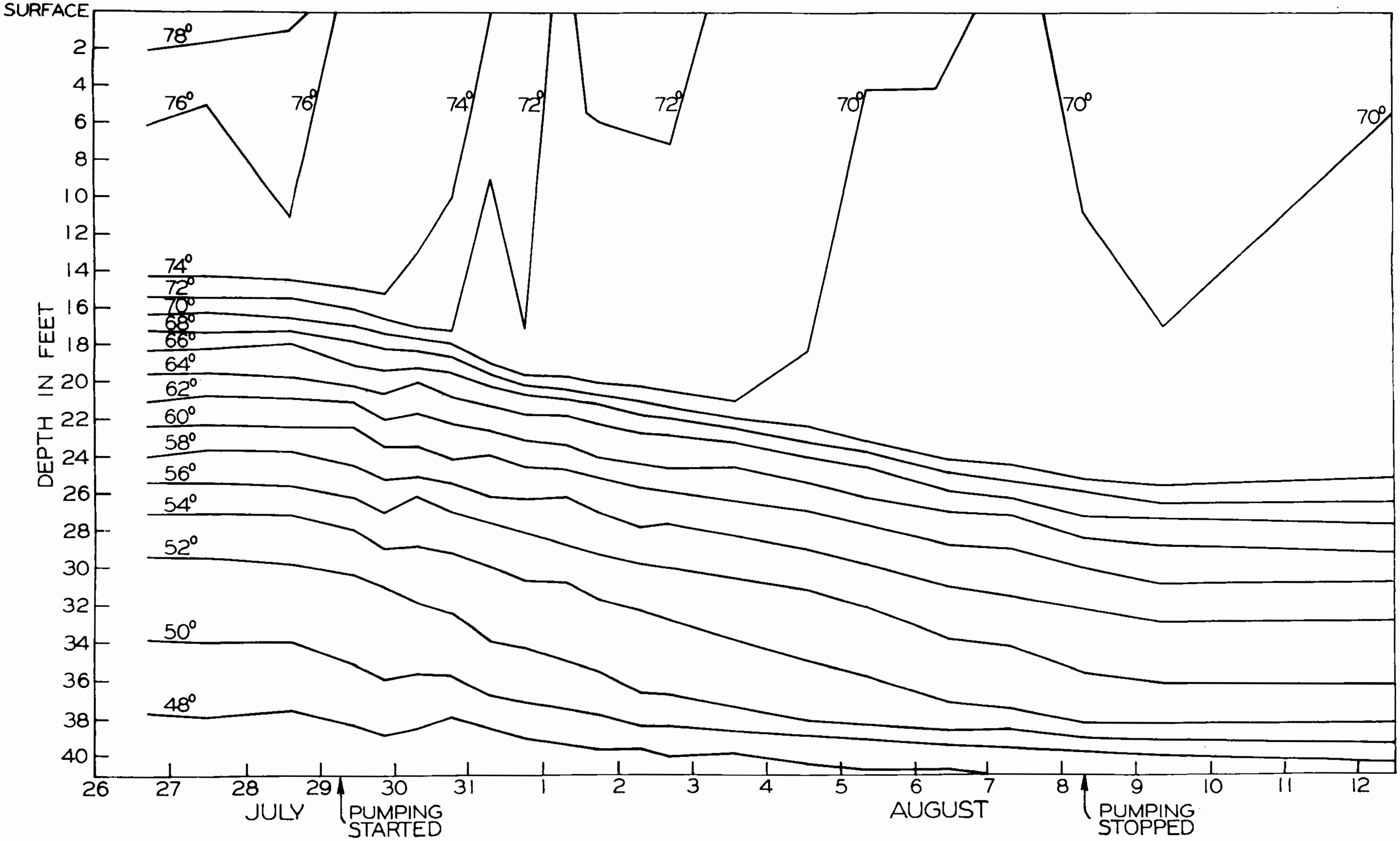
Water Movements

The principal changes in the water masses of the lake as pumping progressed were (1) a steady increase in the depth of the epilimnion, (2) sinking of the thermocline at a nearly constant rate, and, as would be expected, (3) a decrease in the thickness of the hypolimnion as the bottom water was displaced (Figure 3). The upper limit of the thermocline moved from 13 feet to 25 feet. The volume of the epilimnion was thus increased by 49.9 percent. A major portion of this increase apparently was due to the displacement of the bottom water to the surface. This is indicated by the steady downward slope of the isotherms of the thermocline during the period of pumping (Figure 3). The observed increase in volume is 12.0 percent greater than the theoretical increase based upon the volume of bottom water pumped. The additional increase appears to be due to displacement of the thermocline by thermally induced and wind induced water movements. Water movements arising from a combination of the cooling effect of the inflowing bottom water and from convective and radiational cooling of the surface waters brought about a marked increase in depth of the epilimnion on the nights of July 29, 30, and 31 (Figure 3). On these nights air temperatures fell below 40°F. and steam fog developed over the lake surface. Similar thermally induced water movements are apparent during the period from August 3 to August 6.

The upper isotherms of the thermocline were displaced vertically through a frustum of the lake basin whose volume approximates the volume of water pumped from the intake. The 68° isotherm descended through a frustum whose volume is 18 percent of the lake volume. This approximates the volume of water pumped from the bottom (20.7 percent). Isotherms below 65° showed progressively greater negative deviation from this theoretical displacement, suggesting greater vertical mixing. Below the intake (39 feet) there was little change in temperature. At the 40 foot depth there was an increase of 2.0°F. and at 41 feet only 1.2°F. Eddy diffusion initiated by the flow at the intake apparently was responsible for these temperature changes. Sinking of the isotherms to the intake level led to the establishment of a sharp temperature gradient below the intake, thus mixing of this stratum was made more difficult.

The mean temperature of the lake water was 67.9°F. on July 29 and 67.2° on August 8. The small change indicates that pumping had

Figure 3.—Temperature changes in West Lost Lake.


SURFACE
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
DEPTH IN FEET
78°
76°
76°
74°
72°
72°
70°
70°
70°
74°
72°
70°
68°
66°
64°
62°
60°
58°
56°
54°
52°
50°
48°
26
27
28
29
30
31
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3
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5
6
7
8
9
10
11
12
JULY
PUMPING STARTED
AUGUST
PUMPING STOPPED

distributed heat within the lake basin but had not brought about losses or gains in heat. Following pumping essentially the same thermal conditions were retained during the remainder of August. The epilimnion remained approximately isothermal, and the depth of the thermocline was unchanged. Unfortunately no observations were made in September. By October 5 the lake was isothermal to a depth of 35 feet. The temperature at this time was 58.2°F.

Pumping was discontinued after 10 days since it was apparent that all of the bottom water rich in phosphorus above the intake had been displaced. Water entering the intake at this time was similar in chemistry and in temperature to water originally present in the thermocline. Doubling the pumping time would have displaced the volume of water remaining between the upper limit of the thermocline and the intake, but would not have increased the concentration of phosphorus in the photosynthetic zone.

Turbidity and Transparency

Prior to the experiment, the turbidity of water collected between the surface and the 29-foot level was 3 p.p.m. or less. Between 29 feet and 36 feet, turbidity increased from 2 to 12 p.p.m., and between 36 feet and the maximum depth there was a further increase of 2 p.p.m. Suspended detritus gave a pink cast to water samples from 36 feet and below when viewed in direct light. This particulate material could be removed by filtration using a coarse filter, or by centrifugation with a plankton centrifuge. Centrifugation removed 33 p.p.m. of organic matter from water collected at 39 feet. Microscopic examination showed that this material was chiefly plankton detritus of which trichomes of *Oscillatoria* sp. were predominant.

Soon after the start of the pumping a decrease in turbidity occurred below 29 feet as the deeper water containing suspended material was replaced by transparent water of the thermocline. By August 4, turbidity was 3 p.p.m. or less in all parts of the lake except in the stratum below the level of the water intake.

The addition of the turbid bottom water to the epilimnion caused no measurable decrease in transparency. Measurements made with the underwater photometer indicated little change during the period from July 29 to August 3. However, a sharp decrease occurred between August 3 and August 5 (Figure 4). On August 5, a 12 percent decrease in percentage of surface light transmitted to the three-foot level and a decrease of from 10 percent to 15 percent in light transmitted to other levels of the epilimnion was observed. A logarithmic plot of the transparency data of August 3 and August 5 shows that the greatest decreases in transparency were above 12 feet although smaller changes are indicated to a depth of 36 feet. The time and depth of those changes in transparency are correlated with major increases in phytoplankton. The increases in volume of phytoplankton between July 31 and August 5 (Figure 8) were greatest in the upper 13 feet although there was a smaller increase at 29 feet.

Oxygen, Alkalinity and Conductivity

As the bottom water was displaced, the oxygen-rich water of the thermocline moved progressively lower into the lake basin. Isopleths of dissolved oxygen in the lake basin during pumping show a slope comparable to that of the isotherms (Figure 5). However, a somewhat more rapid downward movement of dissolved oxygen is suggested by the

Figure 4.—Depth of penetration of various percentages of surface light.

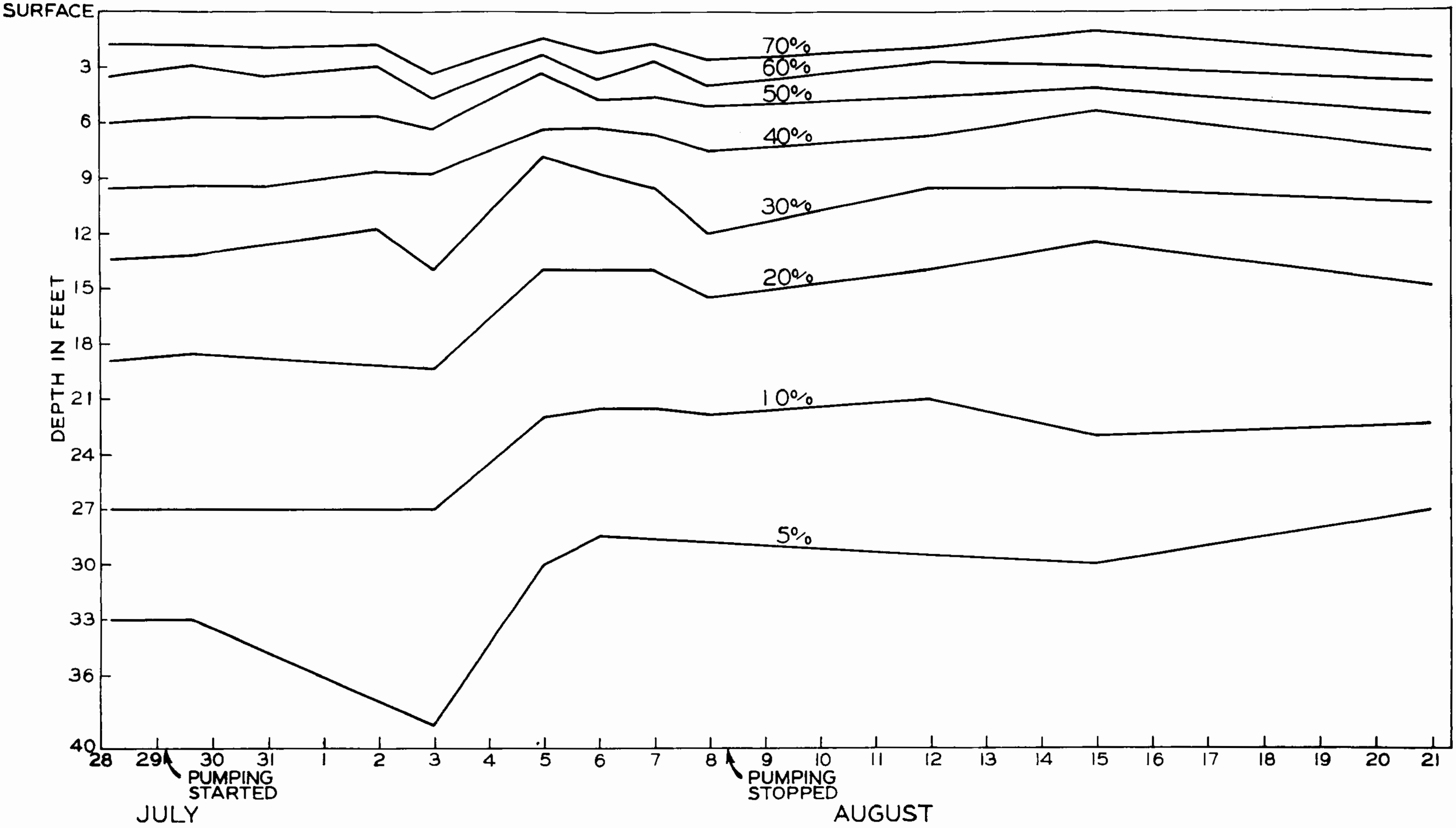
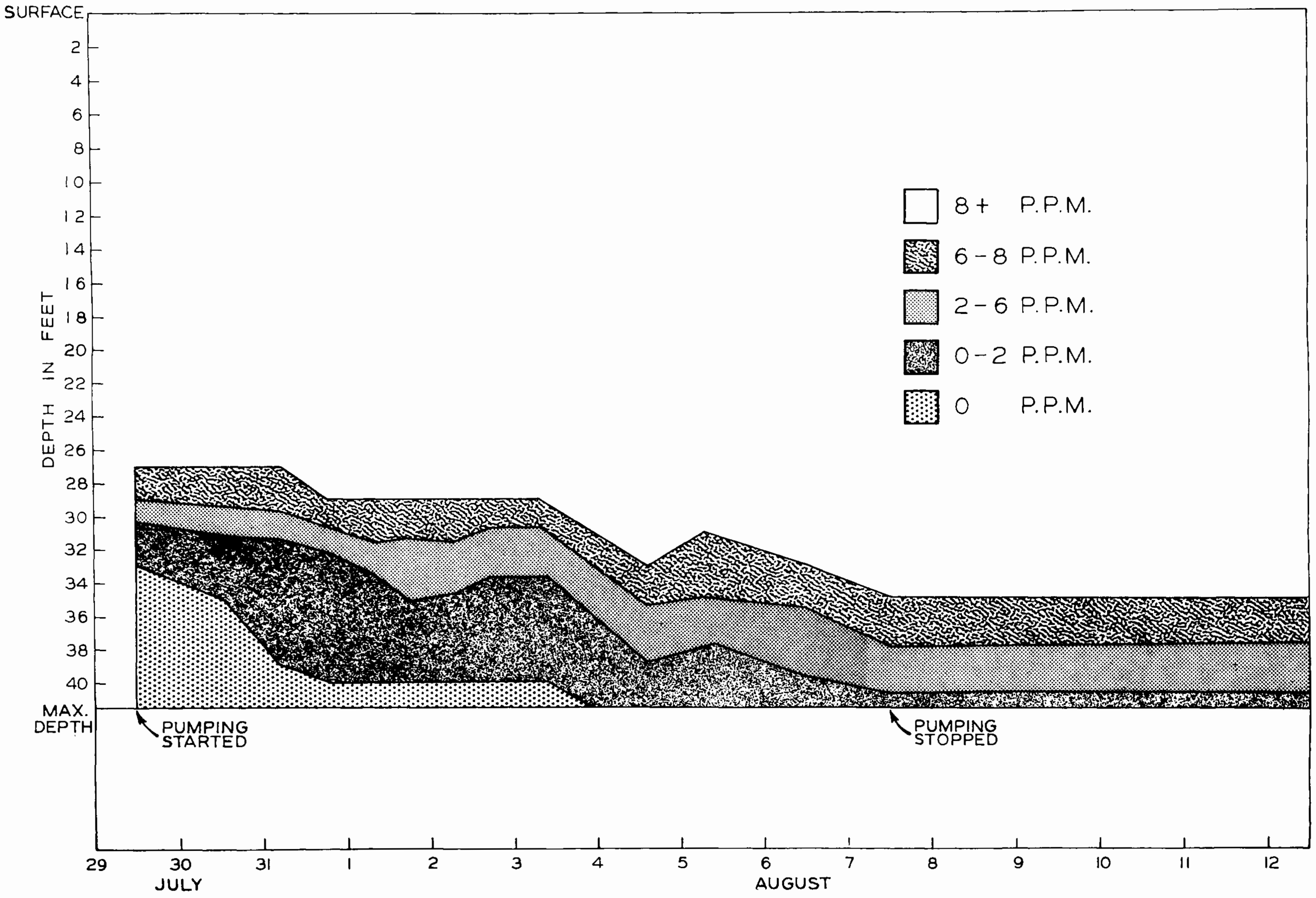

SURFACE
3
6
9
12
15
18
21
24
27
30
33
36
40
DEPTH IN FEET
70%
60%
50%
40%
30%
20%
10%
5%
28
29
30
31
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
PUMPING STARTED
PUMPING STOPPED
JULY
AUGUST

Figure 5.---Changes in dissolved oxygen of West Lost Lake.


SURFACE
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18
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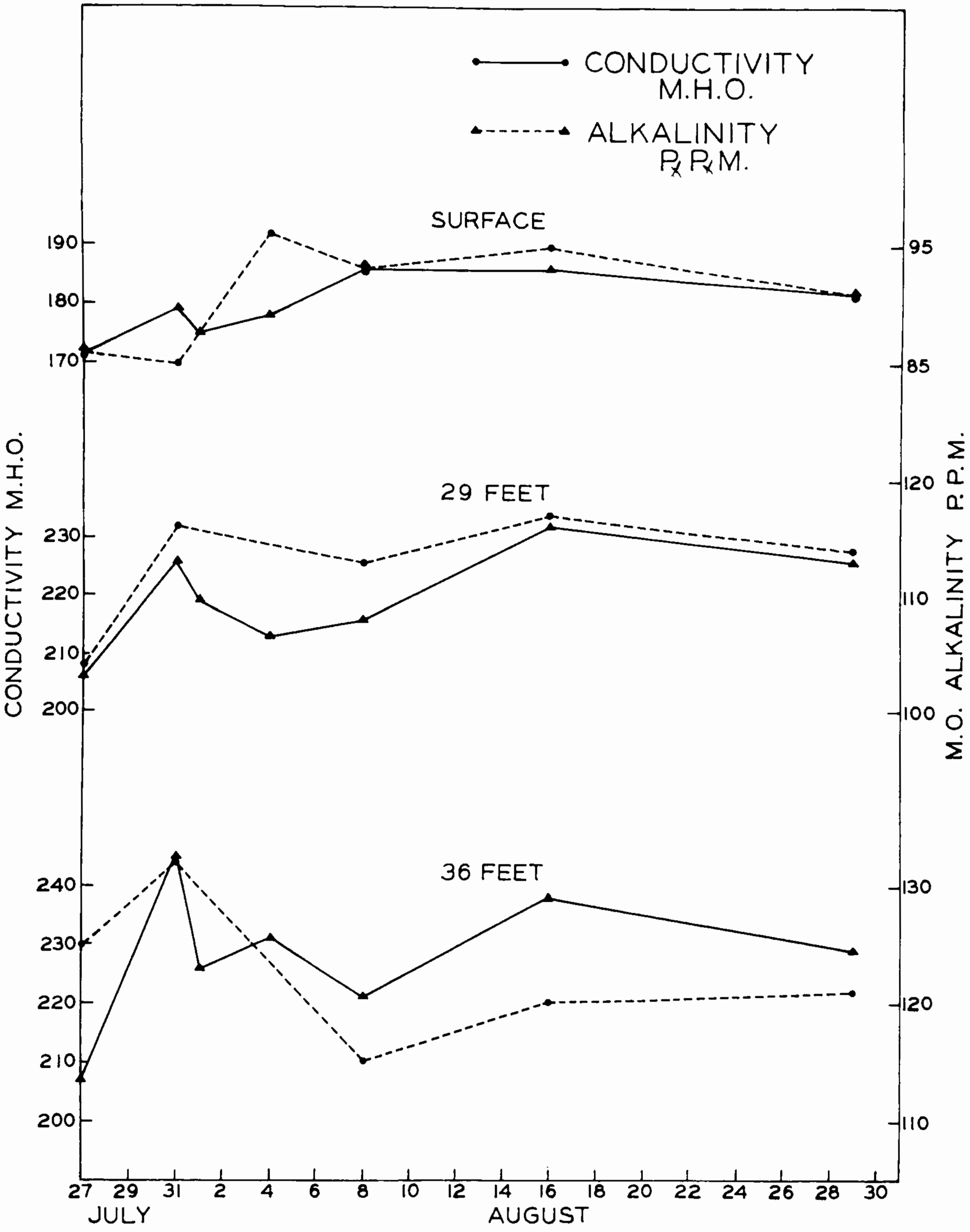
22
24
26
28
30
32
34
36
38
40
MAX. DEPTH
DEPTH IN FEET
8+ P.P.M.
6-8 P.P.M.
2-6 P.P.M.
0-2 P.P.M.
0 P.P.M.
PUMPING STARTED
PUMPING STOPPED
29
30
31
1
2
3
4
5
6
7
8
9
10
11
12
JULY
AUGUST

presence of traces of oxygen at the intake level (39 feet) after only 48 hours of pumping. This is apparently associated with eddy currents arising from the convergent flow at the water intake rather than the sinking of the thermocline water. Traces of oxygen were present at the bottom of the lake (41 feet) after five days of pumping, and the oxygen had increased to 1.8 p.p.m. at the 39 foot level on the fifth day. When pumping was discontinued, oxygen values greater than 5 p.p.m. were to be found in all parts of the lake basin with the exception of the stratum below the intake.

The increases in alkalinity and specific conductivity that appeared at the 29 and 36 foot levels during the first 48 hours of pumping (Figure 6) suggest that a movement of bicarbonate took place from the mud into the water. Alkalinity and conductivity decreased somewhat at 29 and 36 feet furing the remainder of the pumping period as water at these depths was gradually replaced by thermocline water lower in dissolved salts. The inflow into the epilimnion of bottom water of high alkalinity and containing aggressive carbon dioxide led to a gradual increase in the conductivity and alkalinity of the epilimnion. On August 4 alkalinity at the surface and 13 foot depths was 15 p.p.m. greater than observed on July 29. Phenolphthalein alkalinity increased throughout the epilimnion between July 31 and August 4. On August 8 phenolphthalein alkalinity was encountered for the first time at a depth of 29 feet, and there was a further large increase at the surface, 13 feet and 20 feet. This increase in carbonate coincided with increases in phytoplankton in the epilimnion and thermocline.

Figure 6.—Changes in conductivity and alkalinity.


CONDUCTIVITY M.H.O.
ALKALINITY P.P.M.
SURFACE
29 FEET
36 FEET
CONDUCTIVITY M.H.O.
M.O. ALKALINITY P.P.M.
190
180
170
230
220
210
200
240
230
220
210
200
95
85
120
110
100
130
120
110
27
29
31
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4
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12
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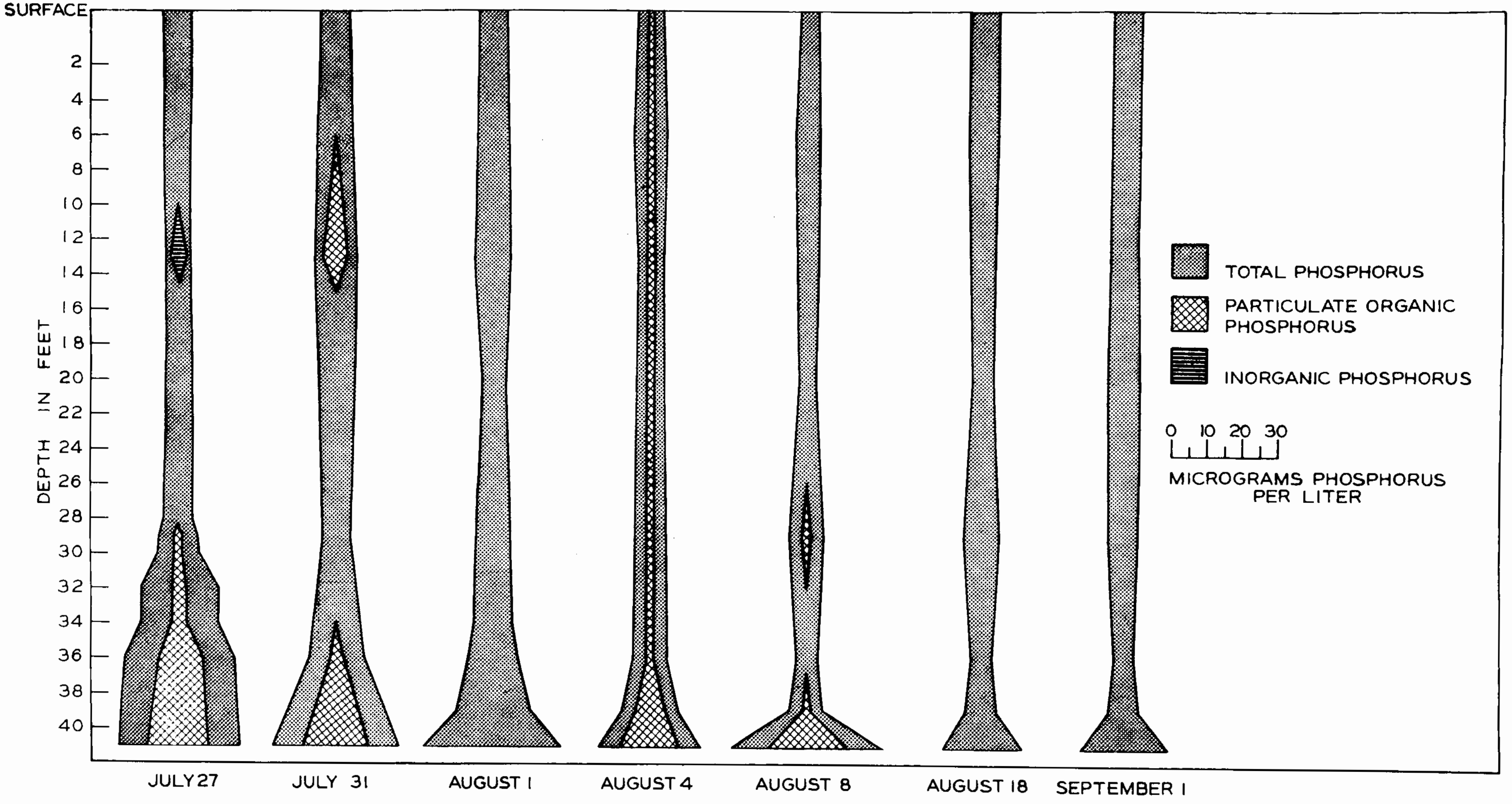
26
28
30
JULY
AUGUST

Phosphorus

The distribution of phosphorus within the lake during the experiment and for a three-week period following the cessation of pumping is shown in Figure 7. On July 27 total phosphorus varied only slightly between the surface and the 29-foot depth. From 29 to 41 feet the total phosphorus concentration increased from 7 to 31 micrograms per liter. Filtration of water samples removed 40 percent of the phosphorus present at 36 feet and 51 percent of that present at 41 feet, indicating that the suspended plankton detritus contributed heavily to the phosphorus content of the bottom waters. The phosphate of the filtered fraction varied only slightly below 36 feet, showing that the increase in total phosphorus below this level was due principally to the phosphorus of suspended detritus.

Approximately 52 percent of the available hypolimnetic phosphorus was transferred to the surface during the first three days of pumping. The first clear indication of increased biological activity appeared after 7 days of pumping. The steady removal of phosphorus from the bottom water by pumping is indicated in Figure 7. On August 4, the concentration of phosphorus at the intake had fallen to 16 micrograms per liter, and 80 percent of the available phosphorus had been removed. By August 8, phosphorus at the intake was not appreciably greater than at several points within the epilimnion. The mean total phosphorus of the epilimnion increased by 2.8 micrograms per liter during the first 48 hours of pumping but thereafter decreased steadily. On August 4, it was approximately equal to the amount present at the start of the experiment, and by August 8 it was slightly below this value (Table I). A theoretical increase

Figure 7.--Vertical distribution of phosphorus. The width of each graph represents total phosphorus. The fraction of particulate organic phosphorus and inorganic phosphorus is indicated by cross-hatching. Analyses for particulate organic phosphorus were not made on August 1, 18, and September 1.


SURFACE
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30
32
34
36
38
40
DEPTH IN FEET
JULY 27
JULY 31
AUGUST 1
AUGUST 4
AUGUST 8
AUGUST 18
SEPTEMBER 1
TOTAL PHOSPHORUS
PARTICULATE ORGANIC PHOSPHORUS
INORGANIC PHOSPHORUS
0 10 20 30
MICROGRAMS PHOSPHORUS PER LITER

Table 1.—Mean total phosphorus of epilimnion water from July 27 until the fall overturn. The phosphorus averages were calculated from samples at two depths on July 27 and July 31, and from four depths on the remaining dates. Averages were weighted for the volume of water of the corresponding strata.

Date	July 27	July 31	August 1	August 4	August 8	August 18	September 1	October 6
Mean total phosporus Micrograms per liter	7.46	10.26	9.48	7.48	6.01	7.42	8.15	7.45

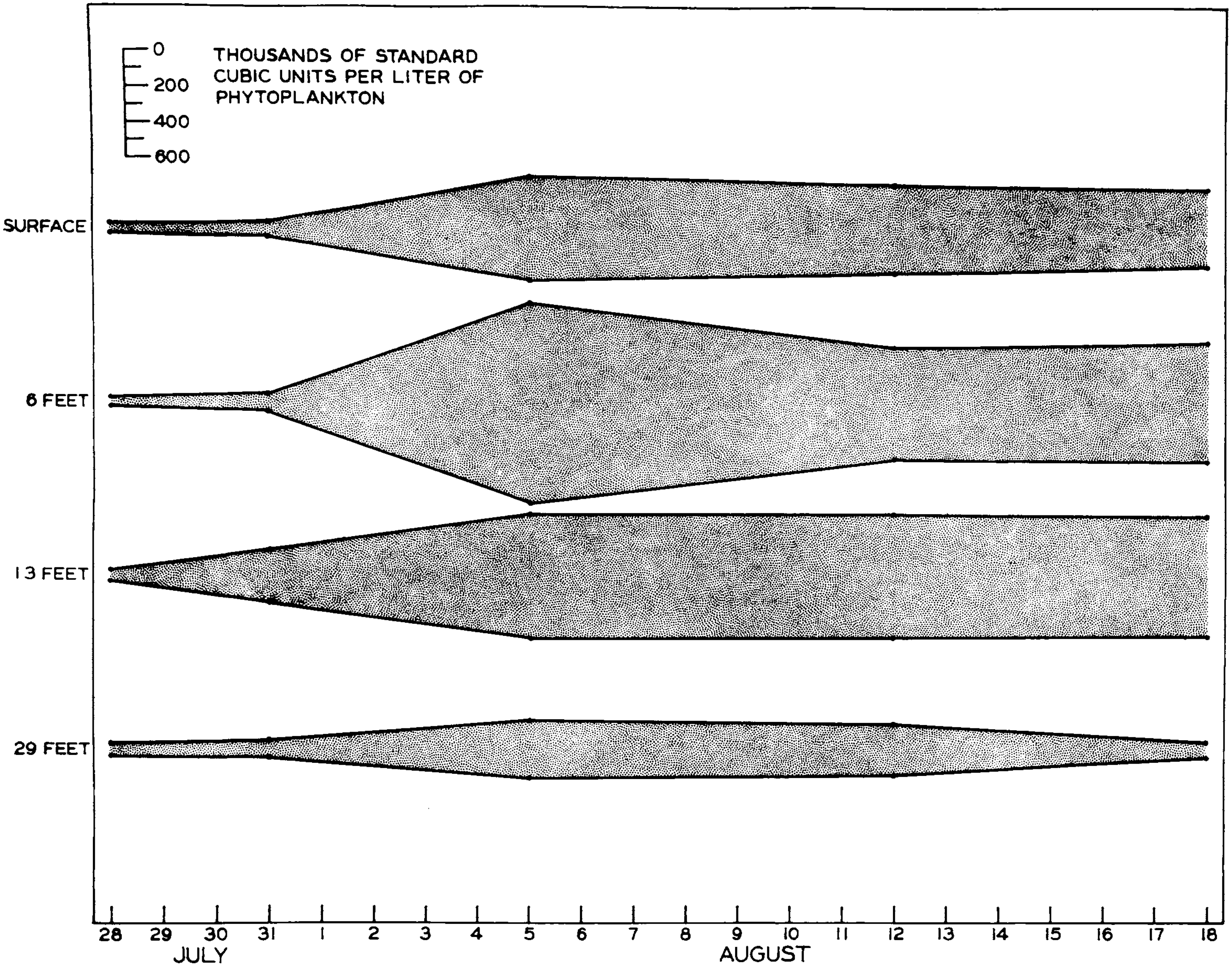
of 3.35 micrograms per liter would be expected on August 8 on the basis of the quantity of hypolimnetic phosphorus added to the epilimnion. Thus it is apparent that a loss of both dissolved and sestonic organic phosphorus took place between July 31 and August 8. Small quantities of particulate organic phosphorus were detected at the 13 foot depth on July 31, throughout the epilimnion and thermocline region on August 4, but only at the 29 foot depth on August 8. In other samples the difference in total phosphorus between filtered and unfiltered samples was so small as to give no reliable indication of sestonic organic phosphorus. The transitory appearance of particulate phosphorus in the water mass suggests that the particulate phosphorus introduced at the surface was rapidly lost by sedimentation and that little if any of the added phosphorus was directly incorporated into the plankton.

Inorganic phosphorus was present in detectable quantities in only one sample collected during the entire course of the investigation. This was at the bottom of the epilimnion (13 feet) on July 27. In all other samples, readings of the colorimeter were never more than one or two scale divisions greater than readings made on distilled water blanks to which chemical reagents had been added. Since the error involved in reading the colorimeter in this portion of the concentration scale approaches this difference between unknown and blanks, little can be said regarding the concentration of inorganic phosphorus except that it never exceeded a concentration of 1 m icrogram per liter. The absence of detectable quantities of either dissolved or sestonic inorganic phosphorus at any depth indicates that little inorganic phosphorus had been regenerated from the mud by reductive processes as noted in Esthwaite Water by Mortimer (1941), and also indicated that little if any inorganic phosphorus was transferred to the epilimnion in the form of ferric or calcium phosphate as occurs in other lakes at time of the fall overturn (Hutchinson, 1941; Einsele, 1936, 1938). None of the iron determinations made on July 27 by the Dipyridyl method were positive for either ferric or ferrous iron indicating that the concentration of inorganic iron was less than 20 micrograms per liter.

Plankton

The phytoplankton of the lake at the time of the experiment was of the cyanophycean type. Over 95 percent of the algae present consisted of colonies of Chroococcus dispersus (Keissl). Sphaerocystis schroeterii (Chodat) was second in abundance but did not make up over 4 or 5 percent of the volume in any sample. Colonies of Coelastrum sp., Nephrocytium sp., Crucigenia rectangularis (A. Braun), Oocystis sp., and Dinobryon divergens (Imhof) were present but not common. There was little change in the species composition of the phytoplankton during the experiment and during the succeeding three week period. The increase in the volume of phytoplankton cells between July 28 and August 5 (Figure 8) is in part due to an increase in the average size of colonies of Chroococcus, but principally to an increase in the number of colonies. At 13 feet the average volume of Chroococcus colonies increased by 50.5 percent between July 28 and August 5. During this period the number of colonies increased from 945 colonies per liter to 10,509 colonies per liter. Between August 5 and August 12 the average colony size decreased slightly, but there was a further increase in the number of colonies to 14,184

Figure 8.--Changes in volume of phytoplankton.


0
200
400
600
THOUSANDS OF STANDARD CUBIC UNITS PER LITER OF PHYTOPLANKTON
SURFACE
6 FEET
13 FEET
29 FEET
28
29
30
31
1
2
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JULY
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per liter. After this initial phase of rapid growth, phytoplankton production remained sufficiently high to sustain a standing crop in the epilimnion 8 to 10 times greater than was present on July 28.

Both plankton and transparency data suggest that the pulse began in the lower part of the epilimnion on July 31 and then spread to the surface water. A fivefold increase in plankton volume occurred between July 28 and 31 at 13 feet. Increases at 6 feet and at the surface were small and were not significant statistically. Small decreases in transparency took place between 9 and 15 feet during this period, although the transparency of the upper part of the epilimnion did not decrease significantly until August 3.

Confidence limits of counts at 6 feet on August 5 do not overlap limits of counts at the surface and 13 feet. This indicates a definite concentration of plankton at the 6-foot depth. On August 12 and 18, however, the 95 percent confidence limits of counts at the surface, 6 feet and 12 feet all overlapped considerably, indicating that the algae were more uniformly distributed.

The increase in the volume of living algae between July 31 and August 5 increased the mean ash-free dry weight of seston of the epilimnion by 31.2 percent. A decrease in the weight of seston occurred at 29 feet, although there was an increase in the volume of phytoplankton cells. This was apparently due to the displacement of detritus-laden water of the hypolimnion by water from the thermocline, low in detritus but containing more living algae. The seston of September 1 again showed a predominance of *Chroococcus*. The average weight of seston had increased substantially over that on August 12 (Table 2). On October 6, the lake was isothermal down

Table 2.--Mean ash-free dry weight of seston of epilimnion. Mean values were calculated from samples at three depths on each date and weighted for volume of water of corresponding strata.

	July 31	August 6	August 12	August 18	September 1	October 6
Mean Seston milligrams per liter	17.6	23.1	22.6	23.2	34.1	24.7

to 35 feet, although the temperature of the water remained high (58.2°F.). The mean weight of seston on this date was approximately the same as between August 6 and August 18. However, the phytoplankton differed qualitatively in that Crucigenia and Sphaerocystis were more abundant than Chroococcus.

An observation of interest recorded during the pumping experiment was an apparent increase in periphyton growth on submerged logs and detritus in shallow water. It was particularly conspicuous on the wooden floor of the barge used at the end of the discharge pipe. Here a bright green carpet of periphyton developed on the detritus from the hypolimnion which had settled to the bottom of the barge. The periphyton growth consisted chiefly of masses of Sphaerocystis, but included Chroococcus, Spirogyra, Lyngbia and numerous diatoms.

Direct comparison of the phytoplankton during this study with that during normal years and during the period of fertilization is not possible. The estimates of phytoplankton made by Tanner (1952) before fertilization in 1948 and after the addition of fertilizer (1949-1950) were made from secchi disk readings. The secchi disk observation of August 12 (four days after pumping) was 15 feet, 8 inches, and is lower than any reading recorded by Tanner in 1948 except in early June. It is well below his average of 23.7 feet for the entire summer of 1948 and compares favorably with his summer average of 13.8 feet for the second summer of fertilization (1950). These limited data suitable for comparison suggest that the transparency level following the plankton increase was less than that to be expected without artificial fertilization, although greater than the average obtained by adding 300 pounds of commercial fertilizer during the summer. It is also noteworthy that in 1948 secchi disk readings increased rapidly during late August and early September. Following pumping in 1952 there was no increase in transparency in late August. This suggests that the stimulus given to phytoplankton production by the pumping sustained phytoplankton growth during the period in which there is normally a decrease in photosynthesis.

The principal Entomostraca of the lake were Daphnia longispina. Small numbers of Ceriodaphnia pulchella, Bosmina longirostris, and Diaptomus oregonensis were recorded. The number of Entomostraca recorded from duplicate 10 liter plankton trap samples was highly variable. It was thus difficult to make comparisons of catches on different dates and at different depths. The data, however, do not indicate an increase in zooplankton comparable to the phytoplankton pulse noted above.

Comparison with Events of Fall Overturn

The experiment simulated qualitatively, although not quantitatively, many of the events taking place in small inland lakes during the autumnal overturn. The water masses of greatest physical and chemical dissimilarity were mixed and water movements were initiated which made possible exchange of electrolytes between the bottom soils of a large part of the lake basin and the superimposed water. Oxygen was introduced into the hypolimnion and the aggressive carbon dioxide, and dissolved and suspended substances of the bottom waters were brought into the photosynthetic zone. Certain environmental conditions, however, were quite different from those normally attending the fall circulation. Temperatures in the upper water remained high and the total quantity of heat in the entire lake remained nearly constant. There was little precipitation and little surface runoff entering the lake during this period. The amount of solar radiation reaching the lake surface was greater and more constant at this season than in the fall. If seasonal climatic changes were largely eliminated from the events of the autumnal overturn, it would then appear that the biological changes observed during the experiment were directly or indirectly related to the mixing of the water masses which occurs during thle normal seasonal overturn. The increase in phytoplankton appears to be a direct response to artificial circulation, since the observed increase in algae does not appear to be characteristic of this or of the other Pigeon River lakes at this season, except immediately after the addition of fertilizer. The observed phytoplankton pulse differs from spring and fall pulses in other lakes (Welch 1952, Birge and Juday 1922), in that it involved chiefly a single species and that there was not a succession of predominant species following the initial pulse. This species (Chroococcus dispersus) was the predominant species before pumping was started. The absence of changes in the ratio of predominant to subordinate forms following the pulse is surprising. Hutchinson (1944) suggests that minor changes in the nutrient level may bring about succession of one species by another, because of slight physiological advantage in competition for nutrient.

Discussion

The transitory increase in total phosphorus of the epilimnion, followed by a rapid return to the level encountered at the start of the experiment suggests that sedimentation and perhaps adsorption by bottom materials and littoral vegetation removed phosphorus from the system until it returned to an equilibrium value. From their study of the rate of decrease of radioactive phosphorus from Bluff Lake, Nova Scotia (Hayes et al, 1952) postulated an active exchange of phosphorus between the water and the participating lake solids (plants and animals, as well as bottom muds) and suggest that the phosphorus added to lakes in fertilization experiments is rapidly lost to the solids until an equilibrium is established. At equilibrium, there is a small net increase which is usually only a small fraction of the initial increase after fertilization. The total phosphorus concentration at this time represents the participating phosphorus of the new equilibrium level. They suggest that the disappearance of phosphorus when stratification is broken up in the autumn may be due to a rapid equilibration of the phosphorus brought into the upper water with the living organisms rather than solely to the precipitation of inorganic phosphorus upon oxidation in the epilimnion as suggested by Einsele, (1938). The rapid return to approximately the initial level in West Lost Lake Suggests that some process of this type tended to stabilize the phosphorus level. Since the initial increase in phosphorus was only 38 percent, the equilibrium value would probably not be sufficiently above the initial level to be detected.

The quantity of phosphorus added to the epilimnion by pumping is small when compared to the quantity used in fertilization experiments. The theoretical addition was 239 grams of phosphorus, which is equivalent to the phosphorus contained in 43 pound of commercial fertilizer containing 6 percent P_2O_5. Since there are few data to indicate that pumping increased except temporarily the total quantity of phosphorus in the epilimnion, it must be supposed either that phosphorus was not a nutrient limiting the growth of Chroococcus, or that the added phosphorus in some way increased the availability of the organic phosphorus in the epilimnion without increasing the total quantity present in the water. The heavy periphyton growth on the bottom of the discharge barge suggests that the detritus and organic matter brought up from the bottom was more susceptible to breakdown and release of nutrient than organic matter originally present in the epilimnion. A slow release of phosphate from the detritus that settled to the bottom in the littoral zone may have sustained an increase in plankton for a considerable period, even though an increase in soluble phosphate in the water was not evident. Lund (1950) cites the work of Mackereth (private communication) who found that Asterionella cells can remove phosphate from water at concentrations below 0.06 micrograms per liter. Very likely Chroococcus can also remove and store inorganic phosphorus at a concentration below that which could be detected chemically. Thus, the data do not negate the possibility that phosphorus was a nutrient utilized in the plankton pulse, although they throw little light upon the mechanism involved.

The experiment demonstrates that artificial circulation of many smaller trout lakes is possible during the summer at least to an extent sufficient to displace the water of the hypolimnion to the surface. Although the production of plankton was not stimulated to the extent achieved during fertilization, the treatment may have increased the carrying capacity of the lake for fish beyond that which could be safely achieved by artificial fertilization. At the conclusion of the experiment, all of the water of the lake above the intake was within the range of temperature and concentration of oxygen suitable for trout. The plankton and bottom food organisms of a major portion of a lake basin were thus made available. The procedure overcomes objections raised to artificial fertilization of natural lakes (Hasler, 1947), such as hastening eutrophication, creating obnoxious odors and increasing weed growth.

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