# LONG-TERM EFFECTS OF LIME APPLICATION TO SOME SOFT-WATER BOG LAKES IN NORTHERN MICHIGAN

Thesis for the Degree of M. S.
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## ABSTRACT

# LONG-TERM EFFECTS OF LIME APPLICATION TO SOME SOFT-WATER BOG LAKES IN NORTHERN MICHIGAN

by Ronald R. Garton

Calcium compounds were applied to Stoner Lake, Michigan in June, 1952, by T. F. Waters at the rate of 26.5 pounds of hydrated lime ($Ca(OH)_2$) and 6.2 pounds of ground limestone ($CaCO_3$) per acre-foot of water. In the summer of 1953 Waters added lime in a slurry to Starvation Lake at the rate of 50 pounds per acre-foot and to Timijon Lake at the rate of 37 pounds per acre-foot. The lime was added with the expectation that it would bring about chemical changes in the lake waters which would result in a higher rate of biological productivity for the lakes. In order to determine the effects of lime addition, Waters conducted a series of chemical and biological tests upon the three limed lakes and three unlimed control lakes both before and after lime application. Significant changes were noted (Waters, 1953, 1956) so the present study was undertaken in 1963 to determine whether the effects noted shortly after lime addition were still evident after a ten-year period. In order to answer this question the original methods of chemical and biological sampling were followed as closely as possible.

Results of chemical and physical determinations indicate that there were no significant changes in either dissolved oxygen concentration, light penetration as measured by Secchi disc, or apparent color. Hardness and alkalinity had declined from immediate post-liming levels but were still significantly higher than before lime was added to the lakes, especially in the deeper areas of the limed lakes. Conductivity and total phosphorus had also decreased from immediate post-liming levels but were still considerably higher than before addition of the lime with concentration increasing toward the bottom of the lakes. The pH of the lakes was higher than before liming, also, but differed from the others in that the greatest changes still evident in 1963 were in the upper part of the lake and the water just off the bottom seemed to be returning to the pre-lime acid conditions at a faster rate. Adsorbed calcium in the bottom deposits of Stoner Lake was about nine times as high as before liming and four to five times as high as it was immediately after lime was added.

Results of biological sampling indicate that there may have been a great increase in concentration of bottom organisms but it was not possible to prove a statistical significance because of the extreme variability between samples. Yellow perch in Stoner Lake showed a faster rate of growth than Waters found before liming but it was not possible to positively tie this in with addition of the lime.

Ronald R. Garton

Information obtained in 1963 does indicate that the initial chemical changes brought about by lime addition to soft-water bog lakes in 1952 and 1953 are still evident after a ten-year period and, in some cases, are quite substantial. Sufficient data are not available to show an increase in biological productivity due to lime application.

# LONG-TERM EFFECTS OF LIME APPLICATION TO SOME SOFT-WATER BOG LAKES IN NORTHERN MICHIGAN

By

Ronald R. Garton

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1967

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I also wish to thank Mr. Eugene H. Buck and my wife, Margo, for their help with the data collection in the field.

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# INTRODUCTION

With the American population expanding at such a rate in both size and mobility there is becoming an ever-increasing demand for outdoor recreation. And, fishing is a very important part of outdoor recreation as measured either in terms of dollars or man-hours spent. In the northern areas of the United States there are many lakes which have but little recreational value because productivity is too low for the lakes to support fish in sufficient size and numbers to provide good fishing. If, by some means, these unproductive bog lakes could be made more productive they would be more widely used for recreational purposes. This would, in turn, decrease the pressure on other lakes which are intensely used at this time.

For hundreds of years various types of fertilizer have been used to increase productivity of the land and, more recently, men have made attempts to fertilize waters in a similar manner. Swingle and Smith (1939) used ammonium fertilizers in the south, and both organic and inorganic fertilizers have been used by other workers with resultant increases in productivity. Moyle (1949) and Ball (1948) have suggested that alkalinity may be used as an index of productivity of a lake, and Moyle reported that 40 parts per million total alkalinity appeared to be the separation point between soft-water, unproductive lakes and hard-water, productive lakes. Since the bog lakes which have been mentioned as being so unproductive commonly have well below 40 parts per million total alkalinity, a possible method of increasing productivity would be to increase the alkalinity.

Probably the easiest way to increase the total alkalinity of lake water is by addition of hydrated lime or limestone directly to the water of the lake. Lime has been used for years in Europe to increase productivity of carp ponds (Neess, 1949). Ball (1947) applied both hydrated lime and limestone to a soft-water bog lake in Michigan with apparently no great effect, supposedly because the addition was too small and some sank into the peat before dissolving. Johnson and Hasler (1954) reported that lime application to Wisconsin bog lakes caused a clearing in color of some of the lakes and an increase in dissolved oxygen, but that no significant increase in production or carrying capacity resulted from the lime application.

The purpose of the present study was to evaluate the long-term effects of the addition of large amounts of hydrated lime to three bog lakes in northern Michigan during the summers of 1953 and 1954. Before addition of the lime by Thomas Waters, "three postulates were made regarding the mechanisms by which biological productivity might be increased by the use of lime, and the sampling program was designed to test these postulates: (1) a greater concentration of bicarbonate alkalinity, offering more available carbon dioxide for photosynthesis, would result; (2) phosphorus would be released either by increased decomposition activities or through ion-exchange phenomena in the mud; and (3) the colloidal organic color would be decreased by flocculation and precipitation caused by combination with calcium" (Waters, 1956, p. 4). Waters tried to define the lakes both chemically and biologically before the lime addition and then again after lime addition to determine what changes were made in the chemistry and biology of the lakes. His study period was too short to determine either the long-range effects of the lime or the effect upon biological productivity.

In 1963 I undertook to duplicate Waters' chemical and biological sampling procedures on the limed lakes and the control lakes to determine what effects of lime application, if any, were still in evidence and to determine the effect of lime addition upon biological productivity.

## DESCRIPTION OF LAKES

Five of the lakes to be studied were selected by Waters in 1953 after a limited survey of small bog lakes in the Hiawatha National Forest. The other lake, Stoner, had been selected previously by the Michigan Institute of Fisheries Research and Ball (1947) for alkalinization and was used by Waters (1953) for his Master's research. Stoner Lake was selected because of its accessiblity and past history of alkalinization; the other five lakes were selected for accessibility and their similarity in size and chemical and biological conditions. Three of the five were colored and the other two were clear-water bog lakes. None have an outlet.

Stoner Lake is surrounded by a forest of hemlock, maple, and birch. Higher aquatic plants were scarce in the lake in 1952 and were even more scarce in 1963 due to lowering of the water level. The primary aquatic plants were *Eleocharis*, *Juncus* and *Scirpus*. A large percentage of the shoreline was overgrown with leatherleaf (*Chamaedaphne calyculata*) and sweet gale (*Myrica gale*).

The five other lakes were completely surrounded by an acid bog mat made up of sphagnum, leatherleaf and many other typical bog plants such as cranberry, *Vaccinium* *macrocarpon* Ait.; bog rosemary, *Andromeda glaucophylla*, Link; bog laurel, *Kalmia polifolia* Wang.; and labrador tea, *Ledum groenlandicum* Oeder. Sedges included cotton grass, *Eriophorum* spp.; *Carex* spp.; and *Rhynchospora alba* (L.) Vohl. Other shore plants present were the pitcher plant, *Sarracenia purpurea* L.; sundew, *Drosera rotundifolia* Wang.; and Waters reported the orchid, swamp pink, *Calopogon pulchellus* (Salisb.) R. Br. but it was not seen in 1963. Higher aquatic plants were scarce in these lakes and consisted of *Nuphar*, *Utricularia*, or *Typha*, either singly or in combination.

The bottom of Stoner Lake was made up of firm sand around almost the entire perimeter. This sand belt extended completely across the central narrow part of the lake and out into the lake on all sides to varying degrees but gave way to brown pulpy peat in the deeper basins at each end of the lake. None of the other five lakes had a beach or sand bottom around the edges. These lakes dropped off very abruptly from the edge with bottoms of brown fibrous peat near the mat and a fine gelatinous pulpy brown peat in the deeper areas.

It should be noted that 1963 data were collected during a general dry period so water levels in the lakes were somewhat lower than when Waters worked on the same lakes in 1953-1955. This was not obvious in the steep-sided bog lakes but was quite evident in Stoner Lake where the bottom had a more gentle slope out from the shore (see Figure 11). In this case, large areas of the shore line were exposed that had been under water when Waters conducted the original experiments.

## Starvation Lake

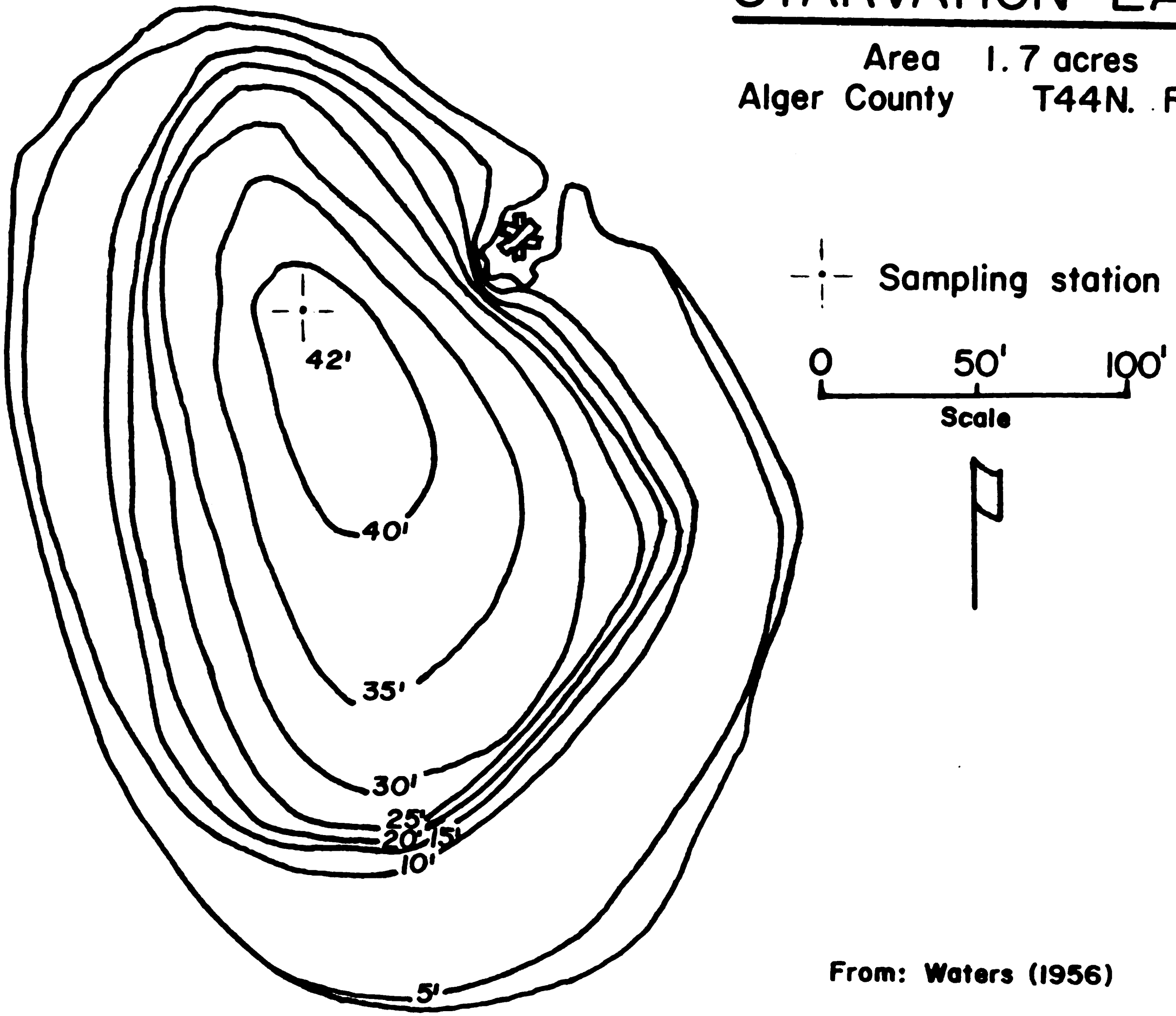
Starvation Lake (Figures 1 and 2) has a surface area of 1.7 acres, a maximum depth of 42 feet, and a volume of 32.6 acre-feet. This is a colored kettle lake in the Newberry moraine surrounded by moderately steep slopes. The entire lake is surrounded by dense forest which is encroaching upon the bog mat. Poplar, pine, and cherry were found on the slopes back from the lake. These gave way to white pine along the landward edges of the mat and some spruce and tamarack were found out on the mat itself. The mat was fairly uniform in width on all but the south side which had a larger bog mat area that apparently drained into the lake. The bottom of the lake sloped steeply on all sides to a low point just north of the center. Waters reported an active beaver lodge on the lake in 1956 but the lodge was no longer occupied in 1963. Waters also reported having made repeated attempts to collect fish by gill nets and angling but with no success. I spent very little effort trying to collect fish but did not catch nor see any and local residents claimed the lake has always been barren of fish.

Figure 1. Starvation Lake - photo taken from north side facing south.

Figure 2. Bottom contour chart of Starvation Lake.

## STARVATION LAKE

Area 1.7 acres
Alger County T44N. R19W. Sec. 1



From: Waters (1956)

## Timijon Lake

Timijon Lake (Figures 3 and 4) has a surface area of 2.0 acres, a maximum depth of 42 feet, and a volume of 43.1 acre-feet. This is a colored pit lake in an outwash plain with gentle slopes on all sides but the west. On this side a dike about 50 feet wide of glacial drift separated the lake from the Big Indian River, a shallow stream about 30 feet wide at this point. It is believed that there is no connection between the river and lake. The slopes around the lake are lightly forested by poplar and birch and some white pine. Spruce and tamarack grow out on the bog mat, in a few instances right up to the water's edge. The mat itself is of moderate, fairly uniform width on all but the southeast side which has an extensive bog mat area. Yellow perch, Perca flavescens (Mitchell), were found to be common in both 1956 and 1963. Waters reported northern brown bullheads, Ameiurus nebulosus nebulosus (LeSueur), in 1956 but none were found in 1963. This may be due to less intensive sampling in 1963.

## Juanita Lake

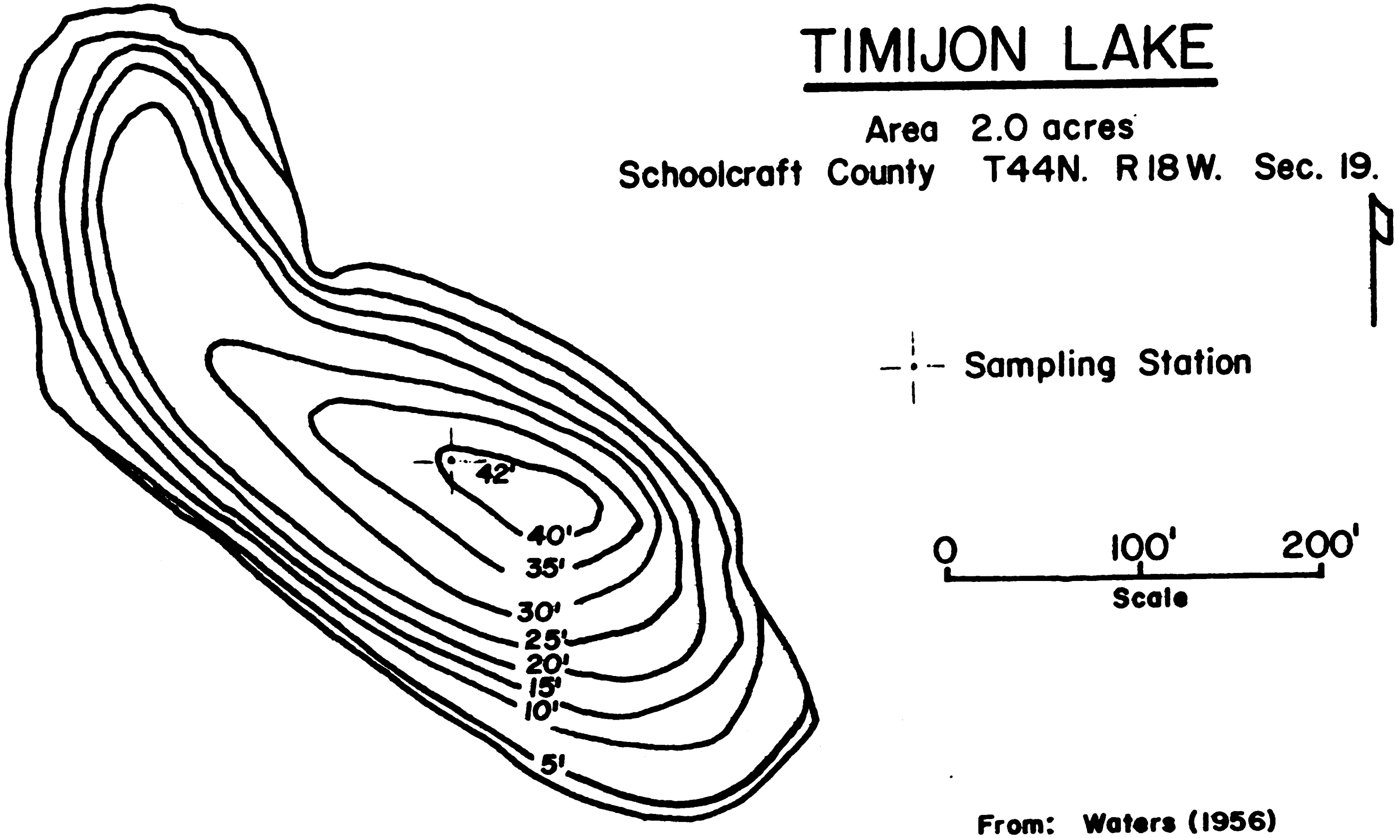
Juanita Lake (Figures 5 and 6) has a surface area of 1.4 acres, a maximum depth of 34 feet, and a volume of 35.1 acre-feet. This is a colored fosse lake with parts of the Newberry moraine on the north and west sides and outwash plain on the rest of the shoreline. Slopes of moraine on

Figure 3. Timijon Lake - photo taken from southern end facing northwest.

Figure 4. Bottom contour chart of Timijon Lake.

# TIMIJON LAKE

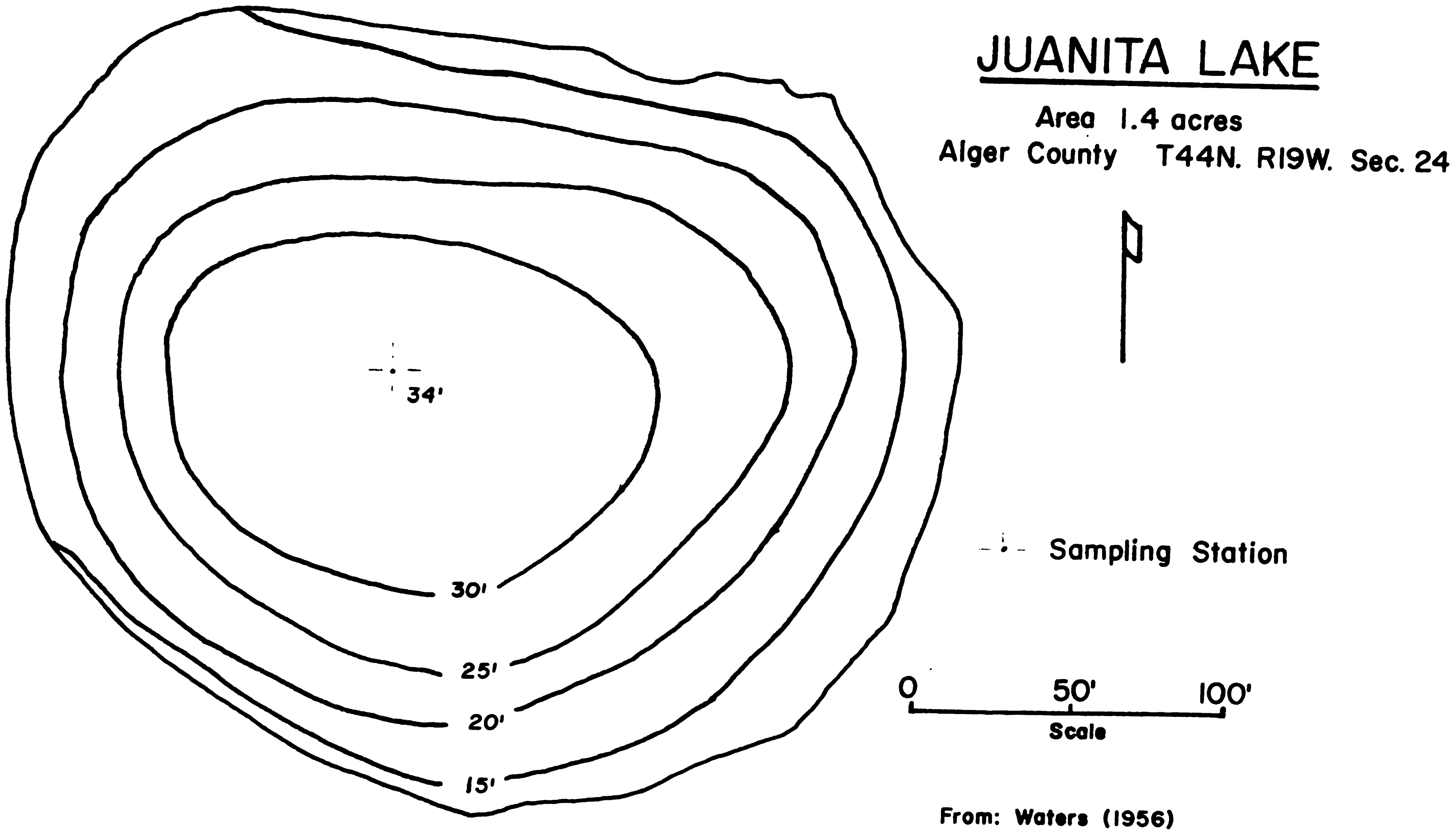
Area 2.0 acres
Schoolcraft County T44N. R18W. Sec. 19.



From: Waters (1956)

Figure 5. Juanita Lake - photo from east side facing west.

Figure 6. Bottom contour chart of Juanita Lake.



From: Waters (1956)

the north and west sides were heavily forested with white pine, birch, and poplar. Forest to the east was thick for about 100 yards. Then, forest was replaced by fields of the Grant farm. An extensive bog mat area was found on the southeast and north sides and Waters noted a small, shallow pond on the north mat but it was not present in 1963. Spruce and tamarack were found on the bog mat, especially on the eastern side where the banks were covered with leatherleaf, *Chaemaedaphne calyculata*. *Utricularia* sp. was very common and thick along the edges of the mat. Yellow perch, *Perca flavescens* (Mitchell), were common in both 1956 and 1963. Residents reported pike and bullheads but none were found by either Waters or myself.

## Irwin Lake

Irwin Lake (Figures 7 and 8) has a surface area of 10 acres and a maximum depth of 38 feet. This is a clearwater fosse lake with Newberry moraine on the east side and outwash plain on the remainder. The surrounding slopes were densely forested, primarily by white pine and birch, on all sides but the west. The west side is forested back a few yards and then forest is replaced by a clearing and road. The bog mat was narrow on all sides with few trees except for some spruce and tamarack, mostly on the eastern edge. The lake had once contained yellow perch, *Perca flavescens* (Mitchell), but was poisoned and restocked with brook trout,

Figure 7. **Irwin Lake - photo taken from north end facing south.**

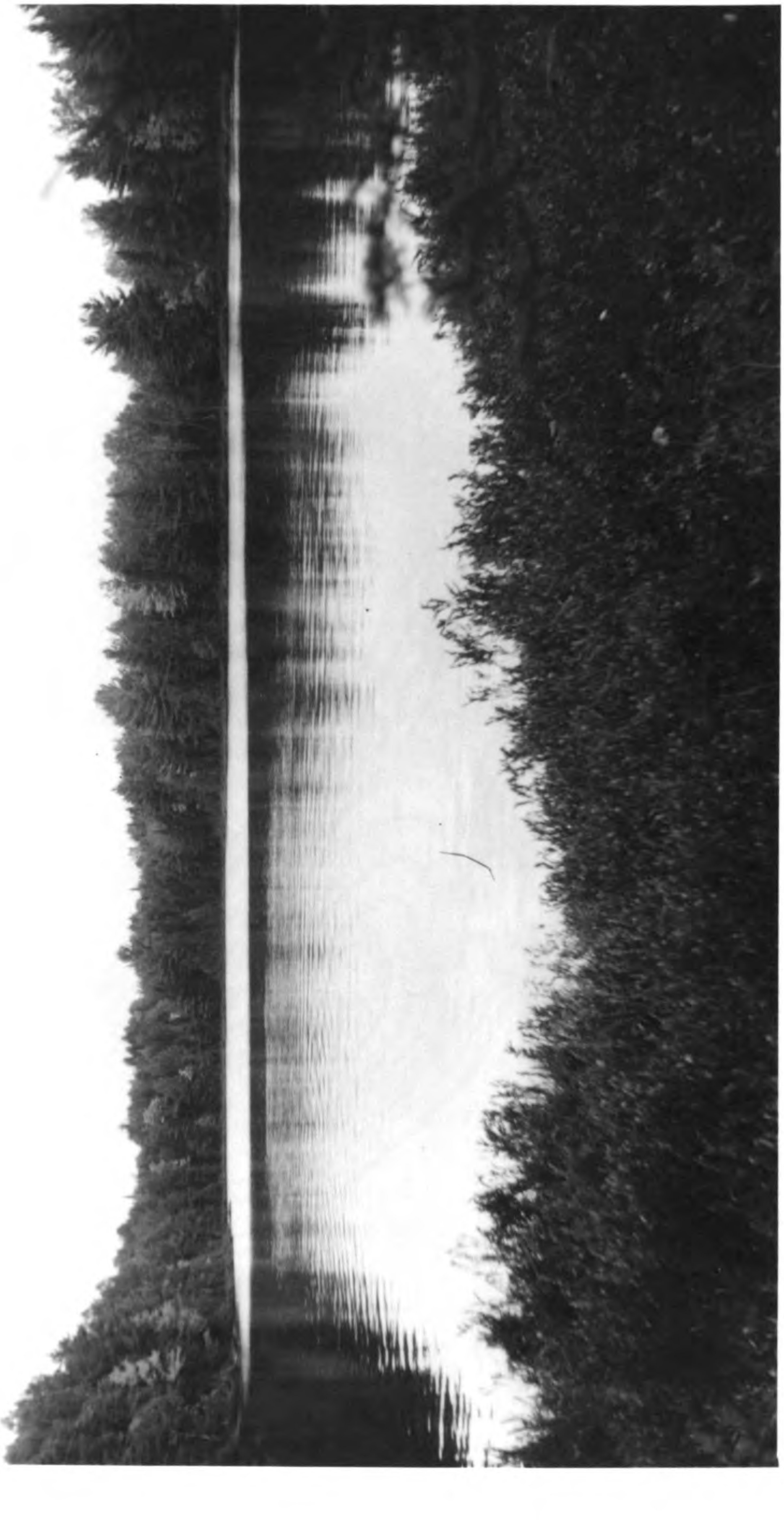
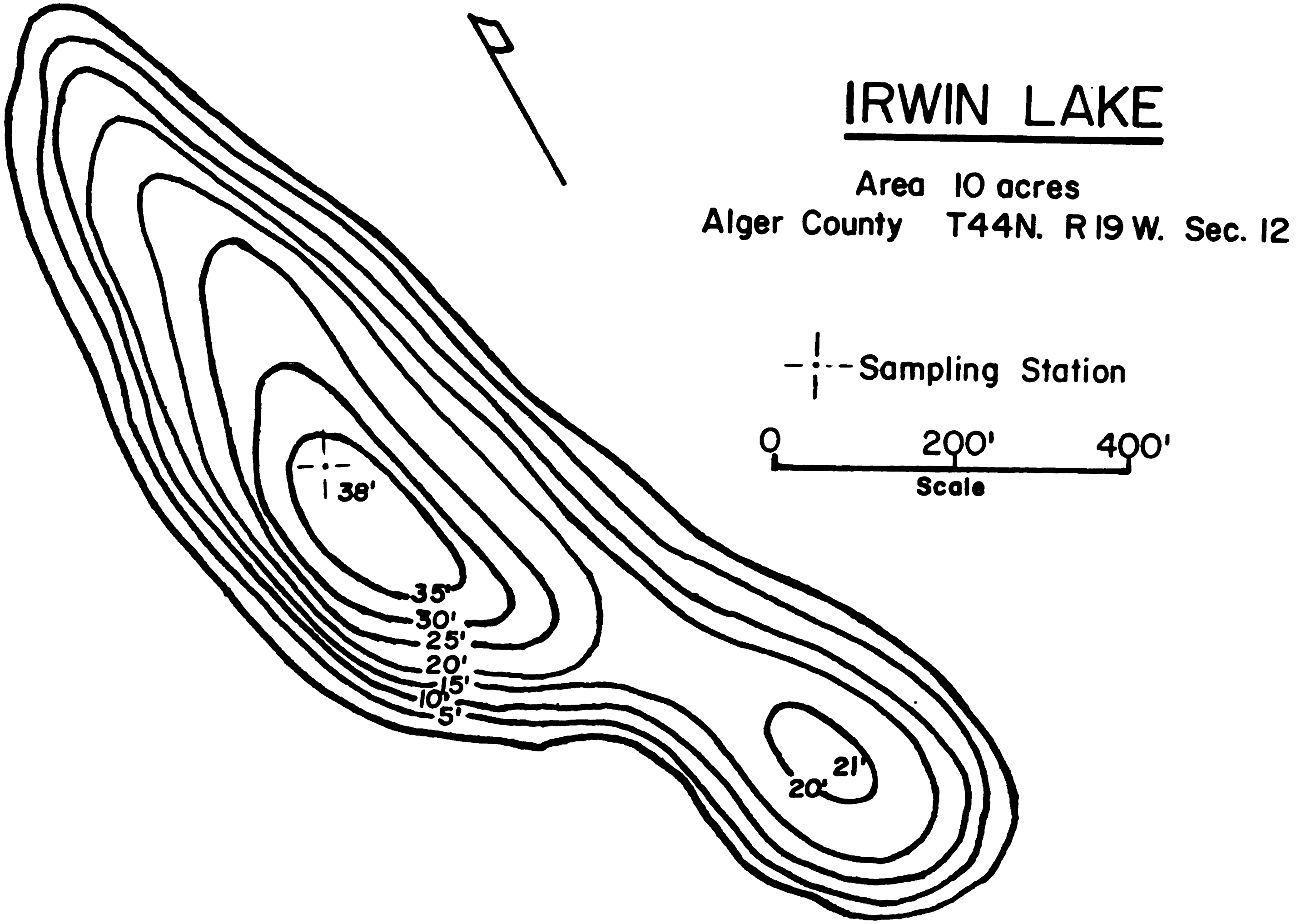


Figure 8. Bottom contour chart of Irwin Lake.



IRWIN LAKE

Area 10 acres
Alger County T44N. R19W. Sec. 12

From: Waters (1956)

*Salvelinus fontinalis fontinalis* (Mitchell), prior to Waters' study. No attempt was made to collect fish here.

## Grant's Lake

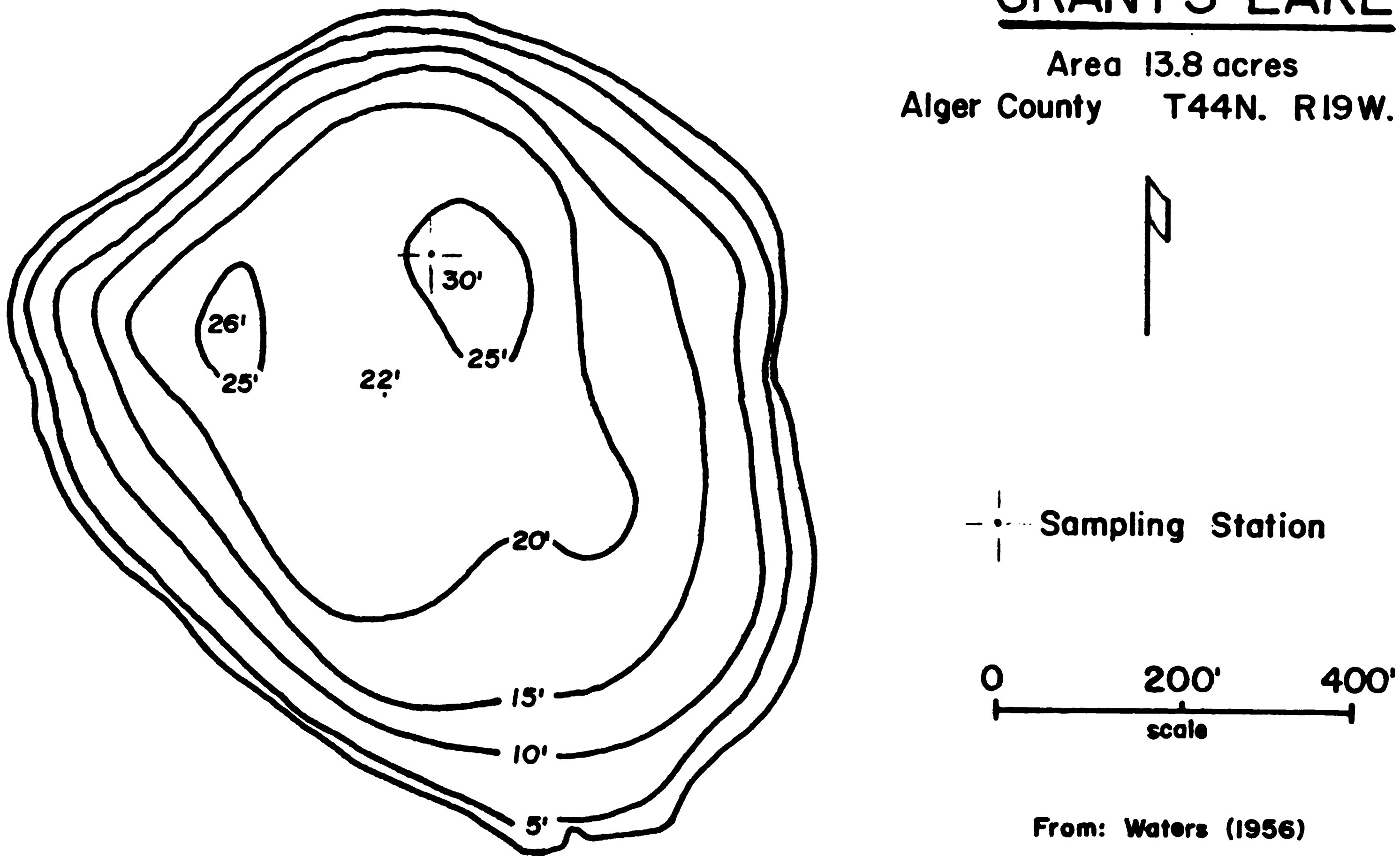
Grant's Lake (Figures 9 and 10) has a surface area of 13.8 acres and a maximum depth of 30 feet. This is a clear-water fosse lake with parts of the Newberry moraine on the north and west sides and outwash plain on the remainder. The surrounding land slopes up quite abruptly to the north but is only moderately sloping to the west and flat to the south and east. The entire area surrounding the lake is moderately forested with birch, poplar, and a few white pine. The bog mat is narrow on all sides and supports only a few spruce and tamarack. *Nuphar* was the predominant aquatic plant and was fairly common along the edges but never really thick. This lake was larger and more shallow than any others except Stoner and did not stratify thermally except in the deepest area in the north central part of the lake. This lake once contained yellow perch, *Perca flavescens* (Mitchell), but they were poisoned and the lake restocked with rainbow trout, *Salmo gairdnerii irideus* Gibbons, and brook trout, *Salvelinus fontinalis fontinalis* (Mitchell). No attempts were made to collect fish here. This lake was called Grant's Lake by Waters and is called the same here but it is also known in the area as Violet Lake.

Figure 9. Grant's Lake - photo taken from north end facing south.

**Figure 10. Bottom contour chart of Grant's Lake.**

## GRANT'S LAKE

Area 13.8 acres
Alger County T44N. R19W. Sec. 24



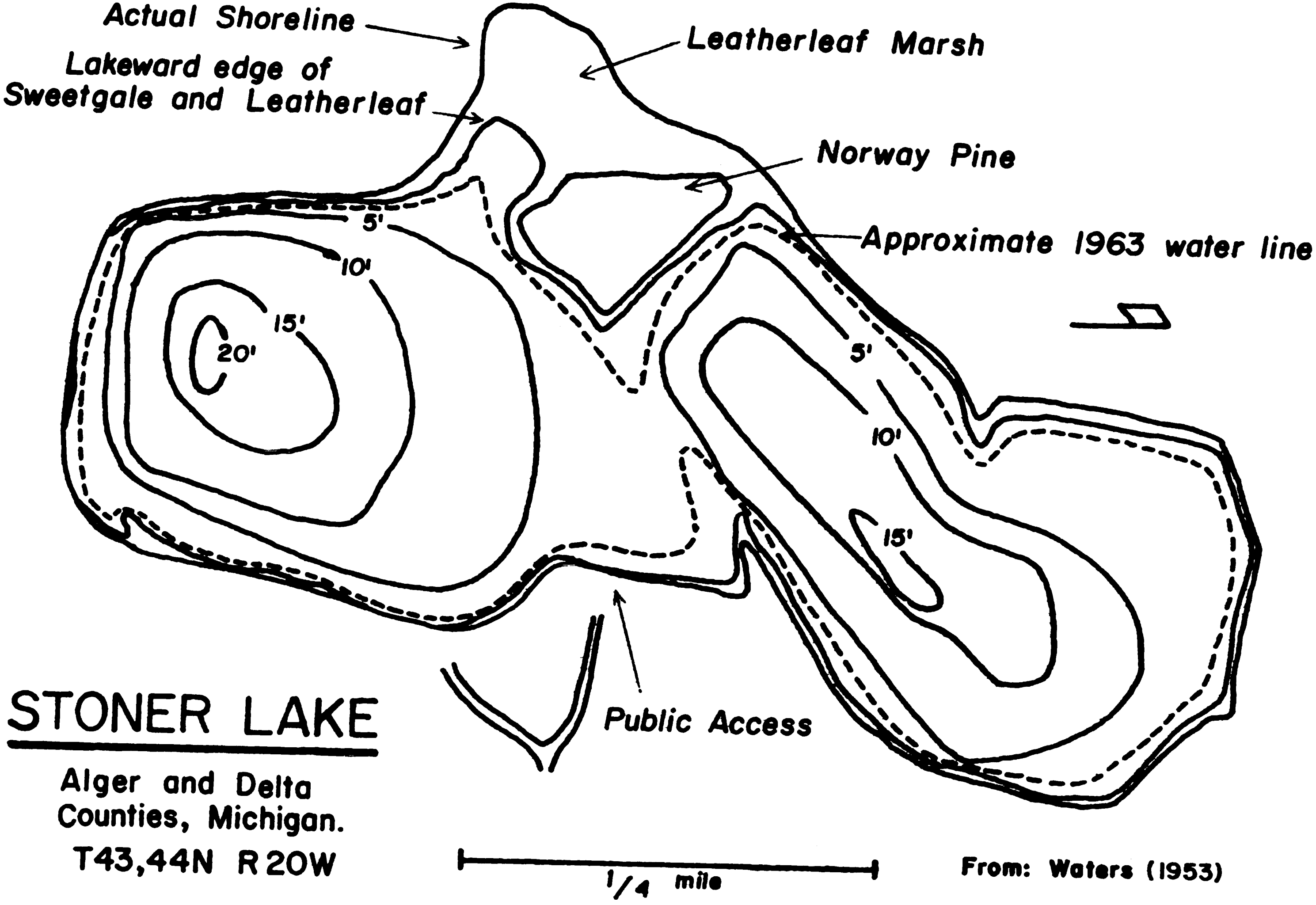
From: Waters (1956)

## Stoner Lake

Stoner Lake (Figures 11, 12 and 13) had a surface area in 1952 of 85 acres with marshes extending the area to about 95 acres. Water level in 1963 was lower than normal so area was probably less than 85 acres at that time. Maximum depth is slightly over 20 feet with an average depth of 6.5 feet. This is a very lightly colored pit lake located in the outwash plain of the Munising moraine. Stoner is essentially a two-basin lake about three-quarters of a mile long and separated in the center by a sand bar which was covered with only about one foot of water in 1963. Unlike the other lakes, the bottom of Stoner Lake does not drop off abruptly but slopes gently to the basins at either end. Out to a depth of about ten feet this bottom is made up of firm sand but this then grades into brown pulpy peat. The surrounding area is forested with hemlock, maple, and birch and nearly the entire shore is lined with leatherleaf, _Chamaedaphne calyculata_, and sweet gale, _Myrica gale_. Some emergent plants were reported and sampled by Waters but these plants, _Eleocharis_, _Juncus_ and _Scirpus_, were above the high-water mark in 1963. Waters reported a fish population made up of yellow perch, _Perca flavescens_ (Mitchell), common white suckers, _Catostomus commersonnii commersonnii_ (Lacepede), and bluegills, _Lepomis macrochirus macrochirus_ Rafinesque, with the yellow perch in such numbers as to show evidence of stunting. Angling and seining in 1963 yielded yellow perch

Figure 11. Stoner Lake - photo of east shore of Stoner Lake facing north. Photo taken in 1963. During Waters' studies in 1953 the sand bar running out into the lake was under water.

Figure 12. Bottom contours and shoreline of Stoner Lake.

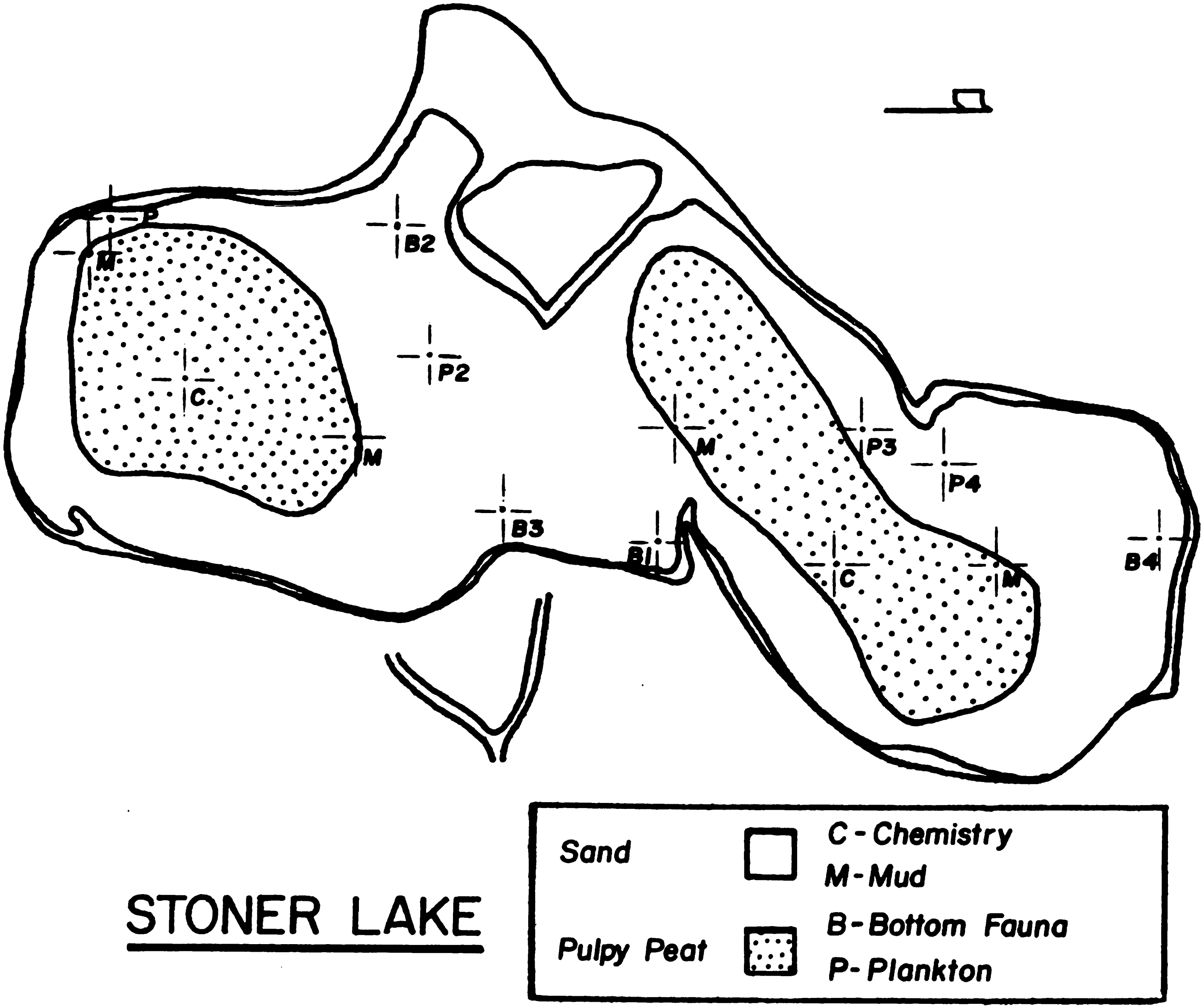


STONER LAKE

Alger and Delta
Counties, Michigan.
T43,44N R20W

From: Waters (1953)

Figure 13. Sampling stations and bottom types of Stoner Lake.



STONER LAKE

Adapted From: Waters (1953)

(all under five inches long), a few small bluegills, and northern pike, Esox lucius Linnaeus, up to 28 inches long. The pike have been planted within the last few years on a voluntary basis by the residents of the area and recent catches up to 39 inches long were reported. The number of pike planted is unknown.

## METHODS

In all phases of sampling the techniques and methods used by Waters were followed as closely as possible to avoid the introduction of bias caused by use of different methods. In order to get a more complete evaluation of the lakes two complete series of samples were taken, one series the last week of July and first week in August when the lakes were stratified as to temperature, and one series at the end of September after some, but not all, of the lakes had undergone the fall overturn.

### Chemical and Physical

Chemical sampling was conducted at the deepest part of each lake; this was generally at or quite near the center as is illustrated on the charts of the lakes. Since Stoner is a two-basin lake, one sampling spot was picked at the deepest part of each basin. At the beginning of each sampling run temperatures were taken at one foot intervals below the surface with an electric resistance thermometer and the temperature profile plotted. Water samples were then taken by Kemmerer water sampler at the following levels: (1) central epilimnion, always taken at three feet; (2) top of thermocline which was established at sampling time; (3)

center hypolimnion; and (4) bottom waters, one foot above the mud surface. In cases where the center of the hypolimnion and the bottom waters were too close together to be sure of different samples, the two were combined into one sample, which was taken one foot above the bottom. See Figures 14-19 for temperature profiles and sampling depths.

At the time of the second sampling period in 1963 Stoner and Grant's Lakes had completed the fall overturn and were of nearly uniform temperature from top to bottom. The other lakes were much cooler in the epilimnion than they were during the first sampling period in 1963 but they were still stratified. The two lakes in which mixing occurred were less protected from the wind than the others and were the shallowest of the lakes tested.

As water samples were collected from each of the levels described above, they were analyzed immediately for dissolved oxygen by the rapid Winkler method (Ellis, Westfall, and Ellis, 1948) with the Alsterberg (sodium azide) modification ("Standard Methods for the Examination of Water, Sewage, and Industrial Wastes," American Public Health Association, 1955). The pH was determined by the use of a Beckman portable pH meter and alkalinity was determined according to "Standard Methods" with the pH meter used to determine the end point of titration. Color was determined by use of the Taylor Color Comparator and light penetration was measured by means of the Secchi disc. A conductivity bridge

Figure 14. Sampling depth as related to water temperature - Starvation Lake.

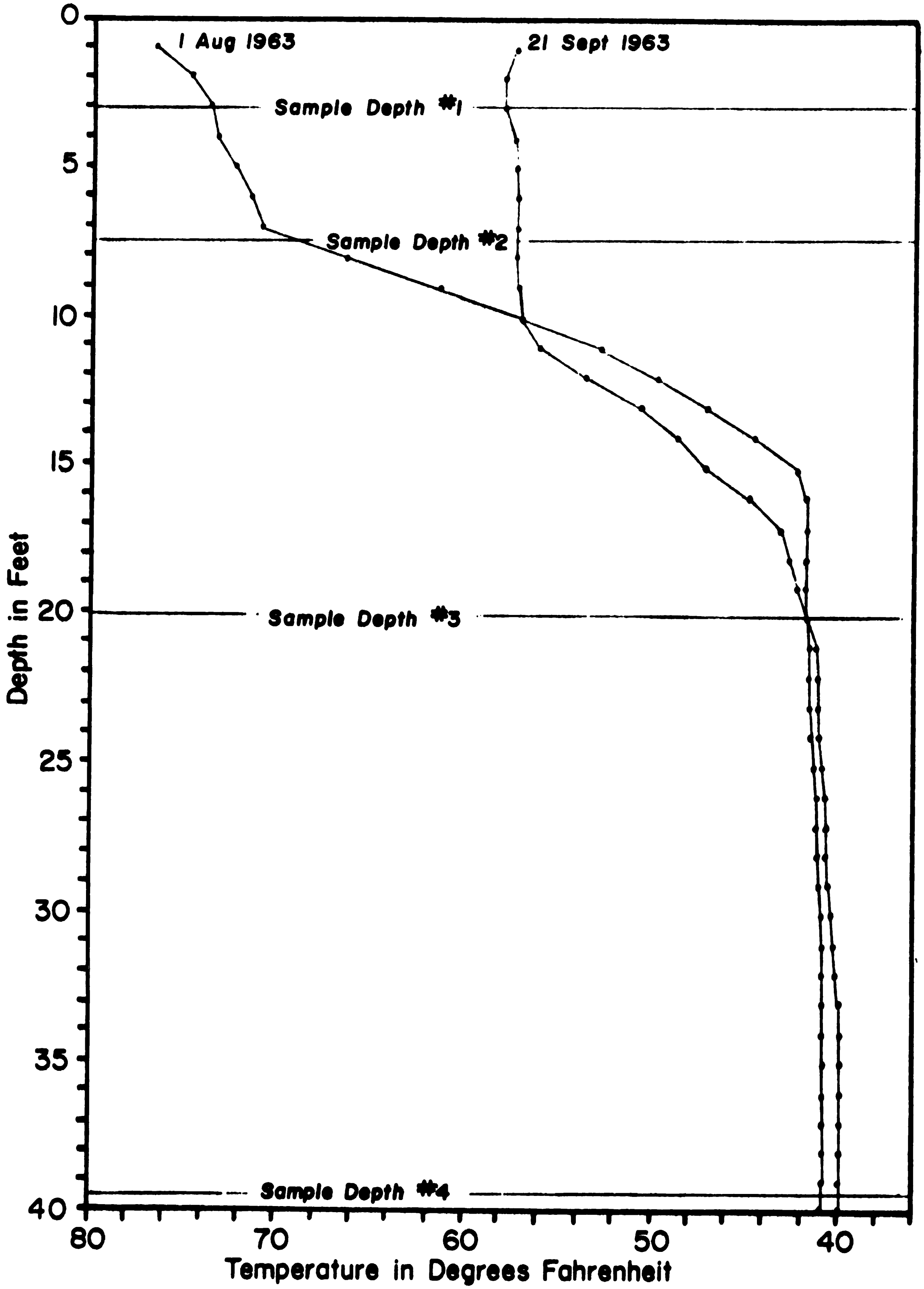

1 Aug 1963
21 Sept 1963
Sample Depth #1
Sample Depth #2
Sample Depth #3
Sample Depth #4
Depth in Feet
0
5
10
15
20
25
30
35
40
80
70
60
50
40
Temperature in Degrees Fahrenheit

Figure 15. Sampling depth as related to water temperature - Timijon Lake.

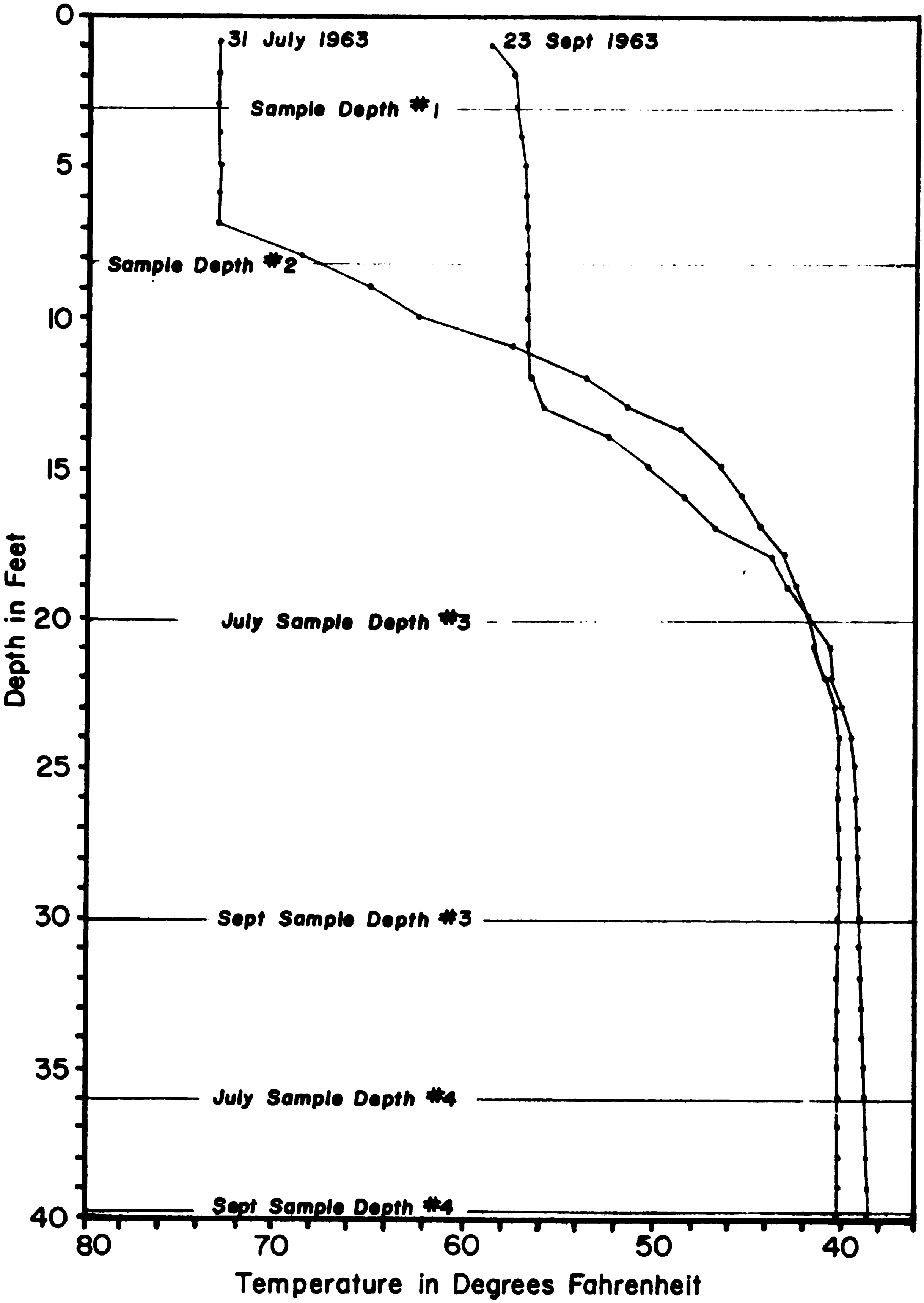

31 July 1963
23 Sept 1963
Sample Depth #1
Sample Depth #2
July Sample Depth #3
Sept Sample Depth #3
July Sample Depth #4
Sept Sample Depth #4
Depth in Feet
0
5
10
15
20
25
30
35
40
80
70
60
50
40
Temperature in Degrees Fahrenheit

Figure 16. Sampling depth as related to water temperature - Stoner Lake.

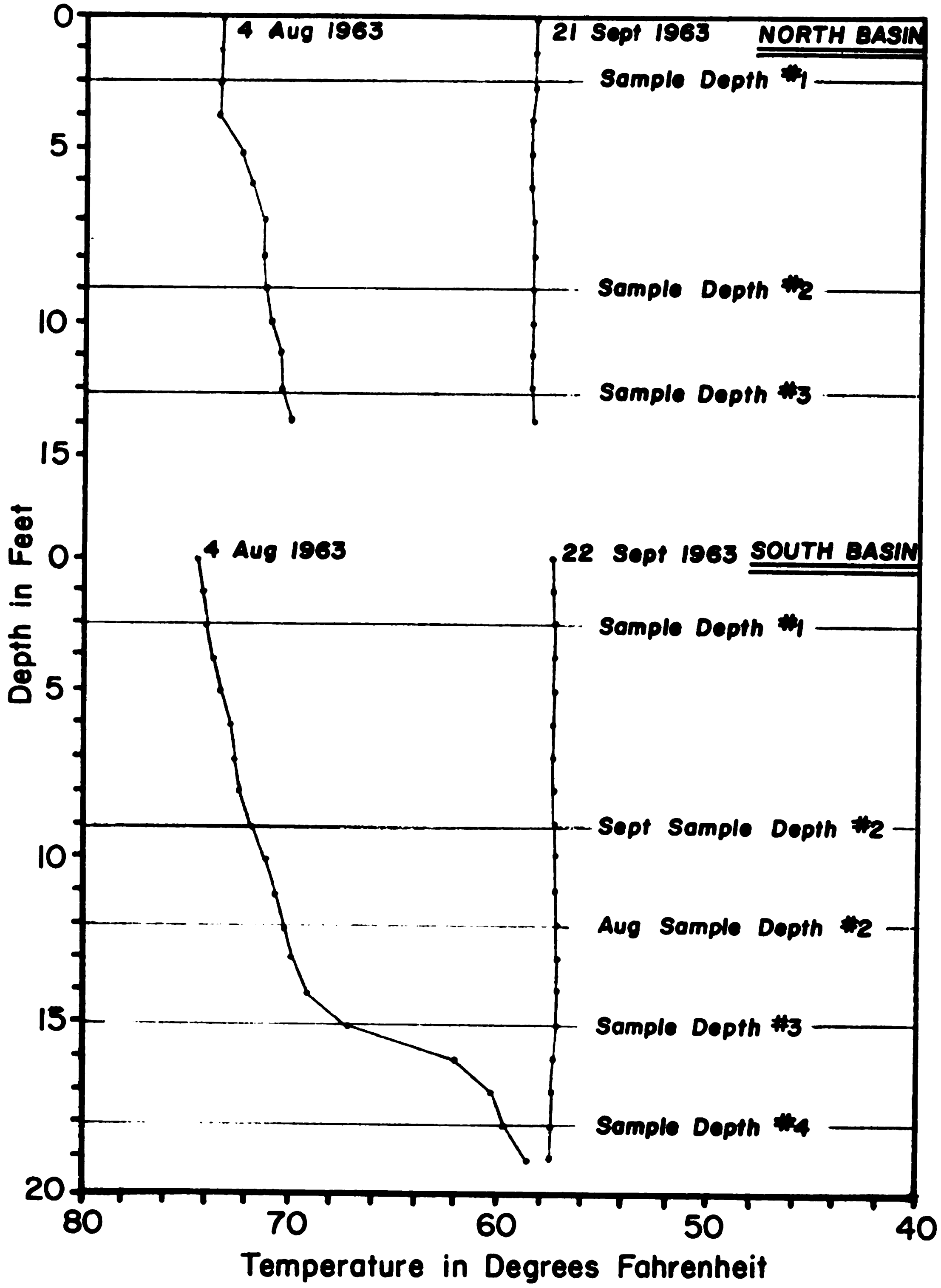

4 Aug 1963
21 Sept 1963
NORTH BASIN
Sample Depth #1
Sample Depth #2
Sample Depth #3
4 Aug 1963
22 Sept 1963
SOUTH BASIN
Sample Depth #1
Sept Sample Depth #2
Aug Sample Depth #2
Sample Depth #3
Sample Depth #4
Depth in Feet
0
5
10
15
0
5
10
15
20
80
70
60
50
40
Temperature in Degrees Fahrenheit

Figure 17. Sampling depth as related to water temperature - Irwin Lake.

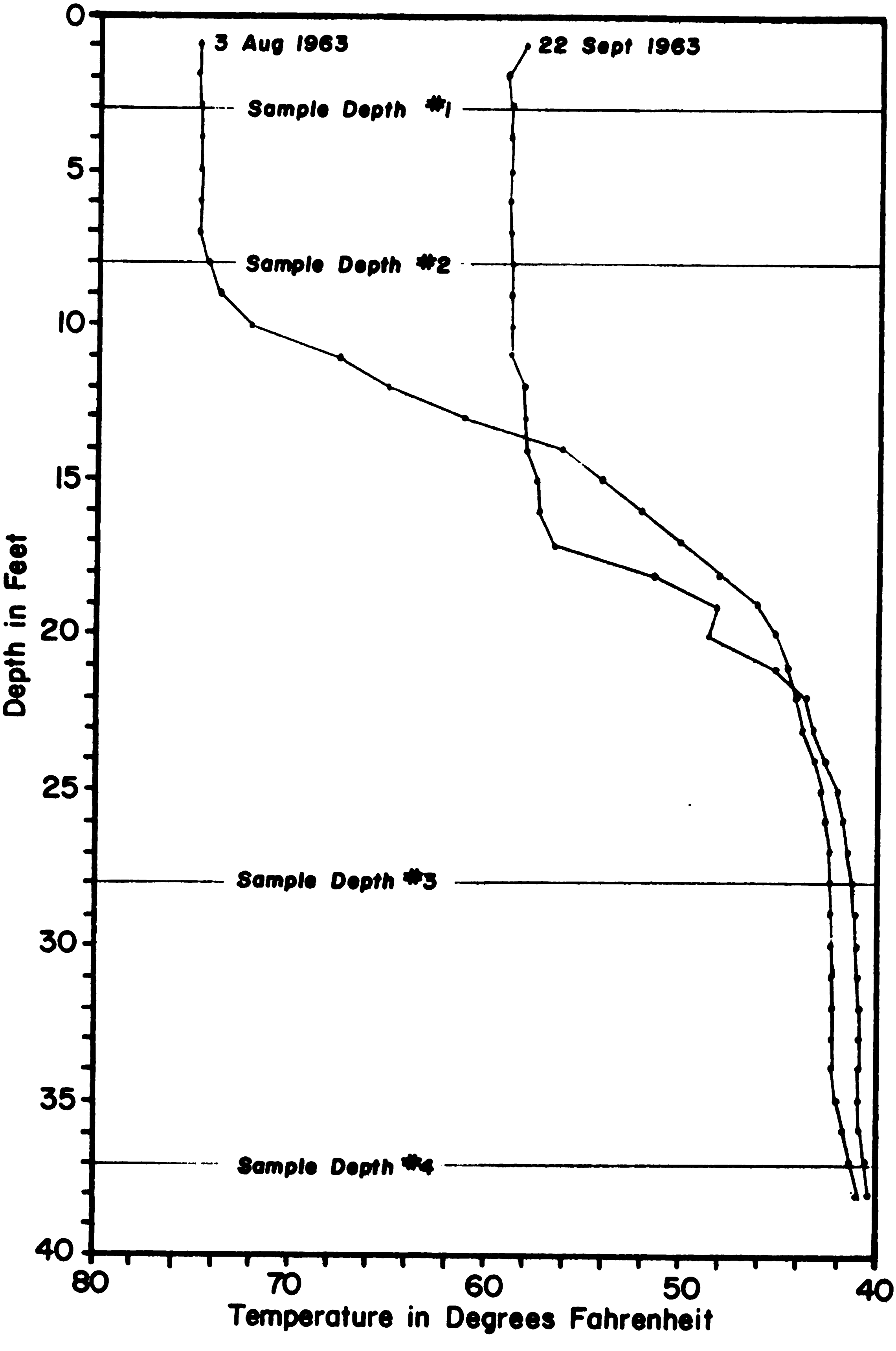

3 Aug 1963
22 Sept 1963
Sample Depth #1
Sample Depth #2
Sample Depth #3
Sample Depth #4
0
5
10
15
20
25
30
35
40
Depth in Feet
80
70
60
50
40
Temperature in Degrees Fahrenheit

Figure 18. **Sampling depth as related to water temperature - Juanita Lake.**

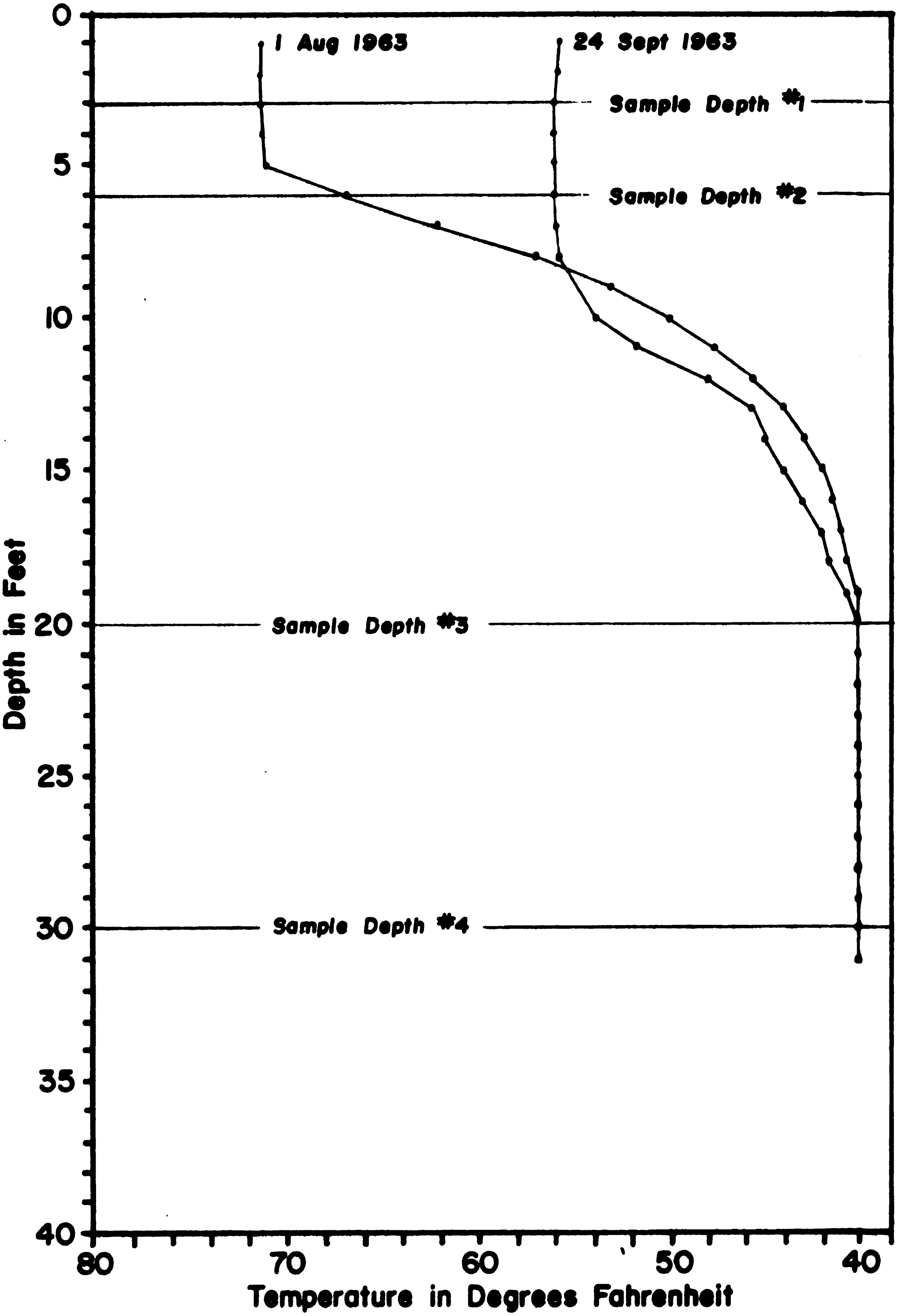
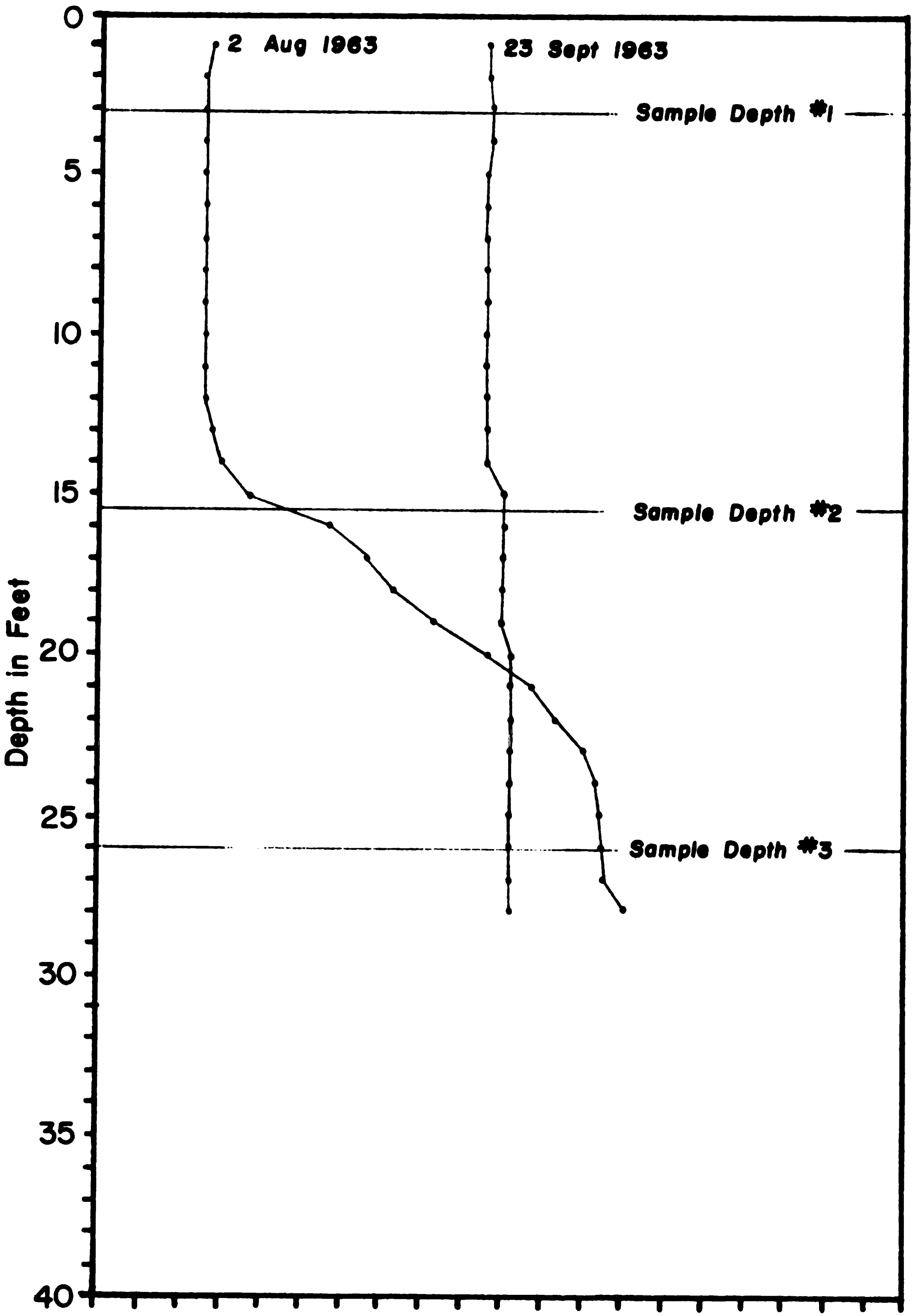

1 Aug 1963
24 Sept 1963
Sample Depth #1
Sample Depth #2
Sample Depth #3
Sample Depth #4
Depth in Feet
0
5
10
15
20
25
30
35
40
80
70
60
50
40
Temperature in Degrees Fahrenheit

Figure 19. Sampling depth as related to water temperature - Grant's Lake.


2 Aug 1963
23 Sept 1963
Sample Depth #1
Sample Depth #2
Sample Depth #3
Depth in Feet
0
5
10
15
20
25
30
35
40
80
70
60
50
40
Temperature in Degrees Fahrenheit

manufactured by Industrial Instruments, Inc. was used to measure conductivity in the field and samples were analyzed for total hardness by the EDTA (versenate) method. A portion of each water sample was taken back to the laboratory where it was later analyzed for total phosphorus using a Klett-Summerson photoelectric colorimeter and the method of Ellis, Westfall, and Ellis (1948).

In addition to the water samples mentioned above, mud samples were collected from each of the three limed lakes - Starvation, Timijon, and Stoner. In the first two the mud samples were taken at the same spot as the water samples but in Stoner there were four mud samples taken at spots designated by Waters in 1953. Each mud sample was taken with an Ekman dredge so that the mud-water interface was included. Then, the top three centimeters of mud were scooped off and taken back to the laboratory for determination of adsorbed calcium, using the method of Cheng and Bray (1951) with modifications. Each sample was filtered through Whatman Number 1 filter paper and then oven-dried at 60 degrees Centigrade and ground to a 200-mesh size. For extraction, 10 ml of 23 percent $NaNO_3$ were added to one gram of screened sample. After shaking for one minute and standing for ten minutes the mixture was filtered through Whatman Number 1 filter paper and the filtrate was analyzed for total hardness (calcium and magnesium) by the EDTA (versenate) method. I accepted Waters' assumption that, since the lime contained practically no magnesium, results of this test gave a good indication of amount of calcium present.

## Biological Sampling

Where possible, biological sampling methods were the same as those used by Waters. But, due to the shorter sampling time available and other circumstances to be mentioned later, biological sampling methods did not parallel those of Waters as closely as did the chemical analyses.

### Plankton

Plankton sampling and analysis of data were done by Waters in two different ways. Samples taken in 1953 on Stoner Lake were taken at four stations as indicated in Figure 13. Sampling was done by pulling a Wisconsin plankton net of 12 cm diameter for 20 feet at a speed such as to just keep the upper rim of the tow net below the surface. One sample was taken at each station at one-week intervals for ten weeks following lime application and samples were taken to the laboratory where they were brought to a constant volume and quantitative counts were made using a Sedgewick-Rafter counting cell. After counting in the cell, conversion was then made to obtain number of organisms per sample but no attempt was made to compute numbers per volume of water.

From the other five lakes plankton samples were taken throughout a two-year period. Two samples were taken from each of the four sampling levels described before for chemical samples. These were taken with a Juday plankton trap holding ten liters, with a net of number 20 silk bolting cloth. The lower two layers were found to contain negligible amounts of plankton so only the top two layers were included in the final analysis. Samples from these two layers were brought to a constant volume and counted in a Sedgewick-Rafter counting cell and converted to total number per volume of water sampled. Using a Whipple ocular micrometer, average volume per cell was calculated for conversion to total volume of plankton per volume of water sampled.

Variability in numbers and volumes of plankton sampled by Waters was so great that I felt that no meaningful comparisons could be made between numbers and volumes of plankton found in 1953-1955 and those found in only two series of samples taken in 1963. A comparison of species composition in the planktonic community would have been of interest but Waters did not give an indication of the relative numbers of individuals in the different species so it is not possible even to determine if there was any major shift in composition of the community.

I did determine the volume of plankton collected. This was done by allowing the plankton to settle naturally in a ten millileter centrifuge tube full of water. After settling for four hours the volume of plankton was read from the graduations on the side of the tube. The Stoner Lake samples can be represented only as volumes of plankton per sample, a sample being the amount of water which passed through the 12 cm diameter Wisconsin plankton net when it was dragged through the water for a distance of 20 feet. Samples from the other lakes were taken with a Juday plankton trap so results can be expressed as volume of plankton per liter of water. These results are included for general interest in Appendix but no attempt is made to compare them to results obtained by Waters.

### Fish

Waters collected fish in Stoner Lake by gill net and by angling throughout the summer of 1952 and recorded length, weight, and sex and took scale samples from behind the left pectoral fin of the yellow perch. Scales from 82 of the perch were examined and ages were determined and total lengths at previous annuli were calculated from a nomograph.

In this study collections were made from Stoner Lake by angling and seine and length was recorded and a scale sample taken from behind the left pectoral fin of the yellow perch. Length at each age was calculated by the same method used by Waters and then rate of growth was calculated for 29 fish in 1963 so it could be compared to that of the fish in 1952. No samples were taken in any lakes besides Stoner since it was the only one sampled at the time of lime application.

## Bottom Organisms

These, like the fish, were sampled only in Stoner Lake since this was the only one sampled at the time of lime application. Samples were taken as near as could be determined to the spots designated by Waters and shown in Figure 13. Waters had picked four stations in the littoral zone of the lake with special effort being made to include varying bottom types among the stations and uniformity of type within the area of each station. Staion 1, near the east shore of the lake, was in a small, shallow, windswept bay 3.5 feet deep in 1952 and about two feet deep in 1963. Bottom was made up of mud and organic material with a thin layer of partly decayed plant material and chironomid cases. Station 2, near the west shore of the lake, was at the mouth of a large, weedy, sheltered bay. Water here was 4.0 feet deep in 1952 and about 3 feet deep in 1963. Bottom was composed of sand and small amounts of pulpy peat. Station 3 was located off a wind and wave swept point on the east shore. Depth was 3 feet in 1952 and slightly less in 1963. Bottom was predominately sand. Station 4 was located in the sheltered north end of the lake in water 2.0 feet deep in 1952 and slightly shallower in 1963. Bottom consisted of sand overlain with a small amount of dead plant material. Growing vegetation was sparse or missing entirely at all stations.

Four Ekman dredge samples were collected at each station and samples were picked and organisms identified and counted and then separated into two groups for volume determination. One group included Oligochaeta and Tabanidae and the other group included all other families. Waters collected at one-week intervals in 1952 and for a ten-week period following lime application. In 1963, samples were taken in the same manner at two different times, once in July and once in September, and counted, identified, and measured for volume by the same method used by Waters.

## Rooted Vegetation

Waters sampled at four stations for weight of rooted emergent vegetation per square meter. This was impossible in 1963 because the water level was so low that all of the sampling stations were on dry land.

# RESULTS AND DISCUSSION

## Chemical and Physical Determinations

### Dissolved Oxygen

Hasler et al. (1951) believed that addition of lime would cause clearing of the water and removal of organic suspensoids. This would increase photosynthesis and decrease the oxygen consumption due to decay of organic matter. The end result would be increased dissolved oxygen concentrations in the thermocline area of lime-treated lakes. Stross and Hasler (1960) tested this hypothesis with a series of light and dark bottle measurements in treated and untreated lakes and found that while oxygen demand equalled production in the untreated lake, demand was only 32% of production in the treated lake. They attributed this to a higher rate of respiration in the untreated lake in which the organic suspensoids had not been precipitated.

Waters (1956) did not find any significant changes in dissolved oxygen concentration after addition of lime nor did I find any notable differences between oxygen levels in 1963 and those in 1955. Oxygen levels on comparable days in 1955 and 1963 are shown in Table 1. At first glance it appears that there was an increase in dissolved oxygen in

Table 1. Dissolved oxygen in parts per million

| Lake | 1 Aug., 1955 | 1 Aug., 1963 | 20 Sept., 1955 | 20 Sept., 1963 |
|---|---|---|---|---|
| Starvation | | | | |
| Level 1 | 5.7 | 6.3 | 5.7 | 6.9 |
| 2 | 2.5 | 4.6 | 4.2 | 6.9 |
| 3 | 0.0 | 0.1 | 0.0 | 0.4 |
| 4 | 0.0 | 0.0 | 0.0 | 0.0 |
| Timijon | | | | |
| Level 1 | 6.7 | 6.5 | 5.1 | 7.6 |
| 2 | 3.7 | 5.2 | 2.0 | 7.7 |
| 3 | 0.0 | 0.0 | 0.0 | 0.1 |
| 4 | 0.0 | 0.0 | 0.0 | 0.1 |
| Juanita | | | | |
| Level 1 | 5.3 | 4.5 | 5.9 | 5.9 |
| 2 | 3.0 | 0.6 | 4.1 | 5.8 |
| 3 | 0.0 | 0.2 | 0.0 | 0.4 |
| 4 | 0.0 | 0.0 | 0.0 | 0.3 |
| Irwin | | | | |
| Level 1 | 8.0 | 7.8 | 7.6 | 8.1 |
| 2 | 8.3 | 7.6 | 8.0 | 8.3 |
| 3 | 6.5 | 0.2 | 2.1 | 0.4 |
| 4 | 0.0 | 0.1 | 0.0 | 0.1 |
| Grant's | | | | |
| Level 1 | 7.7 | 7.8 | 6.9 | 8.2 |
| 2 | 7.5 | 6.3 | 6.9 | * 8.4 |
| 3 | 6.3 | 0.8 | 0.6 | 8.0 |
| Stoner north | | | | |
| Level 1 | 6-8 | 8.1 | 6-8 | 9.1 |
| 2 | 6-8 | 7.7 | 6-8 | 9.1 |
| 3 | 1-6 | 7.4 | 1-6 | 9.2 |
| Stoner south | | | | |
| Level 1 | 6-8 | 7.8 | 6-8 | 9.5 |
| 2 | 6-8 | 7.7 | 6-8 | 9.5 |
| 3 | 6-8 | 7.1 | 6-8 | 9.5 |
| 4 | 1-6 | 2.4 | 1-6 | 9.4 |

[*] 1955 data were obtained before the fall overturn and 1963 data were obtained after the overturn.

Starvation and Timijon Lakes. But, there are increases and decreases equally as great in the untreated lakes. And, Waters' data show that day-to-day variations in 1953-1955 were much greater than variations between comparable dates in 1955 and 1963.

Stoner Lake was stratified during the summer in the north basin and only near the bottom of this basin does the oxygen level fall to such low levels as to preclude the growth of fish. The rest of Stoner Lake had sufficient oxygen during both summer and fall to support fish life. All the other lakes had too little oxygen to support fish below the thermocline during the summer. Grant's Lake had undergone mixing by 20 September 1963 and had sufficient oxygen to support fish at all levels at this time.

The difference in effect of lime application upon dissolved oxygen concentration as noted by Hasler et al. (1951) and Stross and Hasler (1960) and effects as shown by Waters' and my data may be due to differences in efficiency of precipitation of the organic suspensoids by the lime. The first two authors indicated that precipitation of organic colloids was quite marked but Waters found only incomplete precipitation and believed that this was not permanent because the color of the water at all levels returned to former values after about four weeks.

### Light Penetration as Measured by Secchi Disc

Light penetration shown in Table 2, showed no detectable change. At first glance these data, like those of oxygen, seem to indicate that there was an increase in light penetration. But, there was just as much change in the lakes which were not treated with lime, and Waters' data show that daily variations in 1954 and 1955 were greater than the variations between 1955 averages and the averages of the two determinations in 1963.

Table 2. Light penetration measured by Secchi disc--average reading in feet

| Limed Lakes | Average of All Readings Before Liming | Average of All Readings After Liming | Average of Two Readings 1963 |
|---|---|---|---|
| Starvation | 7.1 | 7.8 | 10.8 |
| Timijon | 8.6 | 9.3 | 9.7 |
| Stoner | 6.5 | 6.5 | 7.1 |

| Unlimed Lakes | Average of All Readings 1953-1955 | Average of Two Readings 1963 |
|---|---|---|
| Juanita | 6.9 | 7.5 |
| Irwin | 13.5 | 15.0 |
| Grant's | 17.3 | 12.3 |

These results, like those for dissolved oxygen, disagree with those of Hasler et al. (1951) and Stross and Hasler (1960), probably for the reasons already stated. The organic suspensoids were but partially and temporarily precipitated by the lime Waters added to these lakes.

## Hardness and Alkalinity

The pH in all lakes was such that only methyl orange alkalinity was measured, or, only that alkalinity due to calcium bicarbonate. Alkalinity was expressed as parts per million calcium carbonate and since the test for hardness was also a measure of calcium carbonate, these two determinations should produce identical results and can both be considered here in the same section. Values for alkalinity shown in Table 3 and in Figures 20, 21, 22, and 23 and values for total hardness shown in Table 4 and in Figures 24, 25, 26, and 27 are in very close agreement. My data for total hardness in the lowest levels of Starvation and Timijon Lakes were not reliable due to interference with the hardness test end point so the only measures of $CaCO_3$ at these two sampling levels are the ones obtained from determination of methyl orange alkalinity.

Table 3. Alkalinity--methyl orange in parts per million $CaCO_3$

| Limed Lakes | Average of All Samples Before Liming | Average of All Samples After Liming | Average of Two Samples 1963 |
|---|---|---|---|
| Starvation | | | |
| Level 1 | 4.4 | 20.8 | 8.1 |
| 2 | 4.4 | 21.4 | 8.0 |
| 3 | 5.2 | 26.5 | 14.3 |
| 4 | 11.8 | 113.4 | 62.5 |
| Timijon | | | |
| Level 1 | 3.2 | 27.3 | 7.8 |
| 2 | 3.0 | 29.4 | 7.9 |
| 3 | 3.3 | 39.8 | 11.1 |
| 4 | 7.0 | 60.3 | 22.9 |
| Stoner north | | | |
| Level 1 | overall | overall | 8.7 |
| 2 | average | average | 8.7 |
| 3 | 5.2 | 8.2 | 9.4 |
| Stoner south | | | |
| Level 1 | overall | overall | 8.0 |
| 2 | average | average | 7.9 |
| 3 | 5.2 | 8.2 | 9.8 |
| 4 | | | 7.0 |

| Unlimed Lakes | Average of All Samples 1953-1955 | Average of Two Samples 1963 |
|---|---|---|
| Juanita | | |
| Level 1 | 3.6 | 1.0 |
| 2 | 3.6 | 0.6 |
| 3 | 3.1 | 1.7 |
| 4 | 5.5 | 3.0 |
| Irwin | | |
| Level 1 | 2.8 | 1.2 |
| 2 | 2.6 | 1.3 |
| 3 | 2.5 | 5.5 |
| 4 | 3.6 | 6.6 |
| Grant's | | |
| Level 1 | 2.1 | 1.2 |
| 2 | 2.5 | 0.9 |
| 3 | 2.5 | 1.0 |

Figure 20. Methyl orange alkalinity - Starvation Lake.

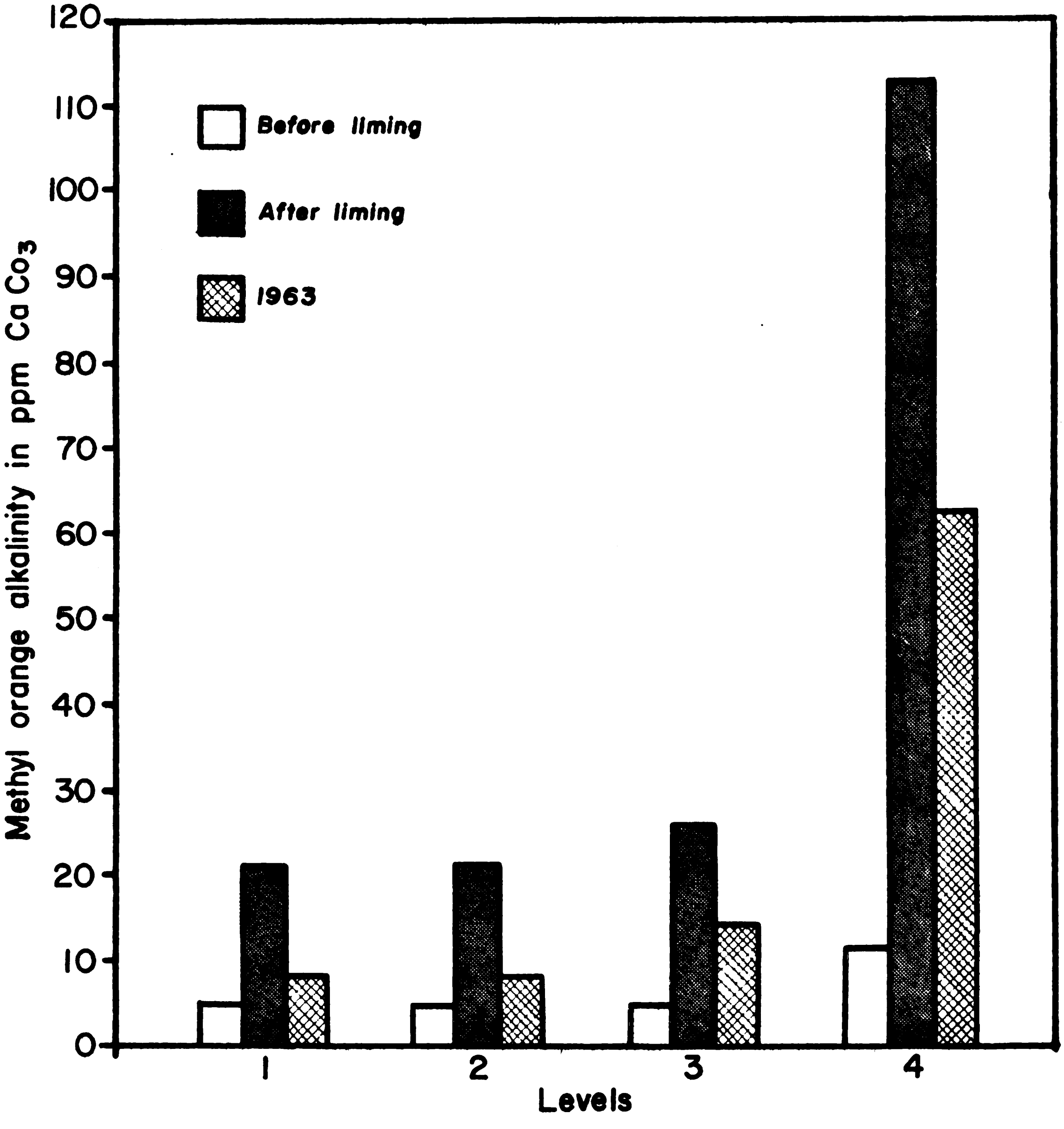

Methyl orange alkalinity in ppm Ca Co$_3$
120
110
100
90
80
70
60
50
40
30
20
10
0
Before liming
After liming
1963
1
2
3
4
Levels

Figure 21. Methyl orange alkalinity - Timijon Lake.

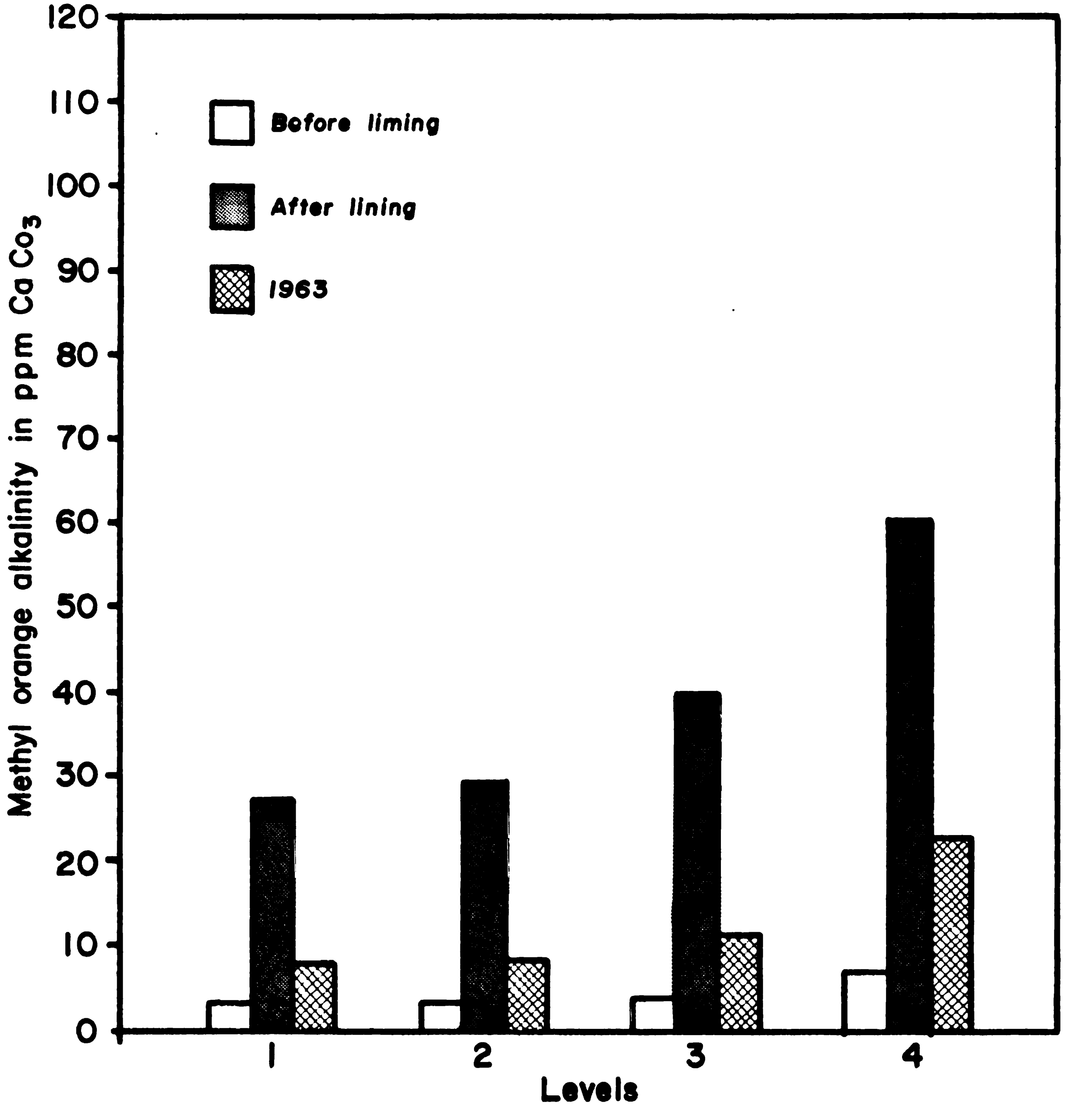

Before liming
After lining
1963
Methyl orange alkalinity in ppm $Ca\,Co_3$
0
10
20
30
40
50
60
70
80
90
100
110
120
1
2
3
4
Levels

Figure 22. Methyl orange alkalinity - Stoner Lake.

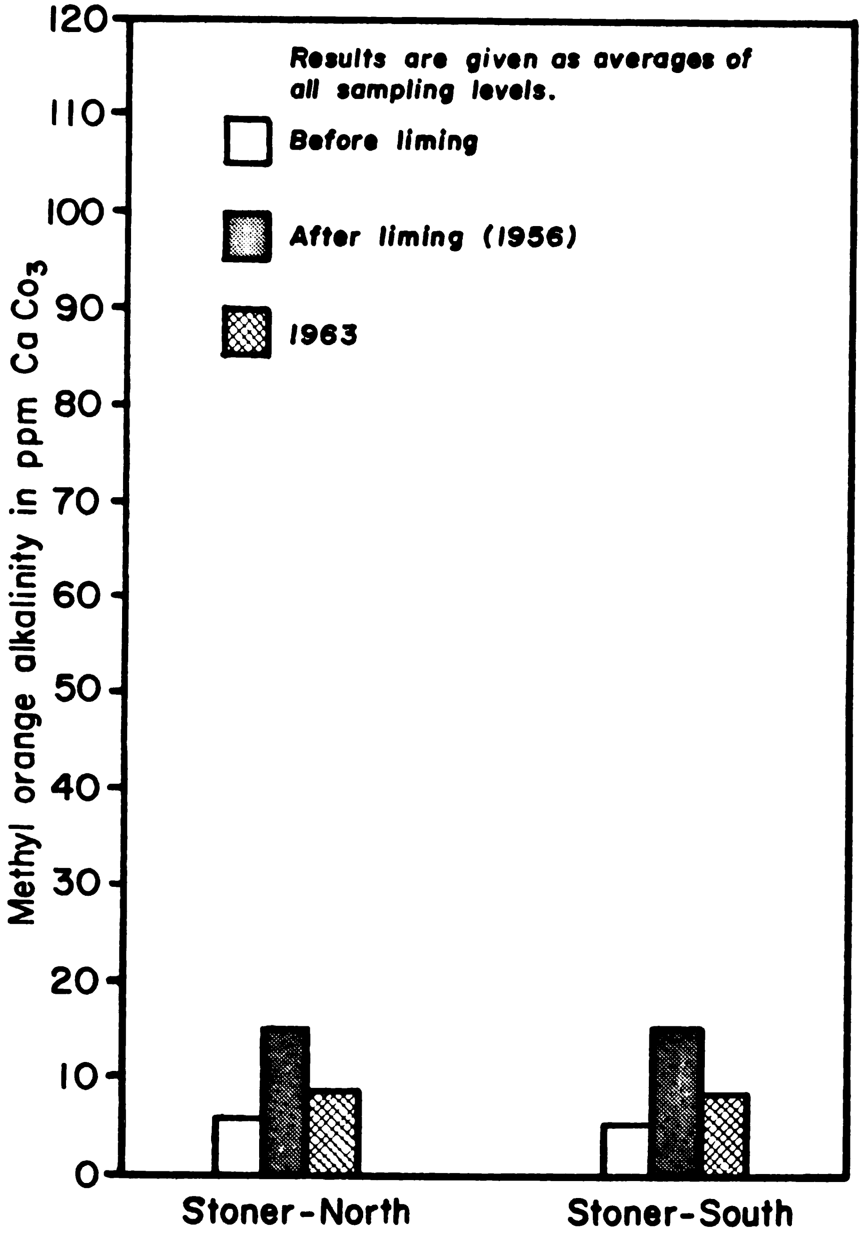

Results are given as averages of all sampling levels.
Before liming
After liming (1956)
1963
Methyl orange alkalinity in ppm Ca Co$_3$
0
10
20
30
40
50
60
70
80
90
100
110
120
Stoner-North
Stoner-South

Figure 23. Methyl orange alkalinity - Unlimed Lakes.

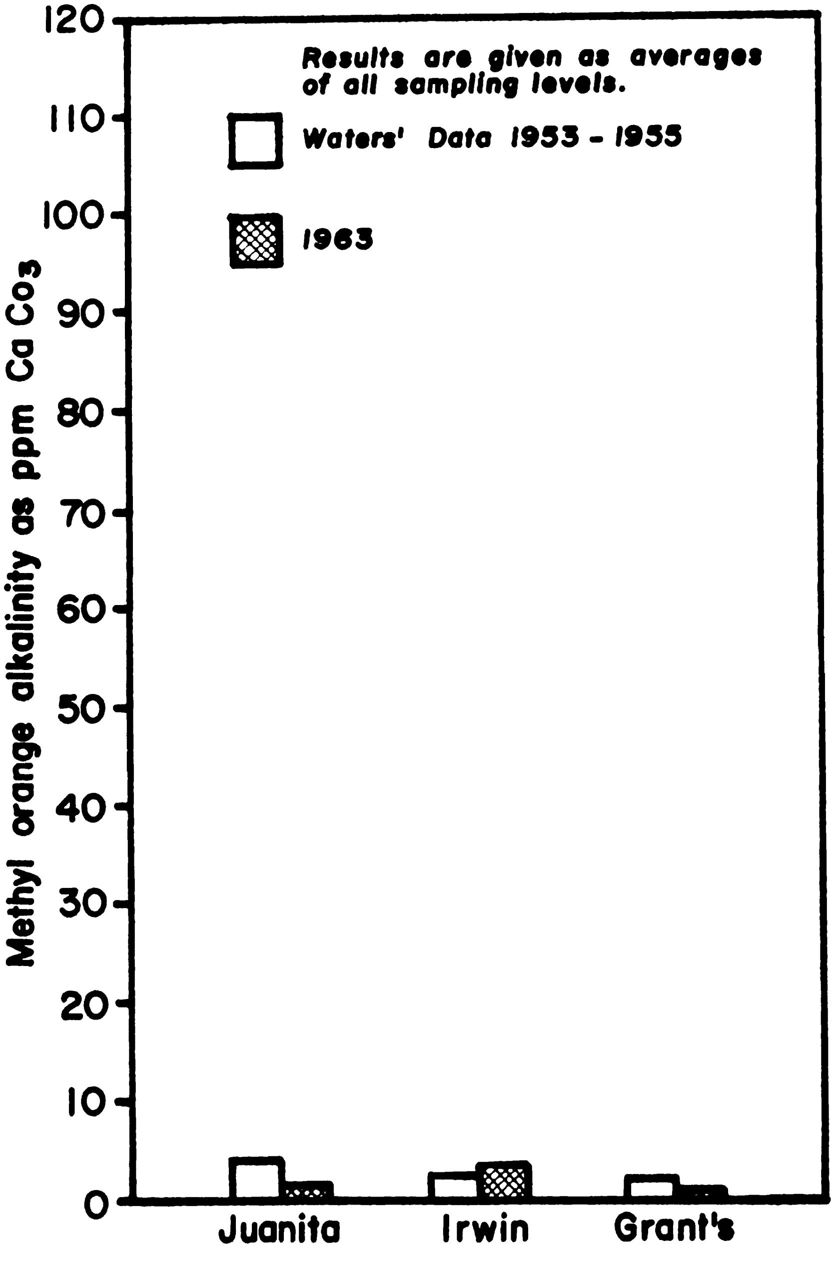
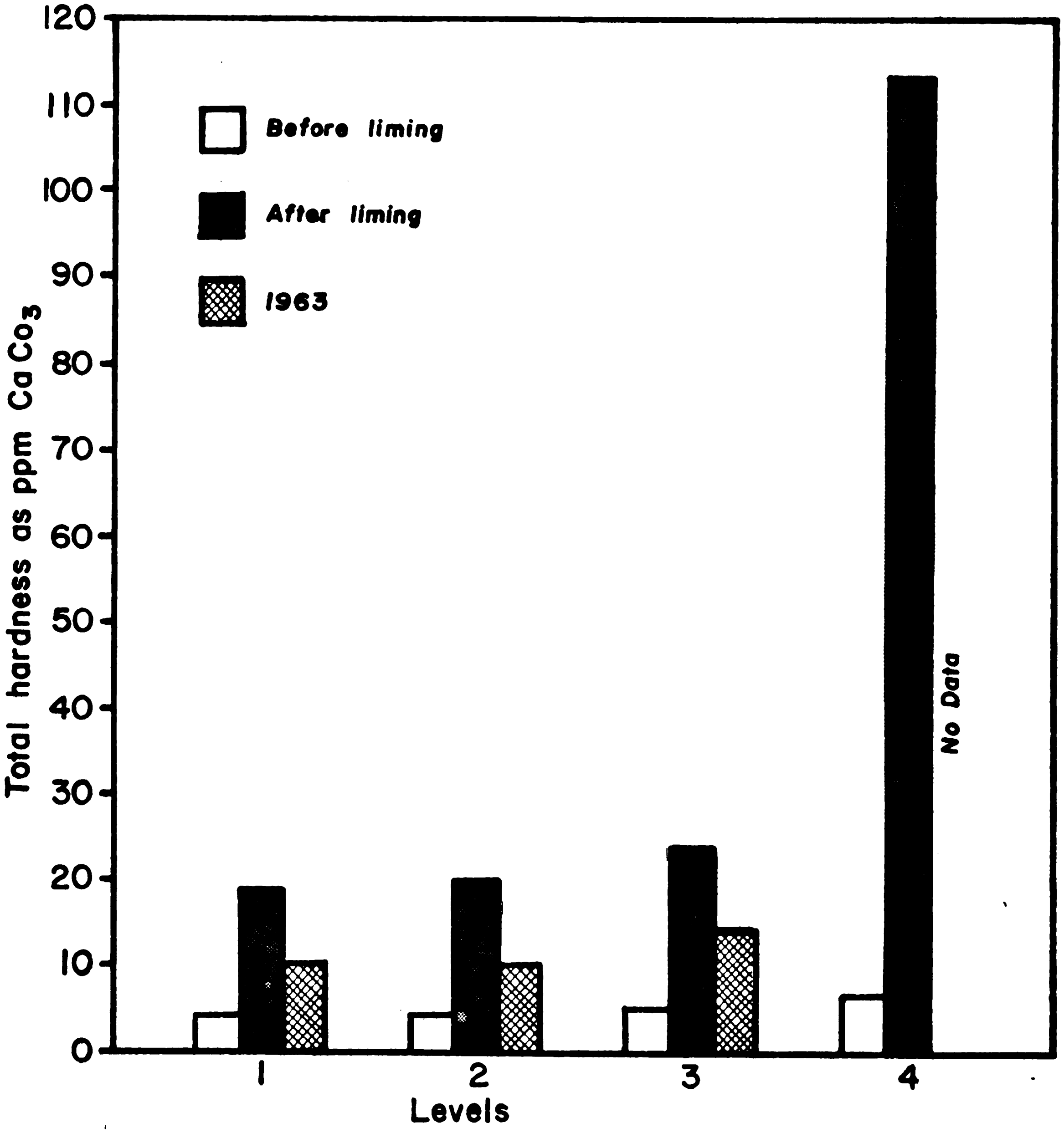

Results are given as averages of all sampling levels.
Waters' Data 1953 - 1955
1963
Methyl orange alkalinity as ppm Ca Co₃
120
110
100
90
80
70
60
50
40
30
20
10
0
Juanita
Irwin
Grant's

Table 4. Total hardness--as parts per million $CaCO_3$

| Limed Lakes | Average of All Samples Before Liming | Average of All Samples After Liming | Average of Two Samples 1963 |
|---|---|---|---|
| Starvation | | | |
| Level 1 | 4.4 | 19.0 | 10.5 |
| 2 | 4.4 | 20.0 | 10.5 |
| 3 | 5.0 | 23.8 | 14.4 |
| 4 | 7.0 | 113.9 | 36.0 |
| Timijon | | | |
| Level 1 | 4.3 | 27.3 | 9.5 |
| 2 | 4.7 | 32.0 | 9.2 |
| 3 | 4.8 | 42.3 | 13.3 |
| 4 | 5.3 | 79.6 | 15.1 |
| Stoner north | | | |
| Surface | No data | 10.1 | 10.9 |
| Level 1 | No data | No data | 11.3 |
| 2 | No data | No data | 10.4 |
| 3 | No data | No data | 11.5 |
| Stoner south | | | |
| Surface | No data | 10.1 | 10.8 |
| Level 1 | No data | No data | 11.3 |
| 2 | No data | No data | 11.5 |
| 3 | No data | No data | 10.6 |
| 4 | No data | No data | 11.6 |

| Unlimed Lakes | Average of All Samples 1953-1955 | Average of Two Samples 1963 |
|---|---|---|
| Juanita | | |
| Level 1 | 4.7 | 4.0 |
| 2 | 4.8 | 3.8 |
| 3 | 4.9 | 5.4 |
| 4 | 5.3 | 4.8 |
| Irwin | | |
| Level 1 | 4.1 | 4.2 |
| 2 | 4.0 | 3.8 |
| 3 | 4.0 | 5.0 |
| 4 | 4.6 | 4.4 |
| Grant's | | |
| Level 1 | 3.5 | 3.8 |
| 2 | 3.8 | 3.6 |
| 3 | 3.9 | 3.3 |

Figure 24. Total hardness - Starvation Lake.



120
110
100
90
80
70
60
50
40
30
20
10
0
Total hardness as ppm CaCo$_3$
Before liming
After liming
1963
No Data
1
2
3
4
Levels

Figure 25. Total hardness - Timijon Lake.

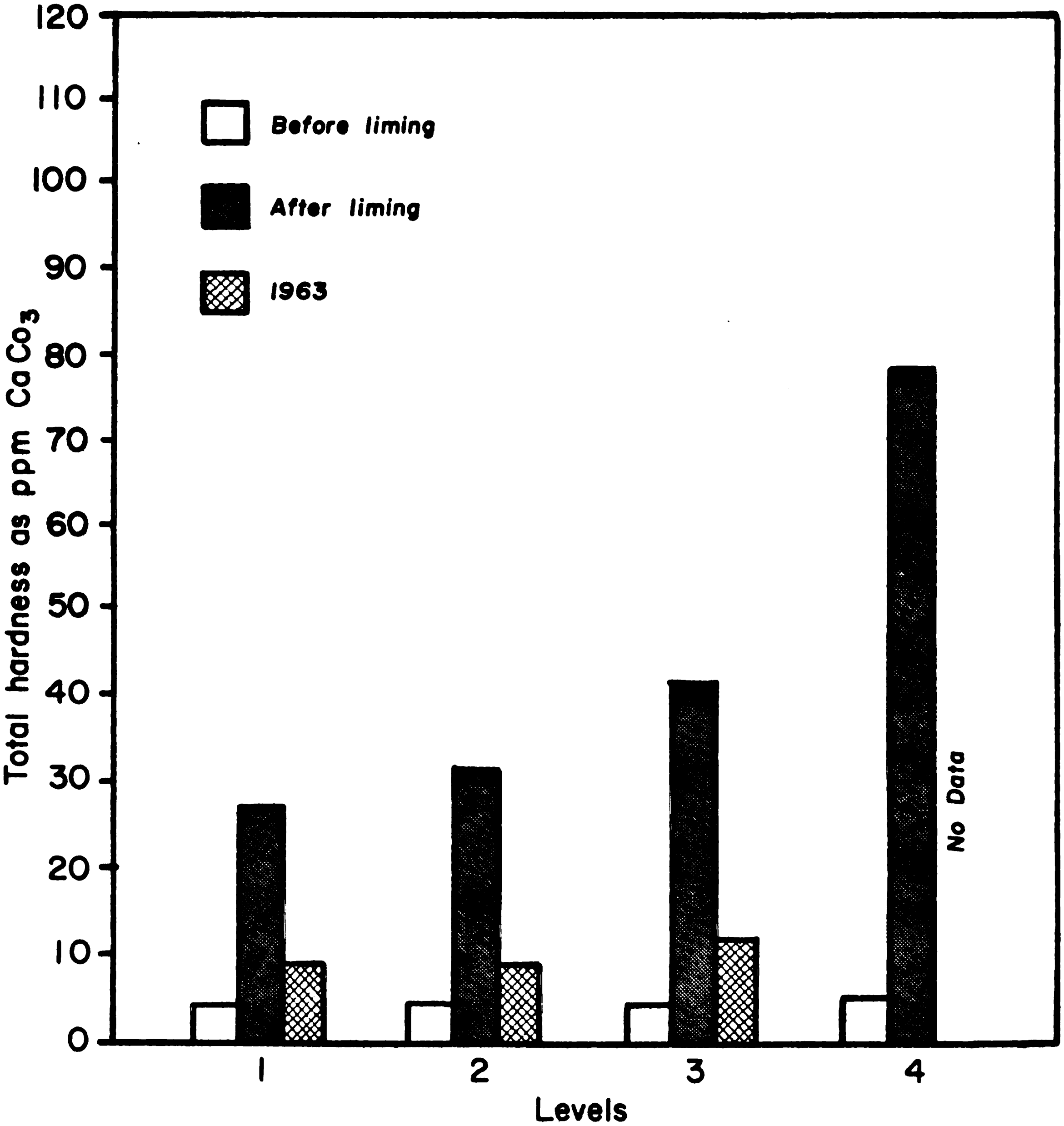

120
110
100
90
80
70
60
50
40
30
20
10
0
Total hardness as ppm CaCo3
Before liming
After liming
1963
No Data
1
2
3
4
Levels

Figure 26. Total hardness - Stoner Lake.

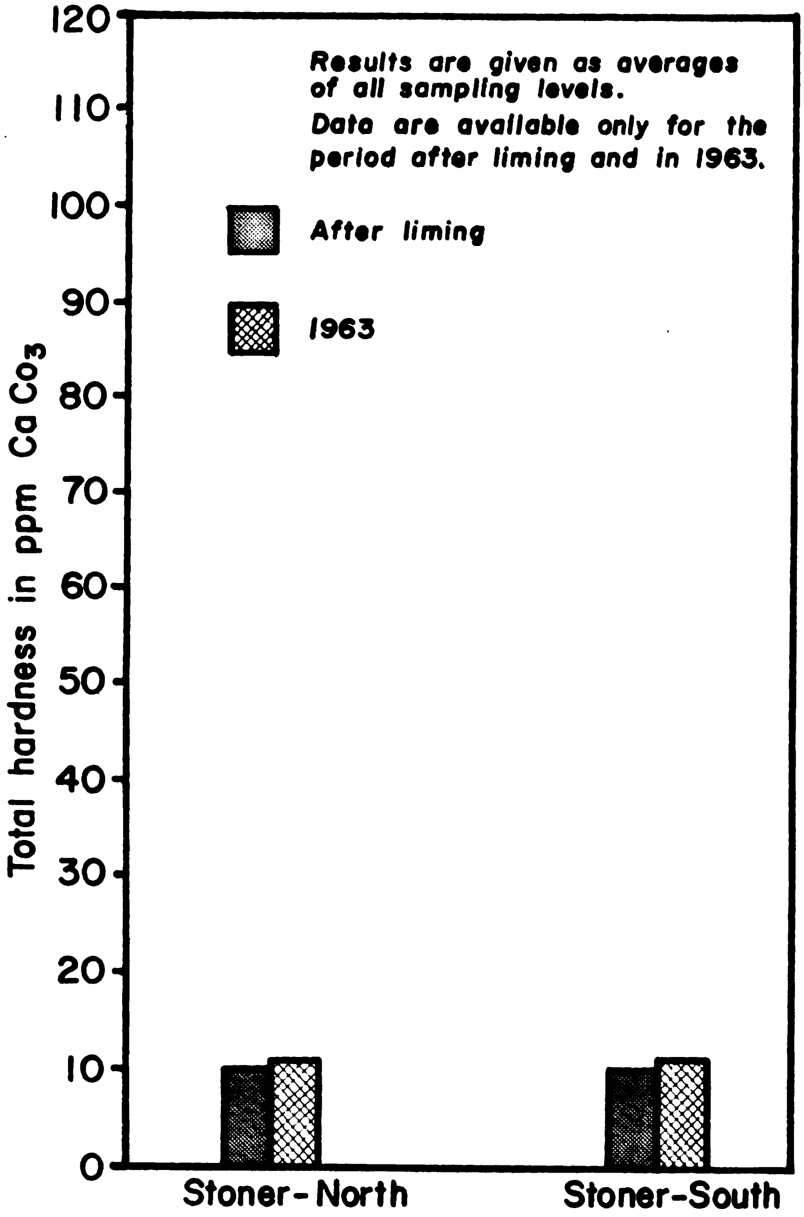
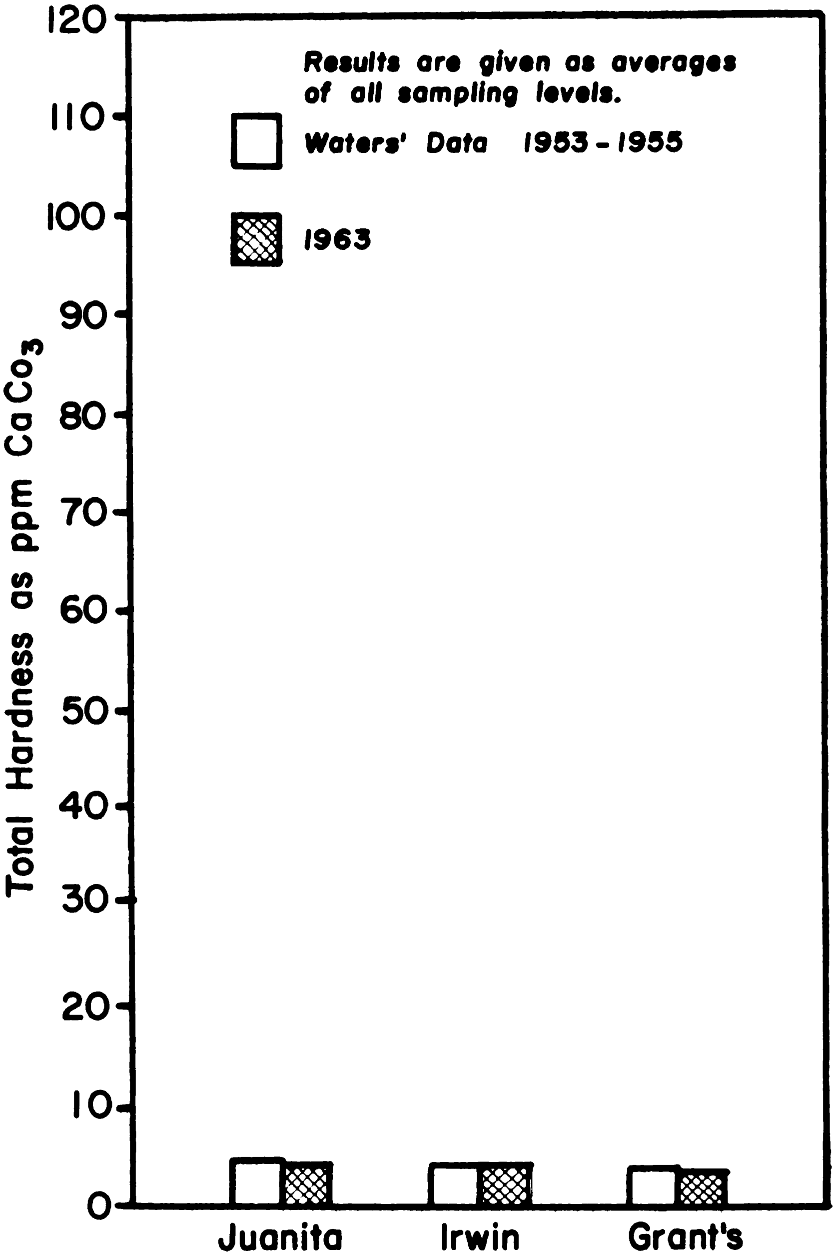

120
110
100
90
80
70
60
50
40
30
20
10
0
Total hardness in ppm Ca Co$_3$
Results are given as averages of all sampling levels.
Data are available only for the period after liming and in 1963.
After liming
1963
Stoner-North
Stoner-South

Figure 27. Total hardness - Unlimed Lakes.


Results are given as averages of all sampling levels.
Waters' Data 1953 - 1955
1963
Total Hardness as ppm CaCo3
120
110
100
90
80
70
60
50
40
30
20
10
0
Juanita
Irwin
Grant's

One of the prime objectives of the addition of the lime was to bring about increases in hardness and alkalinity, in this case both represented as parts per million $CaCO_3$. Waters (1956) had already determined that there was an increase in $CaCO_3$ shortly after the lime was added. Data from the 1963 study indicate that levels of $CaCO_3$ have decreased from those just after addition of the lime but they are still considerably higher than before liming.

No data for total hardness are available for Stoner Lake before the lime addition but alkalinity determinations indicated very low levels of $CaCO_3$, about 6 parts per million as compared to averages of 73 - 151 parts per million in eight non-bog lakes in southern Michigan tested by Hooper (1956). Addition of lime brought the alkalinity up to 15 parts per million $CaCO_3$ (Waters and Ball, 1957). Still, $CaCO_3$ levels were very low even after liming if Stoner is compared to non-bog lakes in Michigan. This level seems to have declined to about 9 parts per million by 1963. After liming of Stoner Lake many bags of lime were left opened along the shore to be dissolved by wave action to keep adding more calcium during the next year. This may have been partially successful but a large number of the bags seem to have been sealed off by a layer of silt before wave action could cause them to dissolve. In 1963 they still had the same general shape and some still had paper on them (Figures 28 and 29). But, many were at least partly dissolved so

Figure 28. Bag of lime barely submerged along eastern shore of Stoner Lake. Bag is about two-thirds of original size.

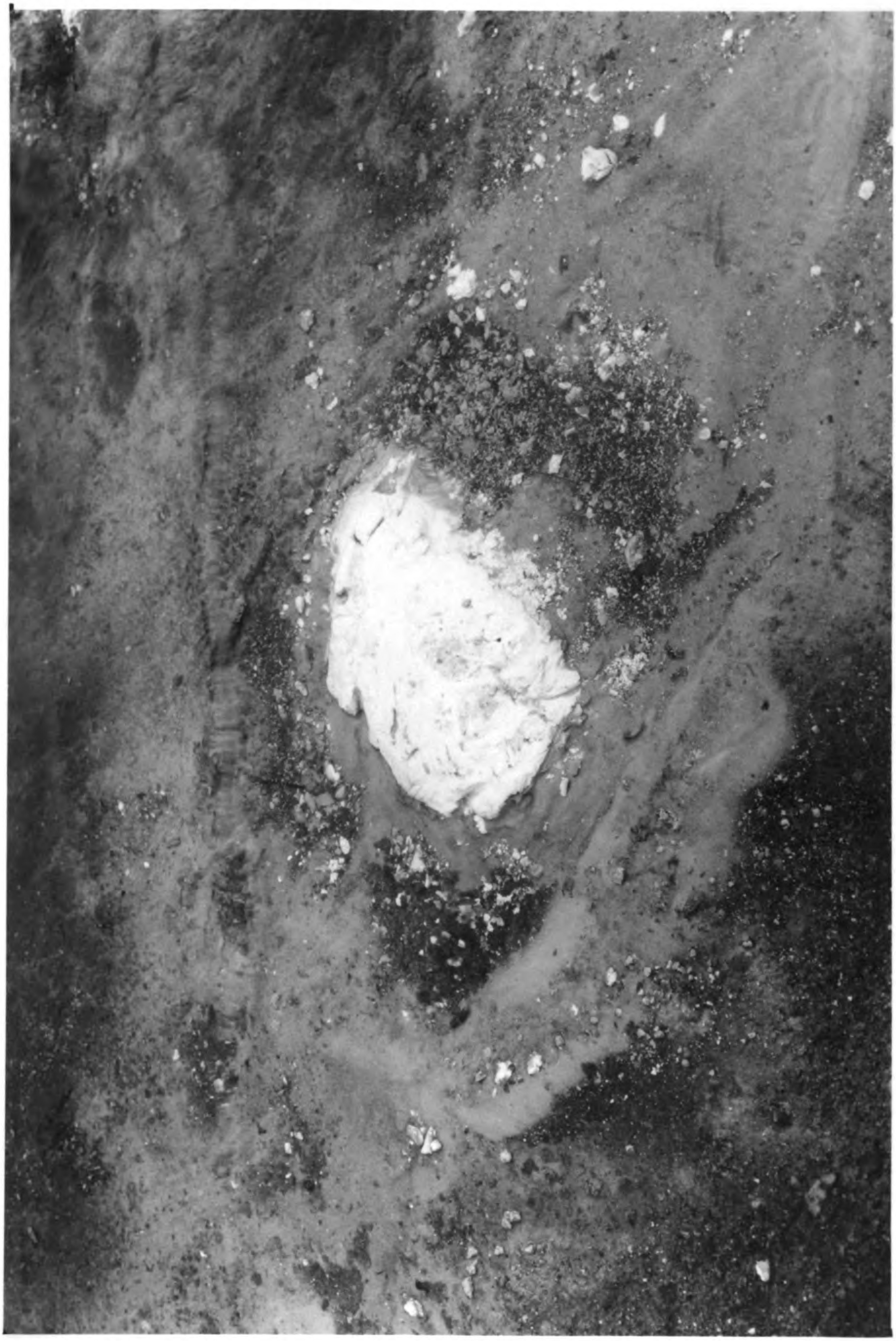


Figure 29. **Photo showing effect of stirring on old bag of lime. Although largely undissolved the lime is still soft and slick to the touch.**

this may have helped maintain levels of $CaCO_3$ brought on by the lime which was dissolved into the water initially.

Total hardness and alkalinity in Timijon Lake were equal to about 5 parts per million $CaCO_3$, the same as in Stoner Lake, before lime application but the lime seemed to have much greater effect here than in Stoner so that $CaCO_3$ values were as much as 15 times higher in some levels of the lake after liming. By 1963, alkalinity and hardness had dropped to 25 to 35 percent of the high values obtained just after liming, but they were still two or more times as high as before the lime was added. The lime was added to Timijon Lake at two different times and was added as a slurry in water. This may have had an effect upon the way the $CaCO_3$ was taken up by the water and may be a reason for there being larger increases in $CaCO_3$ in Timijon Lake than in Stoner Lake where the lime was added as powder and may have sunk into the flocculent bottom deposits.

From Figures 21 and 25 we may see that before lime addition the hardness and alkalinity were nearly constant in the first three sampling levels but increased in the fourth level near the bottom. After addition of lime there was a general increase in hardness and alkalinity at all levels but the greatest concentration of $CaCO_3$ was, and still is, found in that layer of water just off the bottom. Since this condition seems to persist it seems evident that this water just off the bottom is not being circulated throughout the upper portions of the lake as would be normal during spring and fall overturns. In this case it would appear, then, that Timijon is truly a meromictic lake as was proposed by Waters (1956).

In 1963, the $CaCO_3$ at all levels was still two or three times as high as before liming but the concentration had decreased greatly from the immediate post-liming period. This seems to indicate that the lime added to the lake water is slowly being removed from solution in the water, possibly to be incorporated into the bottom sediments, and $CaCO_3$ throughout all levels of the lake is moving toward some equilibrium level. It is not yet possible to determine whether the final equilibrium concentrations will be higher than those found before lime addition.

Starvation Lake had about 5 parts per million $CaCO_3$ at the first three sampling levels and slightly higher concentrations near the bottom, a condition similar to that of Stoner and Timijon Lakes. After addition of lime, Waters found four- or five-fold increases in alkalinity and hardness in the top three sampling levels and increases of 12 times or more in the water just off the bottom. Increases at the higher sampling levels were less than those in Timijon Lake but $CaCO_3$ increase just off the bottom was almost twice as much in Starvation Lake as in Timijon Lake. This is probably because the lime added to Timijon Lake seemed to mix throughout the lake but Starvation Lake was so heavily stratified that the summer application of lime was held above the thermocline until the fall overturn when the summer lime and, later, the lime from the fall application fell directly to the bottom levels of the lake.

Sampling data from 1963 show that $CaCO_3$ concentration in Starvation Lake has fallen to about 50 percent of the amount present just after lime addition. In the top three sampling levels this means a one hundred percent increase over pre-lime concentrations, about the same net increase found in Timijon Lake. But, in the water just off the bottom the $CaCO_3$ concentration in 1963 was still nearly six times as high as before lime was added. This may mean that much of the lime which initially fell to the bottom is still there and never did circulate throughout the rest of the lake water. As in Timijon Lake the $CaCO_3$ seems to be settling toward the bottom and perhaps eventually into the mud, but in 1963 there were still substantial increases in total hardness and alkalinity at all sampling levels.

Waters (1956) believed both Starvation and Timijon Lakes to be naturally meromictic before addition of the lime. Neither showed any increase in oxygen in the lower layers of the lake even after destruction of the thermal stratification in the fall. And, both lakes had higher concentrations of alkalinity at the very bottom levels which was not dispersed by spring or fall overturns. In 1963 this seemed to still be the case so the lakes are probably still meromictic.

In fact, the meromixis may be even stronger due to the additional concentration of $CaCO_3$ to add to the density of the bottom waters.

No lime was added to the three control lakes, Juanita, Grant's and Irwin so no wide fluctuations in hardness or alkalinity were expected nor were any found. $CaCO_3$ by test for total hardness was almost identical to that reported by Waters. The same values reached by the alkalinity test varied somewhat but were still very close.

### pH

With the addition of calcium carbonate to the acid lake waters one would expect free $CO_2$ to be taken from the water to combine with the $CaCO_3$ and $H_2O$ to form $Ca(HCO_3)_2$, calcium bicarbonate. This reduction in the amount of free $CO_2$ in the water would then cause a decrease in the acidity and a rise in the pH of the lake water (Ruttner, 1953) as happened in the lakes to which lime was added.

In Stoner Lake the addition of lime brought about an increase in pH from 6.8 to 8.0 pH units in both basins (Waters and Ball, 1957). By 1963 the pH had decreased to about 7.0, or nearly to the original level (see Table 6 and Figure 30). Bicarbonate alkalinity in Stoner Lake was also reduced almost to the original level by 1963. Waters and Ball (1957) noted that extensive phytoplankton blooms occurred in 1953, 1954, and 1955. With each bloom there appeared to be a decrease in bicarbonate alkalinity, a decrease in free $CO_2$ and an increase in carbonate alkalinity and pH. After each bloom the alkalinity returned to the bicarbonate state. However, during the bloom there was undoubtedly a precipitation of the insoluble $CaCO_3$ so that the total alkalinity of the lake decreased with each bloom. By 1963, blooms presumably had been taking place for ten years and alkalinity and pH were reduced nearly to the pre-liming levels.

Timijon Lake showed a greater change in pH and alkalinity than did Stoner. Upon addition of lime the pH changed from about 5.5 to over 7 at sampling levels 1, 2, and 3 and from 5.5 to over 9 at sampling level 4 just off the bottom (see Table 5 and Figure 31). The greater rise in pH near the bottom probably indicates that much of the $CaCO_3$ added to the water sank immediately to the bottom where the available $CO_2$ was picked up in formation of soluble $Ca(HCO_3)_2$. This reduction in free $CO_2$ caused a greater rise in pH at this level. In 1963 pH had decreased from 1955 levels but was still at least one unit higher than before liming except at sampling level 4 where it was only 0.6 pH units higher. By this time, the pattern had changed. No longer did pH increase from top to bottom as in 1955 but there was instead an even, although slight, decrease in pH from top to bottom.

In 1963, with a higher concentration of bicarbonate alkalinity near the bottom (Figure 21) there was also a greater amount of excess $CO_2$ which lowered the pH in this bottom water. $CO_2$ used up by plankton near the surface would cause soluble $Ca(HCO_3)_2$ to be converted to insoluble $CaCO_3$ which would tend to settle to the lower layers of the lake. Here, excess free $CO_2$ formed by decomposition of dead plant and animal material would combine with the $CaCO_3$ to form $Ca(HCO_3)_2$ which would be held in solution in the water. This seems to be what is happening in Timijon Lake and explains the higher alkalinity and lower pH at this level than near the surface.

An analysis of the Waters (1956) data illustrates this lowering of the pH in the bottom water. Table 5 shows conditions in Timijon Lake on October 19, 1954 just after lime was added and carbonate alkalinity became present in the bottom water and on August 5, 1955, the last date that carbonate alkalinity was present.

On October 19, 1954 when the lime was added all free $CO_2$ disappeared from the bottom waters and none was present again until after August 5, 1955. During this same time a monthly average of 14.0 parts per million $CaCO_3$ was lost from the bottom waters and 3.9 parts per million bicarbonate was added to the bottom waters each month. Since no free $CO_2$ was detected during this time it may be assumed that all $CO_2$ produced by decay of bottom materials was combined with

Table 5. Chemical conditions near the bottom of Timijon Lake on October 19, 1954 and August 5, 1955

| Date | pH | Free $CO_2$ in PPM | $Ca(HCO_3)_2$ Alkalinity as PPM $CaCO_3$ | $CaCO_3$ Alkalinity as PPM $CaCO_3$ |
|---|---|---|---|---|
| 10-19-54 | 11.5 | 0.0 | 29 | 146 |
| 8-5-55 | 8.6 | 0.0 | 68 | 6 |
| Difference | 2.9 | 0.0 | 39 | 140 |
| Difference per month | 0.29 | 0.0 | 3.9* | 14.0 |

*One-half is due to $CO_2$ and one-half is due to $CaCO_2$ which combine 1:1 to form $Ca(HCO_3)_2$.

the $CaCO_3$ to form soluble $Ca(HCO_3)_2$. $Ca(HCO_3)_2$ was formed one-half by $CO_2$ and one-half by $CaCO_3$ so we can assume that only 1.95 parts per million of $CO_2$ was produced per month. Therefore, 12.05 parts per million more $CaCO_3$ was lost from the water than was converted to soluble $(Ca(HCO_3)_2$ so this 12.05 parts per million $CaCO_3$ was lost to the system each month, probably to the bottom of the lake.

During this period when all available $CO_2$ was being combined with $CaCO_3$ to form $Ca(HCO_3)_2$ there was a drop in pH from 11.5 to 8.6 pH units which could not be due to buildup of $CO_2$. This increase in acidity may be attributed to buildup of organic acids in the bottom waters. These organic acids could have been concentrated in the water by two simultaneous mechanisms.

Waters (1956) found that addition of lime caused the formation of stringy, brown gellatinous masses in the lake water which cleared up within a week. Christman (1967) has demonstrated the formation of long high molecular weight polymers of organic acids through the action of light upon the acids in water when $CaCl_2$ was present. Shapiro (1958) found that different salts alter the chemical structure of these acid polymers as observed by chromatography but has not yet definitely tied calcium in as a necessary ingredient to the action. Possibly the stringy gellatinous masses mentioned by Waters were calcium-induced polymers of organic acids in the lake water. These acids sinking to the bottom would lower the pH of the bottom water if the polymers were broken up by bacteria or recombination of the calcium as $Ca(HCO_3)_2$.

Organic acids could also have been concentrated in the bottom water because the acids were taken from the bottom deposits. Before liming there would have been an equilibrium between acids in the bottom and those in the water as measured by pH of the water. With addition of lime the pH of the water rose very rapidly so the equilibrium would be destroyed and organic acids in the bottom could be taken up by the water to produce a new equilibrium and a consequent rapid lowering of the pH of the water in contact with the bottom.

Once the equilibrium was again established between water and mud the pH of the water would no longer continue to be lowered by the organic acids in the bottom. After this initial drop the pH declined at a much slower rate as $CO_2$ production eventually increased beyond the level needed to convert available $CaCO_3$ to $Ca(HCO_3)_2$.

It appears that the same rise in alkalinity near the bottom could have been achieved by addition of 2 parts per million $CaCO_3$ per month as was achieved by addition of 14 parts per million $CaCO_3$ per month because 12 parts per million $CaCO_3$ was lost to the bottom each month since there was only enough $CO_2$ produced to convert 2 parts per million of the insoluble $CaCO_3$ to soluble $Ca(HCO_3)_2$ before it was lost to the bottom. A slower addition of lime might also have prevented the upset of the equilibrium between bottom water and organic acids in the bottom.

Starvation Lake shows the same pattern as Timijon Lake but to a greater degree. The pH was increased by about one pH unit from 5.5 to 6.5 after application of the lime in all levels of the lake except the bottom level and pH increased there by 2.6 units from 5.5 to 8.1 (see Table 6 and Figure 32). The pH had decreased by 1963 at all levels but decrease was greatest near the bottom. The upper three levels showed decreases of less than 0.5 pH units but the pH of the bottom water decreased approximately 2.0 units from 8.1 to 5.9. But, even near the bottom the 1963 pH was nearly half a pH unit higher than before liming. As in Timijon Lake the bicarbonate alkalinity increases near the bottom but it is much more pronounced than in Timijon. The reasons for the pattern are probably the same. Phytoplankton use up free $CO_2$ in the upper regions of the lake. This causes conversion of soluble $Ca(HCO_3)_2$ to insoluble $CaCO_3$ which is precipitated and falls to the lower, dark layers of the lake where $CO_2$ is released by decay of dead organisms. This free $CO_2$ can then combine with the $CaCO_3$ to form $Ca(HCO_3)_2$ again which is held in the bottom waters because of its solubility. An initial sharp drop in pH near the bottom occurred in Starvation Lake just as in Timijon Lake and may be accounted for in the same manner as was the pH drop in Timijon Lake discussed above.

If, as was proposed earlier, Timijon and Starvation Lakes are really meromictic this condition would preclude mixing of the bottom waters with the water of the upper levels so any condition of slightly lower pH and higher alkalinity as just described would not be disrupted by the normal spring and fall overturns because there would be no overturns. However, with no overturns or mixing in the lakes at all one would expect a high build-up of acids in the bottom of the lakes from initial exchange between water and bottom materials and from precipitation of organic acid polymers out of the top layers of water. One would also expect a drastic decrease in $CaCO_3$ and organic acids in the upper layers. Alkalinity does increase from top to bottom (Table 3) and pH does decrease from top to bottom (Table 6) but this may be due to the fact that 1963 sampling was done in the latter part of the summer after the lakes had been stratified for many months. It does not appear that changes from top to bottom are pronounced enough to support the idea of no mixing at all but chemical stratification in the lakes may be keeping mixing to a minimum so there is no full scale spring and fall overturn as in other lakes such as Grant's Lake.

The three unlimed lakes did not show any appreciable changes in pH. One lake showed a decrease and the other two showed an increase in pH but no change was over 0.14 pH units and this could easily be accounted for by changes in phytoplankton levels or changes in pH measuring equipment (Figure 33).

Table 6. pH - average readings at each station

| Limed Lakes | Average of All Samples Before Liming | Average of All Samples After Liming | Average of Two Samples 1963 |
|---|---|---|---|
| Starvation | | | |
| Level 1 | 5.5 | 6.9 | 6.6 |
| 2 | 5.3 | 6.6 | 6.5 |
| 3 | 5.4 | 6.4 | 6.0 |
| 4 | 5.5 | 8.1 | 5.9 |
| Timijon | | | |
| Level 1 | 5.4 | 7.3 | 6.6 |
| 2 | 5.5 | 7.4 | 6.5 |
| 3 | 5.3 | 7.1 | 6.4 |
| 4 | 5.5 | 9.2 | 6.1 |
| Stoner north | | | |
| Level 1 | 6.8 | 6.8 | 7.0 |
| 2 | 6.8 * | 6.8 | 6.9 |
| 3 | ... | ... | 6.9 |
| Stoner south | | | |
| Level 1 | 6.8 | 6.8 | 7.1 |
| 2 | 6.8 * | 6.8 | 7.1 |
| 3 | ... | ... | 6.8 |
| 4 | ... | ... | 6.7 |

| Unlimed Lakes | Average of All Samples 1953-1955 | Average of Two Samples 1963 |
|---|---|---|
| Juanita | | |
| Level 1 | 5.1 | 4.8 |
| 2 | 4.9 | 4.8 |
| 3 | 4.9 | 5.0 |
| 4 | 5.2 | 5.0 |
| Irwin | | |
| Level 1 | 5.2 | 4.9 |
| 2 | 5.1 | 5.0 |
| 3 | 5.1 | 5.6 |
| 4 | 5.3 | 5.7 |
| Grant's | | |
| Level 1 | 5.1 | 5.4 |
| 2 | 5.1 | 5.1 |
| 3 | 5.1 | 4.9 |

*Data were given by Waters (1953) only as average pH among four stations picked at three and nine foot depth in each of the north and south basins.

Figure 30. pH - Stoner Lake.

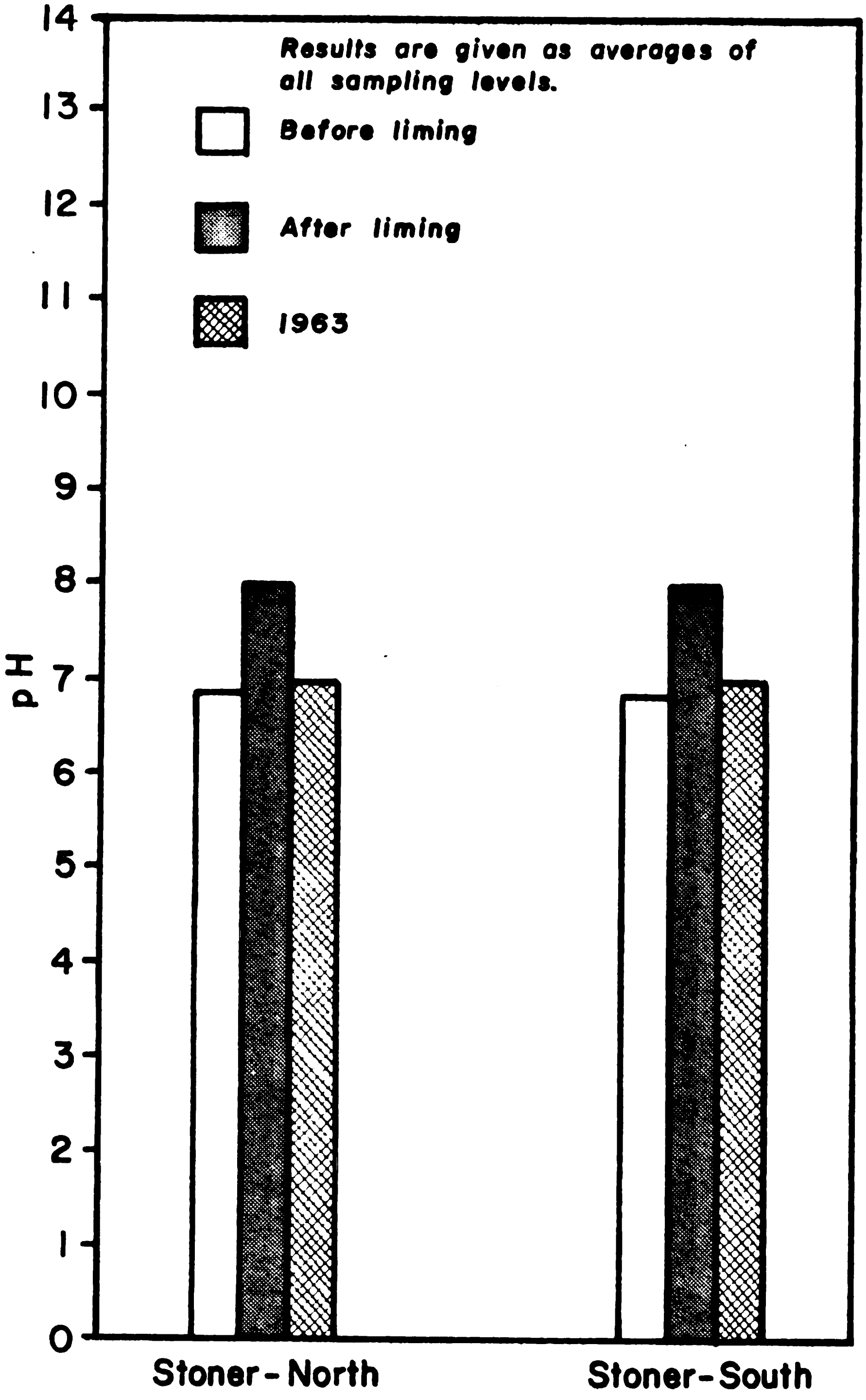

Results are given as averages of all sampling levels.
Before liming
After liming
1963
pH
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Stoner-North
Stoner-South

**Figure 31.** pH - Timijon Lake.

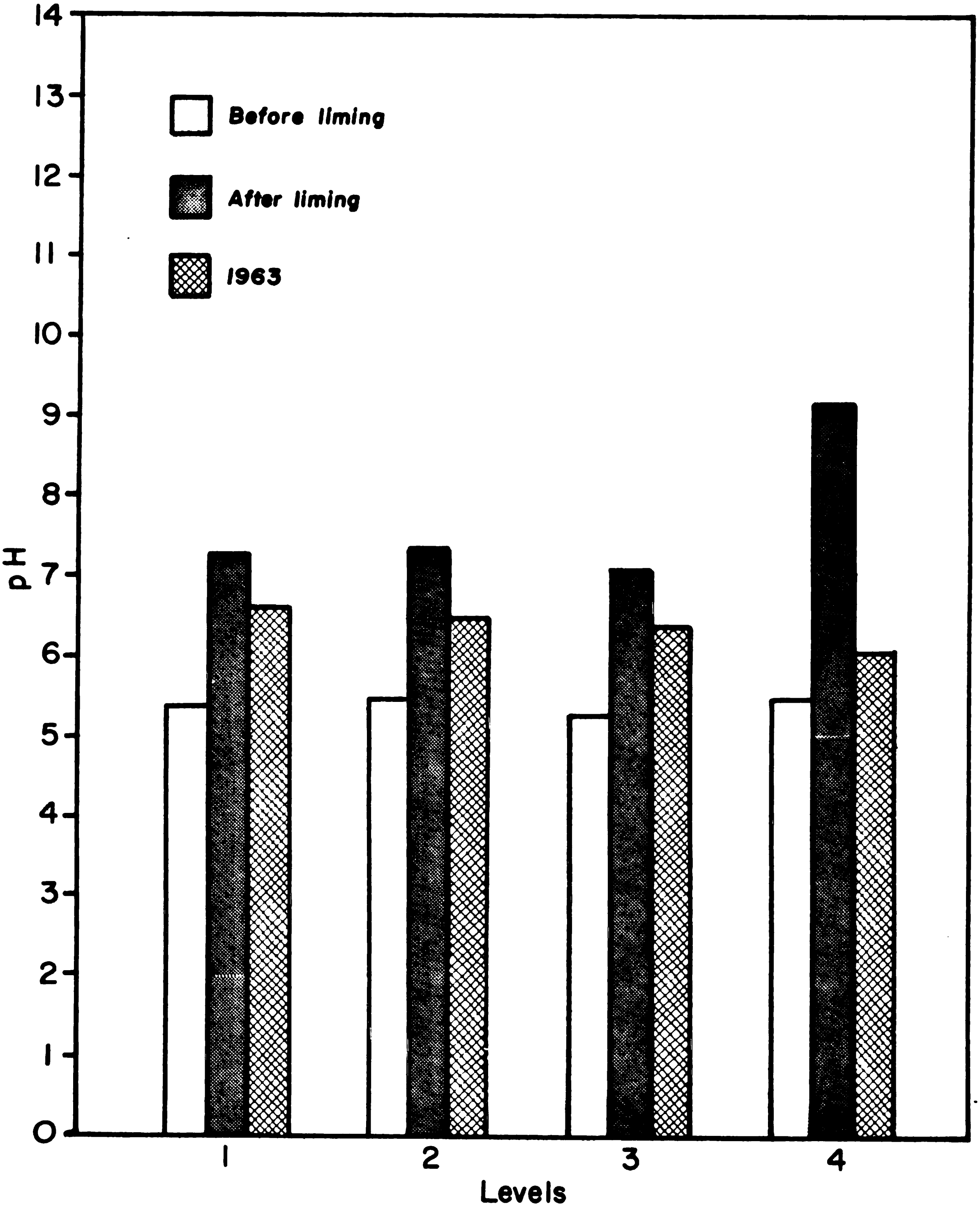
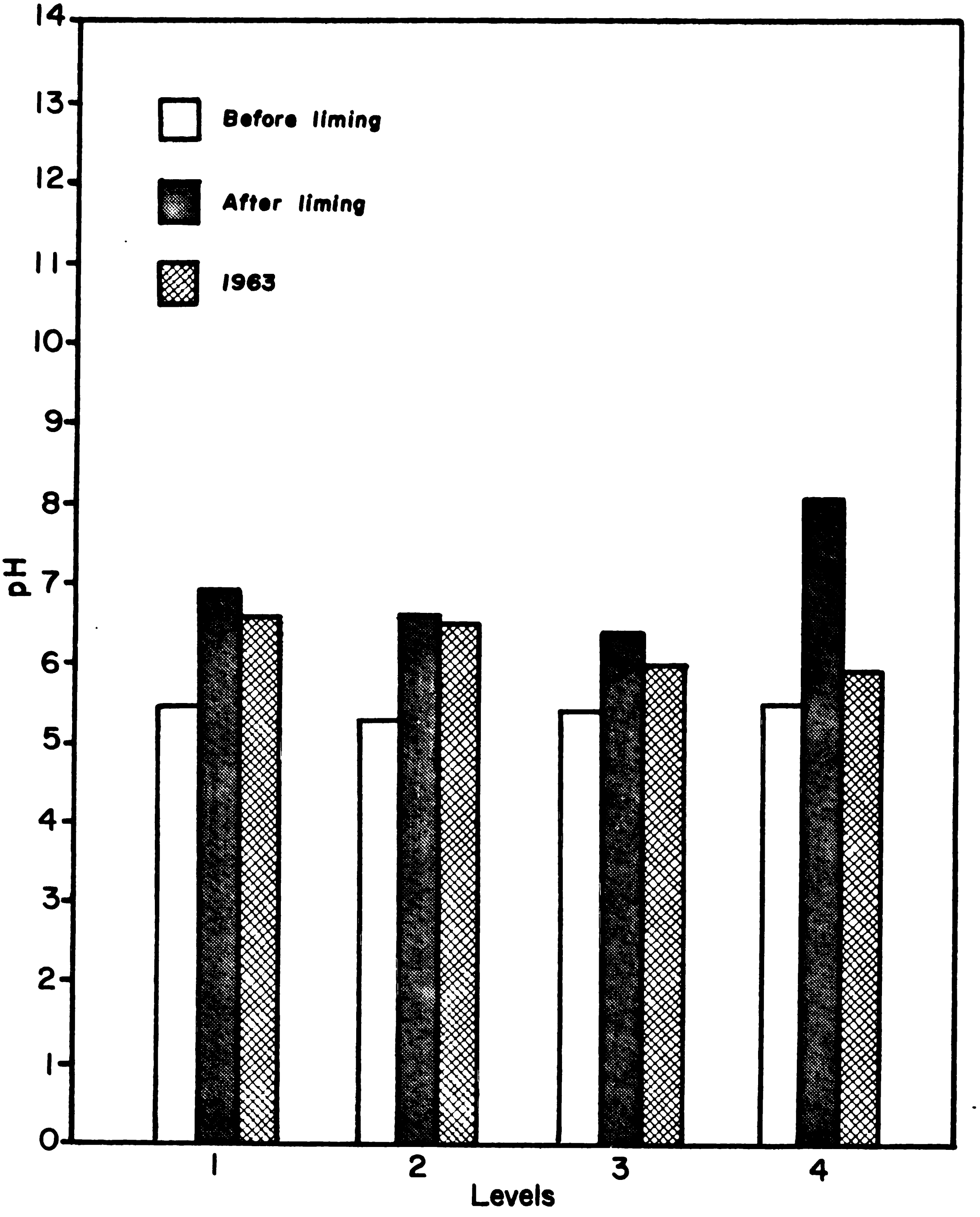
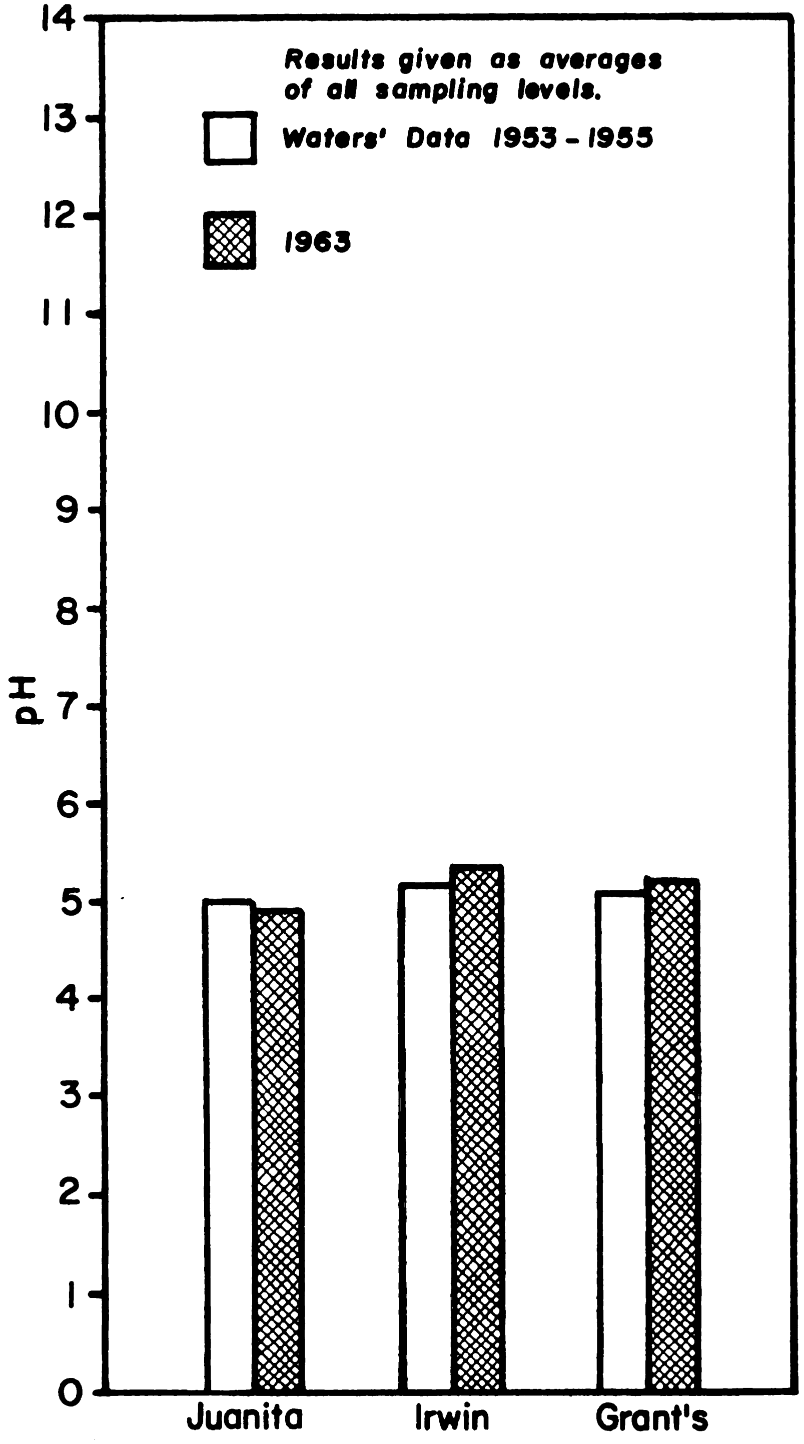

Before liming
After liming
1963
pH
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
1
2
3
4
Levels

Figure 32. pH - Starvation Lake.



14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
pH
Before liming
After liming
1963
1
2
3
4
Levels

Figure 33. pH - Unlimed Lakes.


Results given as averages of all sampling levels.
Waters' Data 1953 - 1955
1963
pH
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Juanita
Irwin
Grant's

## Conductivity

Acids, bases, or salts in solution in water serve as electrolytes and conduct electricity. Thus by measuring the electrical conductivity of a quantity of water it is possible to determine the relative amount of electrolytic materials present in solution. Further, it has been claimed that, normally, the richer a body of water in electrolytes the greater its productivity. Thus, electrical conductivity measurements can be used to give an indication of biological productivity (Welch, 1952).

If the $CaCO_3$ added to the study lakes was taken into solution in the water as calcium bicarbonate this would act as an electrolyte and increase the conductivity of the water. So, relative amounts of $Ca(HCO_3)_2$ in solution were determined by measurement of conductivity.

No data were available on conductivity in Stoner Lake either before or just after addition of lime by Waters so the 1963 data have no basis for comparison to see if conductivity was increased. But, it can be said that the conductivity values found for Stoner Lake in 1963 (see Table 7) are very low as compared to southern Michigan non-bog lakes studied by Hooper (1956). Conductivity in the southern lakes ranged from 133 to 299 micromhos $\times 10^{-6}$ and the highest value found in Stoner was $26.3 \times 10^{-6}$.

Table 7. Conductivity in micromhos x $10^{-6}$

| Limed Lakes | Average of All Samples Before Liming | Average of All Samples After Liming | 1963 | |
|---|---|---|---|---|
| | | | w/cell | w/out |
| Starvation | | | A* | B** |
| Level 1 | 5.6 | 20.7 | 20.2 | 10.8 |
| 2 | 5.8 | 20.6 | 21.9 | 11.9 |
| 3 | 6.4 | 25.4 | 31.7 | 16.9 |
| 4 | 12.6 | 123.8 | 111.3 | 59.4 |
| Timijon | | | | |
| Level 1 | 5.8 | 28.2 | 19.2 | 10.2 |
| 2 | 5.7 | 32.3 | 18.6 | 9.9 |
| 3 | 6.7 | 42.4 | 29.3 | 15.6 |
| 4 | 7.5 | 92.8 | 44.4 | 23.7 |
| Stoner north | | | | |
| Level 1 | No data | No data | 26.3 | 14.0 |
| 2 | No data | No data | 25.9 | 13.8 |
| 3 | No data | No data | 19.8 | 10.6 |
| Stoner south | | | | |
| Level 1 | No data | No data | 20.2 | 10.8 |
| 2 | No data | No data | 21.1 | 11.3 |
| 3 | No data | No data | 20.1 | 10.7 |
| 4 | No data | No data | 22.8 | 11.9 |

| Unlimed Lakes | Average of All Samples 1953-1955 | Average of Two Samples 1963 | |
|---|---|---|---|
| Juanita | | | |
| Level 1 | 7.2 | 15.4 | 8.2 |
| 2 | 7.5 | 15.5 | 8.3 |
| 3 | 7.9 | 16.7 | 8.9 |
| 4 | 8.0 | 15.9 | 8.5 |
| Irwin | | | |
| Level 1 | 7.5 | 12.4 | 6.6 |
| 2 | 7.3 | 13.3 | 7.1 |
| 3 | 7.6 | 12.9 | 9.6 |
| 4 | 7.8 | 18.9 | 10.0 |
| Grant's | | | |
| Level 1 | 7.0 | 12.2 | 6.5 |
| 2 | 7.0 | 11.8 | 6.3 |
| 3 | 7.0 | 14.1 | 7.5 |

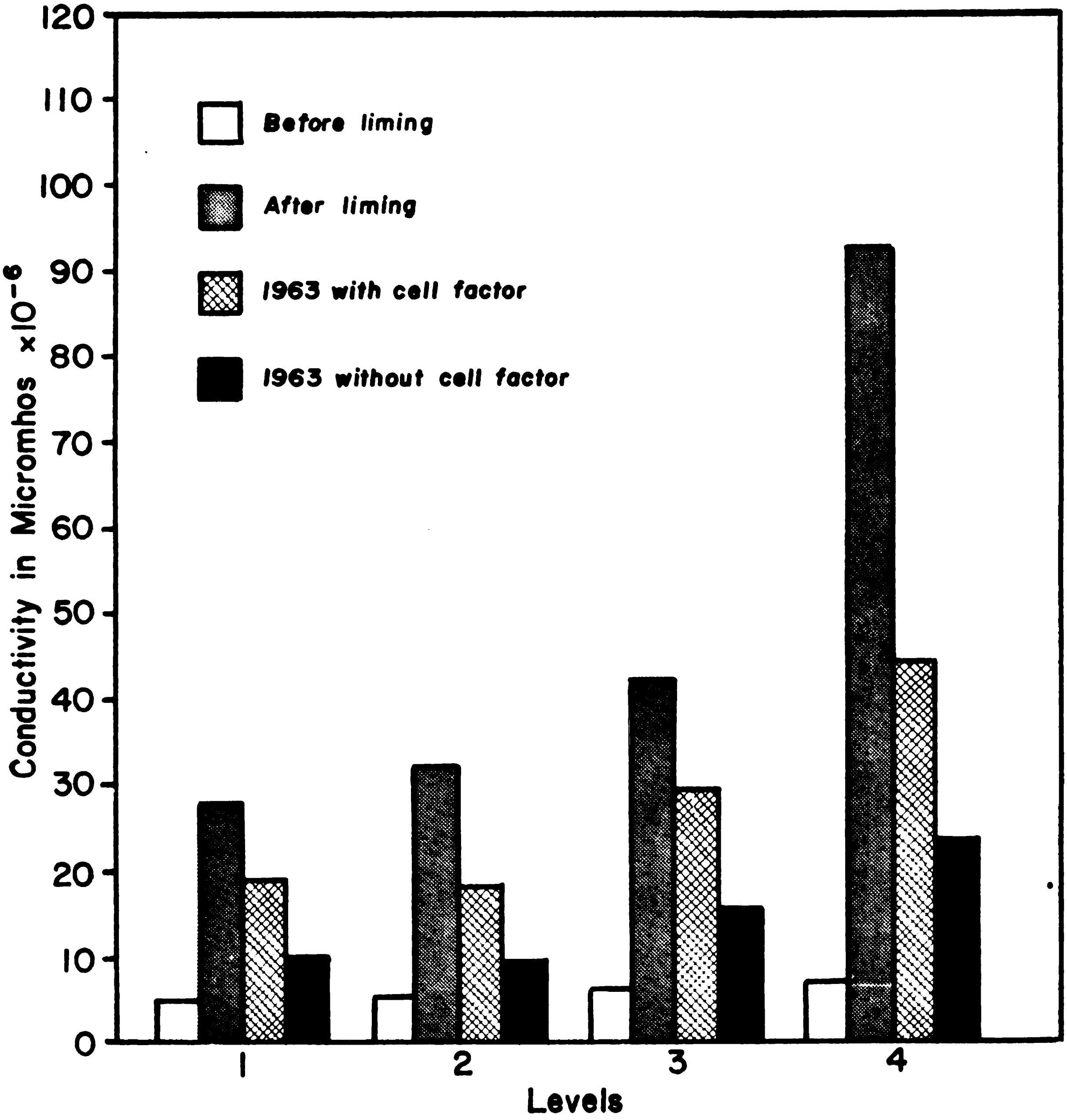
*With cell correction. **Without.

Before and after liming data from Waters (1956) are obtained without the use of the cell factor so are comparable to column B of the 1963 data.

Conductivity in both Timijon and Starvation Lakes was found to increase greatly with addition of lime (Table 7, Figures 34 and 35) with greatest increases to be found in the deeper regions of the lakes. Increases as much as six-fold were noted at the three upper sampling stations and a ten-fold increase in conductivity was found at the deepest sampling stations in both Timijon and Starvation Lakes. This increase in conductivity parallels the increase found in hardness and alkalinity.

Data for 1963 are given in two different ways. One set of data was computed in the correct manner using the cell factor determined for the conductivity meter used. The other set of data was computed without use of the cell factor. This was done because data computed with a cell factor for the unlimed lakes (Figure 36) showed an increase in conductivity when there was no corresponding increase in hardness nor alkalinity and no apparent reason for an increase in conductivity. Data without the cell factor matched very closely the data obtained by Waters for the unlimed lakes. Waters (personal communication) affirmed the fact that no cell factor had been used in his computations. So, data without the cell factor are comparable to Waters' data. Data computed with the cell factor are comparable to data computed correctly by other workers.

Figure 34. Conductivity - Timijon Lake.



120
110
100
90
80
70
60
50
40
30
20
10
0
Conductivity in Micromhos ×10⁻⁶
Before liming
After liming
1963 with cell factor
1963 without cell factor
1
2
3
4
Levels

Figure 35. Conductivity - Starvation Lake.

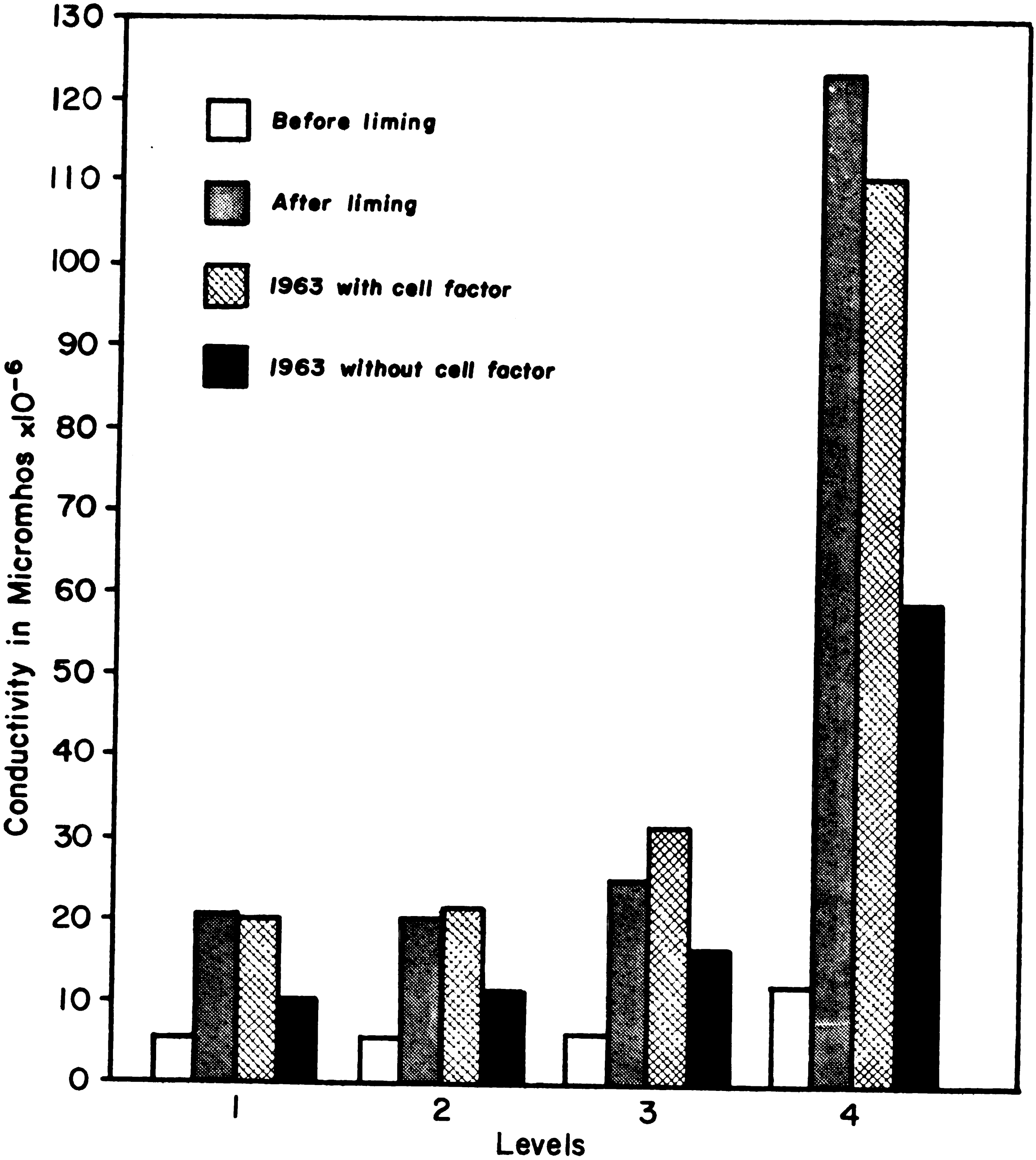
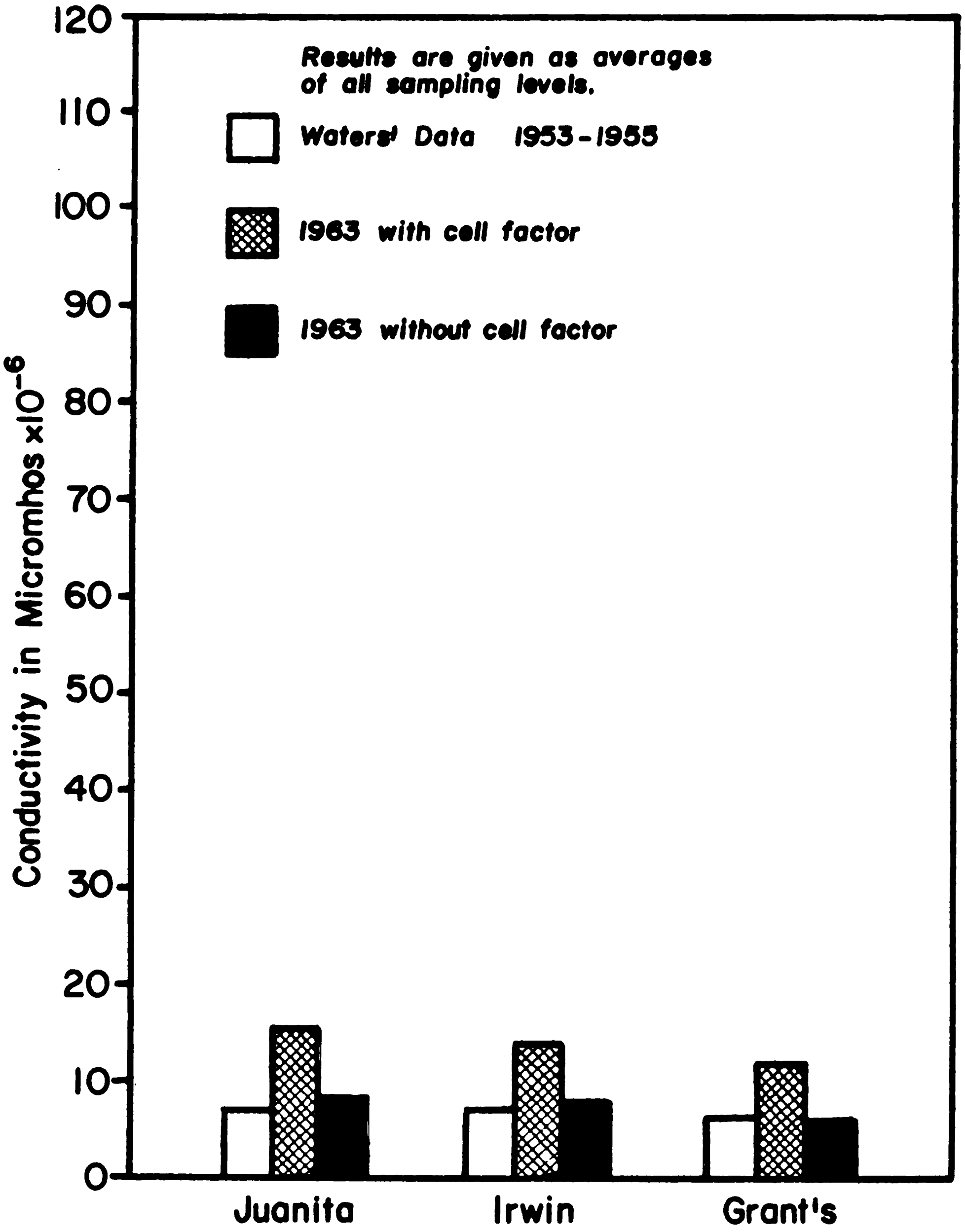

130
120
110
100
90
80
70
60
50
40
30
20
10
0
Conductivity in Micromhos x10^-6
Before liming
After liming
1963 with cell factor
1963 without cell factor
1
2
3
4
Levels

Figure 36. Conductivity - Unlimed Lakes.


Results are given as averages of all sampling levels.
Waters' Data 1953-1955
1963 with cell factor
1963 without cell factor
Conductivity in Micromhos x10$^{-6}$
0
10
20
30
40
50
60
70
80
90
100
110
120
Juanita
Irwin
Grant's

Data from 1963 show that conductivity in Starvation and Timijon Lakes has decreased to approximately one-half of post-lime levels in Starvation Lake and about one-third of post-lime levels in Timijon Lake. Still, after a nine-year period, conductivity in both lakes was over twice as high as before lime was added at the upper levels and three to five times as high in the water just off the bottom. Even so, conductivity is still low in these lakes when compared to that in more productive eutrophic lakes in southern Michigan.

Maximum conductivity in Starvation Lake in 1963 was measured as 111.3 micromhos x $10^{-6}$ just off the bottom but was less than 32 micromhos x $10^{-6}$ in the other layers. In Timijon the maximum 1963 conductivity measured (using the cell factor) was 44.4 micromhos x $10^{-6}$ in the water just off the bottom and less than 30 micromhos x $10^{-6}$ in the rest of the water. Using conductivity as an indicator of productivity we would expect that both Timijon and Starvation Lakes, even after lime application, are still very unproductive as compared to eutrophic lakes in southern Michigan where Hooper (1956) found the conductivity to range from 133 to 299 micromhos x $10^{-6}$.

The three unlimed lakes underwent very little change in conductivity during the ten-year period. This was to be expected since there was no change in hardness, alkalinity or pH during this period.

## Color

The dark tea color of bog lakes may be a factor controlling productivity because the intensity of the color controls the depth to which light may reach to support photosynthesis. Thus, any means of clearing up or lessening the color intensity of these lakes would promote an increase in productivity if sufficient nutrients were already present.

Johnson and Hasler (1954) reported an initial increase in light penetration of 60 percent and an increase of 160 percent over a two-year period in a portion of Peter-Paul Lake, Wisconsin, which had been treated by addition of lime. On the basis of this and other information Waters (1956) had anticipated a reduction in color after lime was added to the Michigan lakes. He expected this decrease in color to be caused by flocculation and precipitation of organic colloids caused by their combination with calcium.

When Waters added lime not only was there no reduction in color but there was an increase for a short time in the lower levels of Timijon and Starvation Lakes. This Waters attributed to partial flocculation of the colloids which caused them to cling together in brown strings in the water. This lasted only a few days and then color returned to pre-lime intensity. The studies of Christman (1967) and Shapiro (1958) suggest that the brown gellatinous masses mentioned by Waters might actually be long-chain polymers of organic acids, the formation of which was brought about by the presence of calcium. Concentration of these polymers in the bottom waters would cause an increase in color and also an initial decrease in pH as was discussed in the pH section of this thesis.

Waters assumed at this time that the incomplete flocculation and precipitation was the result of too little lime. Stross and Hasler (1960) indicated that there are reasons for incomplete clearing other than too little lime. They said that the nature of the color-causing colloids is peculiar to lake-type and that lakes surrounded by bog mat often failed to clear after addition of lime. One lake of this type was maintained in a clear state by acidification with sulfuric acid to a pH of 4.0 (Zicker, 1955 as quoted by Stross and Hasler, 1960) which indicates a difference in physical properties of the colloids.

In 1963 Stoner Lake was slightly clearer than in 1953 (Table 8) but all the other five lakes, including controls, had color increases. Since the lakes had returned to pre-lime levels of color by 1955 and since the percent increase in color was just as great in the control lakes as in those to which lime was added, I believe this color increase was due to other factors, such as rainfall, in 1963. In 1963, sampling was carried out in late July and in early September and color varied drastically between these two dates with the darkest color occurring during the July sampling series. This may have been due to rainfall and runoff

Table 8. Color in standard color units.

| Limed Lakes | Average of All Samples Before Liming | Average of All Samples After Liming | Average of Two Samples 1963 |
|---|---|---|---|
| Starvation | | | |
| Level 1 | 83 | 82 | 70 |
| 2 | 86 | 86 | 100 |
| 3 | 90 | 129 | 118 |
| 4 | 120 | 153 | 143 |
| Timijon | | | |
| Level 1 | 58 | 50 | 85 |
| 2 | 66 | 58 | 130 |
| 3 | 58 | 64 | 140 |
| 4 | 88 | 140 | 215 |
| Stoner north | | | |
| Level 1 | Given only as 80 P.C.S. with no change after addition of lime | | 40 |
| 2 | | | 50 |
| 3 | | | 50 |
| Stoner south | | | |
| Level 1 | | | 50 |
| 2 | | | 50 |

| Unlimed Lakes | Average of All Samples 1953-1955 | Average of Two Samples 1963 |
|---|---|---|
| Juanita | | |
| Level 1 | 89 | 135 |
| 2 | 119 | 135 |
| 3 | 116 | 205 |
| 4 | 152 | 135 |
| Irwin | | |
| Level 1 | 31 | 28 |
| 2 | 33 | 23 |
| 3 | 29 | 53 |
| 4 | 49 | 63 |
| Grant's | | |
| Level 1 | 13 | 20 |
| 2 | 14 | 35 |
| 3 | 24 | 70 |

leaching through the bog mat in greater quantity than usual during or just before July. The plan of clearing the color by addition of lime was not successful when Waters completed the project in 1953 and time did not increase the effectiveness of the lime in this respect.

## Phosphorus

Phosphorus is quite often the limiting factor in productivity of fresh water, not because it is needed in large amounts but because water is so frequently deficient in even the small amount necessary (Hutchinson, 1957). Since this is especially true in bog lakes, any effect which liming might have upon phosphorus concentration in the lake waters would be very important. An increase in phosphorus would tend to increase productivity but a decrease might completely cancel out any favorable effects of lime addition such as increase in alkalinity or pH.

Waters experimented with lime addition to bottles of water containing lake bottom mud and found that, after a thorough shaking, the amount of dissolved phosphorus in the water increased. He attributed this increase to the addition of lime which raised the pH and alkalinity of the water and caused phosphorus to be released from the mud (Waters, 1956). Macpherson, Sinclair and Hayes (1958) tried similar experiments with phosphorus release from mud to distilled water in an agitated bottle and demonstrated that the release of phosphorus from the lake muds was influenced by pH with sharp increases in release occurring at about pH 6.5 and minimal transfer of P from mud to water occurred at pH values from 5.5-6.5. This would be very important in the lakes studied because lime application brought pH from about 5.5 to about 7.0 so there should have been an increase in release of phosphorus if pH were the important factor.

But, there is an important difference between the bottle experiments and the experiment conducted on an actual lake. The bottles of mud, water and lime were thoroughly agitated and mixed and this was not the case with the lake bottom. Zicker, Berger, and Hasler (1956) added lime to undisturbed bottles with a clear mud-water interface and found that the lime only affected phosphorus release from the top one-fourth inch of the mud and was unable to penetrate far enough to have any effect below that level. They found that lime addition actually suppresses the amount of phosphorus in the water due to adsorption of phosphate ions onto the surface of the calcium particles. Maximum release of phosphorus was attained by acidification of previously limed mud-water systems. Hasler (1957) and Stross and Hasler (1960) reported that lime application to lakes in the Michigan-Wisconsin border region caused precipitation of phosphorus to the bottom with the lime.

Waters (1956) found that lime addition did increase phosphorus levels in Starvation and Timijon Lakes and my 1963 analyses (Table 9) showed sustained phosphorus levels in these two lakes in the lower regions and a large increase in phosphorus in Starvation Lake near the bottom. No data are available for Stoner Lake before liming. Waters attributed these increases to release of phosphorus from the mud because of the lime application. This is not consistent with the findings by Zicker, Berger and Hasler (1956) that lime precipitated phosphorus in undisturbed mud-water systems. But, the increase in phosphorus concentration parallels the increase in hardness and alkalinity at lower levels of the two lakes. This could indicate a buildup of phosphorus because it was adsorbed onto the calcium particles which were precipitated out from the upper water levels as $CaCO_3$ and held at these levels or it could mean that phosphorus was introduced at time of liming as an impurity in the lime. Waters (1956) claims that analysis of the lime showed only a negligible amount of phosphorus present (a lime solution of 75 PPM alkalinity contained only about one PPB phosphorus) but even a very small amount would be important if it settled to the lower levels of the lakes and was concentrated there.

The increase in pH of the bottom water could also have an effect upon release of phosphorus from the mud to the water. Both Timijon and Starvation Lakes have bottoms which are composed largely of organic material which forms

Table 9. Total phosphorus in parts per billion P

| Limed Lakes | Average of All Samples Before Liming | Average of All Samples After Liming | Average of Two Samples 1963 |
|---|---|---|---|
| Starvation | | | |
| Level 1 | 14.7 | under 10 | under 10 |
| 2 | 12.3 | 14.0 | 15.5 |
| 3 | 30.3 | 34.7 | 12.0 |
| 4 | 192.0 | 236.7 | 617.0 |
| Timijon | | | |
| Level 1 | under 10 | under 10 | under 10 |
| 2 | under 10 | 15.8 | under 10 |
| 3 | 10.0 | 15.8 | 38.0 |
| 4 | 20.3 | 153.0 | 43.0 |
| Stoner north | | | |
| Level 1 | No data before liming | | under 10 |
| 2 | | | under 10 |
| 3 | After liming 24.2 average at 3 and 9 feet in both basins | | under 10 |
| 4 | | | 18.0 |
| Stoner south | | | |
| Level 1 | | | under 10 |
| 2 | | | under 10 |
| 3 | | | under 10 |
| 4 | | | under 10 |

| Unlimed Lakes | Average of All Samples 1953-1955 | Average of Two Samples 1963 |
|---|---|---|
| Juanita | | |
| Level 1 | under 10 | under 10 |
| 2 | 13.9 | under 10 |
| 3 | 16.2 | under 10 |
| 4 | 71.5 | under 10 |
| Irwin | | |
| Level 1 | under 10 | under 10 |
| 2 | under 10 | under 10 |
| 3 | 10.7 | 41.0 |
| 4 | 47.3 | 79.5 |
| Grant's | | |
| Level 1 | under 10 | under 10 |
| 2 | under 10 | under 10 |
| 3 | 16.0 | under 10 |

a very large reservoir of phosphorus. After decay of the organic material the phosphorus becomes available for recirculation throughout the lake water but some sort of bacterial breakdown must occur to make the phosphorus available to the water. Lime addition changed the pH in the bottom waters from slightly acid to slightly alkaline and this could have increased the activity of bacteria in the bottom muds and so hastened the breakdown or organic phosphorus so more of it became available to be taken into solution in the water.

Even the unlimed lakes showed quite wide fluctuations in phosphorus concentration. This fluctuation was upward in some lakes and downward in others so no pattern was apparent. Quite wide weekly fluctuations were also reported by the other workers cited so this seems to be common, especially during periods of plankton blooms.

## Adsorbed Calcium

Tests for adsorbed calcium were made on samples of the bottom mud from Stoner, Starvation and Timijon Lakes but satisfactory results were obtained only from the tests run on the Stoner Lake samples. Determination end points (hardness test) for the Stoner Lake samples were sharp and clear and results of successive runs matched very closely. But, end points for the tests run on Timijon Lake and Starvation Lake were much too indefinite to be reliable and no end point was reached at all for some samples. This was no doubt due to interferences with the test chemicals but I was unable to eliminate the interference. So, only results of Stoner Lake will be discussed here.

Waters (1953) found such variation from day to day on Stoner Lake that he could not claim an increase in adsorbed calcium even though there was a higher average percent of calcium after lime addition. He attributed this variation to problems with his laboratory technique. Later, on Timijon and Starvation Lakes he was able to declare that there was a significant increase in adsorbed calcium in the bottom muds but declined to make quantitative estimates because of the difficulty in telling how much of the calcium was due to adsorbed calcium and how much was due to free carbonates (Waters, 1956). His data do indicate that there was about one and one-half times as much carbonate in the mud after liming as before. My results on Stoner Lake indicate that calcium in the bottom was about nine times as high in 1963 as before liming and about four to five times as high as it was shortly after liming (Table 10). This build-up of calcium carbonate in the bottom mud is occurring at the same time as a long-term decrease in hardness and alkalinity so seems to indicate a slow loss of the lime from the water to the bottom mud. Whether this is due to adsorption of calcium by the mud or to precipitation and settling of calcium carbonate particles is unknown.

Table 10. Adsorbed calcium as percent of dry soil

| Stoner Lake Sampling Station | Before Lime | After Lime | 1963 |
|---|---|---|---|
| M1 | Mean of 0.075 | Mean of 0.14 | 0.65 |
| M2 | | | 0.68 |
| M3 | | | 0.67 |
| M4 | | | 0.69 |

## Biological Sampling

### Bottom Organisms

The ultimate purpose of lime addition to the lakes was to increase the biological productivity of the lakes. If productivity did increase as Waters hoped, we would expect an increase in numbers and volume of bottom organisms and, possibly, a change in composition of the bottom community. However, to show an increase in productivity of bottom organisms due to liming we would not only have to show increases in the numbers and volume of invertebrates but would have to assume that I sampled the same spots Waters sampled, and in the same manner, and that there were no other significant changes in the ecosystem.

I attempted to sample in the exact same spots in the same manner as Waters sampled but exact replication was not possible because the water level in the lake in 1963 was two feet or more below 1953 levels. So, the exact same spot on the bottom was not subject to the same conditions during the two different summers and especially there would have been great differences in sunlight penetration. In some cases the sample site had to be moved farther out in the lake to get the depths anywhere near the same and this introduced the probability that the composition of the bottom was also changing and a change from sand to sandy peat could make a great difference in amount of food and cover.

Since Waters (1953) found quite pronounced seasonal variations in the bottom community I compared my data only with his data collected at the same time of year. My sample data taken in early August and late September are compared in Table 11 with his sample data collected on 31 July, 7 August, 14 August, 21 August, and 28 August.

Although it appears in Table 11 that there was a great increase in numbers and weights of bottom organisms between 1953 and 1963, I was not able to prove a statistically significant increase. It was not possible to show significance by parametric statistics using the F or t test because the variance among my samples was many times greater than that among Waters' samples. And, it was not possible to show significance by the non-parametric Wald-Wolfowitz runs test (Siegel, 1956) because I had only two sampling series and this was not enough for the test.

Table 11. Numbers and volume of bottom invertebrates per square foot of bottom sampled

| | Mean of Waters' Five Samples from 31 July to 28 August 1953 | | | | Mean of Early August and Late September Samples (2) 1963 | | | |
|---|---|---|---|---|---|---|---|---|
| Numbers | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Tendipedidae | 9.0 | 7.8 | 7.4 | 20.2 | 430.0 | 139.5 | 247.5 | 64.0 |
| Ceratopogonidae | 12.0 | 3.8 | 0.4 | 1.2 | 7.5 | 11.0 | 6.5 | 3.0 |
| Tabanidae | 0.2 | 0.0 | 0.0 | 0.0 | 2.0 | 0.0 | 0.0 | 0.0 |
| Odonata | 0.2 | 1.0 | 0.4 | 1.2 | 0.0 | 0.0 | 0.5 | 0.0 |
| Ephemeroptera | 5.0 | 4.2 | 0.2 | 12.6 | 4.0 | 10.5 | 3.5 | 0.0 |
| Trichoptera | 1.6 | 1.2 | 0.6 | 2.0 | 45.5 | 34.5 | 48.5 | 39.5 |
| Coleoptera | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Lepidoptera | 0.0 | 0.0 | 0.0 | 0.4 | 0.0 | 1.0 | 0.0 | 0.0 |
| Oligochaeta, large* | 1.2 | 2.8 | 1.4 | 2.2 | 0.0 | 2.0 | 0.0 | 0.5 |
| Oligochaeta, small** | 4.8 | 3.8 | 0.4 | 19.4 | 4.5 | 3.5 | 8.0 | 0.5 |
| Hydracarina | 1.4 | 0.0 | 0.0 | 0.8 | 0.0 | 0.0 | 0.5 | 0.0 |
| Volume expressed as cubic centimeters x 100 | | | | | | | | |
| Oligochaeta and Tabanidae | 1.4 | 0.4 | 0.6 | 1.8 | 5.0 | 3.0 | 4.0 | 14.0 |
| All others | 6.6 | 4.0 | 1.8 | 9.2 | 14.0 | 13.0 | 31.0 | 6.0 |
| Total | 8.0 | 4.4 | 2.4 | 11.0 | 19.0 | 43.0 | 35.0 | 20.0 |
| Overall averages of all four stations | 6.5 | | | | 29.2 | | | |

*Lumbriculidae.

**Tubificidae.

Upon inspection of Table 11 it appears that there were some very substantial increases in both numbers and volumes with the increases being especially great among the Tendipedidae and Trichoptera. But, variability among these groups was especially great. For example, at Station 1 there were 844 Tendipedidae found in September and only 16 at Station 1 in August. At the same spot there were 91 Trichoptera in September but none in August. It is extremely unlikely that one month would make that much difference so the wide range in numbers is probably a reflection of error in locating the sample spot. So, even with such pronounced increases in average numbers and volumes of bottom organisms it is just not possible to show that there was an overall increase in productivity of bottom organisms.

It may be important to note that Waters' sampling in 1953 did not at any time reveal nearly such large numbers and volumes of bottom organisms as were found in September of 1963. The 1963 increase may really be due, at least in part, to effects of addition of the lime but effects of the probable change in sampling spots due to lowering of the water level must not be ignored. Because the water level was lower the sampling spots had to be taken farther out in the lake to put them at anywhere near the depth at which Waters sampled. This also means that the bottom type would be changing and the organic material of the peat near the center of the lake basins would be increasing in proportion to the amount of sand in the sample. This increase in organic material would make food more available for detritus feeders and would make burrowing much easier for forms such as the Tendipedidae which were found to increase so much from 1955 to 1963.

No changes in community composition were noted. I found no organisms not found by Waters and the only thing he found that I did not was Coleoptera and he only found one in five sampling periods. Stoner Lake was the only one in which bottom samples were taken because it was the only one in which Waters had collected previous data.

## Fish

Yellow perch, *Perca flavescens* (Mitchell), were plentiful in Stoner Lake in both 1953 and 1963. Waters found the population in 1953 to have a bimodal size distribution. The smaller fish fed upon bottom organisms, which were scarce, so these fish were stunted and had a slow rate of growth, and the larger fish fed upon the smaller, which were very numerous, so the larger fish had a relatively high growth rate because of the abundant food supply. To compute mean length and rate of growth Waters divided the sample fish into three groups. Invertebrate feeders were 3.5 to 6.0 inches long and the cannibalistic larger fish were 10.1 inches long or greater. A third group was made up of the fish in between to prevent overlap of the other two size classes.

In the 1963 sample all fish taken fell in the small group 3.5 to 6.0 inches long (Table 12). Not only were no larger fish caught but residents along the lake shore said they had not caught any fish longer than six inches in recent years and no larger fish had been found along the shore after winterkills which were reported by the residents. So, fish caught in 1963 could be compared only with the fish in the smallest group taken by Waters in 1953.

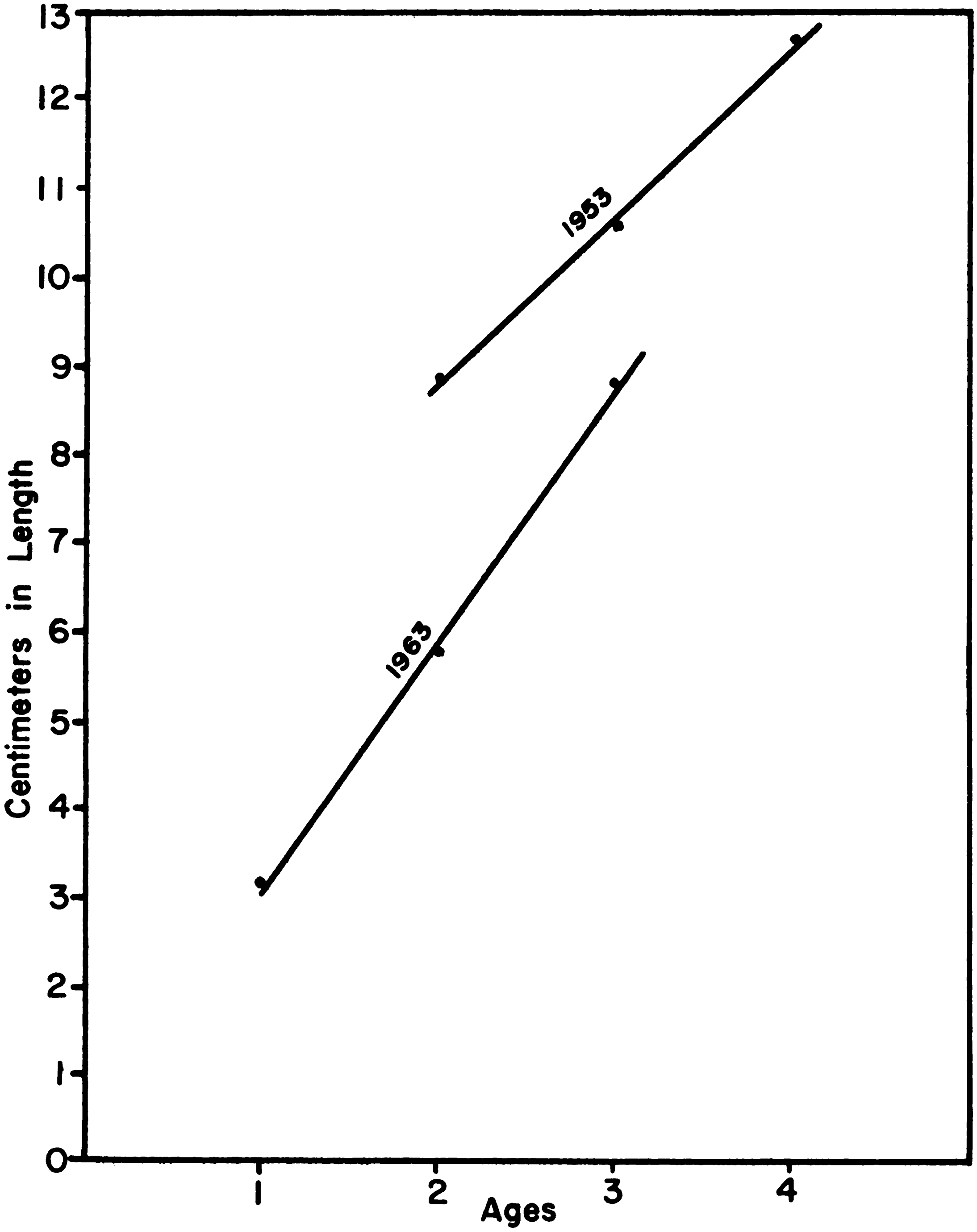
When I plotted a regression using length and age of the fish in the smallest group it appeared that the fish in 1963 were considerably smaller than in 1953 but had a higher rate of growth (Figure 37). This is likely due to several factors besides the addition of lime.

Waters collected the fish in group one by gill net and by angling and believed that this method was unbiased and resulted in a normal distribution of the fish within the group (Waters, 1953). I do not think this would be the case because both angling and gill netting would favor collection of the larger fish within a group of fish 3.5 to 6.0 inches long. I collected by angling and seine. The effect of angling would be the same both times but, since seining was necessarily done in the shallows, it very likely favored collection of smaller fish within the group. So, if Waters' methods were biased in favor of larger fish and mine in favor of smaller fish we would expect just what I found. The fish sampled in 1963 were smaller.

Table 12. Lengths, weights, and ages of Stoner Lake perch

| Length | | Weight | Length in cm at Annuli Formation | | |
|---|---|---|---|---|---|
| Inches | Centimeters | in Grams | I | II | III |
| 3.8 | 9.7 | 8 | 2.7 | 5.1 | ... |
| 3.9 | 9.9 | 12 | 2.8 | 5.9 | ... |
| 3.8 | 9.7 | 8 | 5.0 | 6.9 | ... |
| 4.2 | 10.7 | 11 | 2.6 | 5.0 | ... |
| 4.6 | 11.7 | 17 | 4.0 | 6.9 | ... |
| 4.8 | 12.2 | 19 | 2.8 | 7.5 | ... |
| 4.7 | 11.9 | 20 | 3.4 | 5.4 | ... |
| 4.6 | 11.7 | 14 | 4.0 | 7.2 | ... |
| 4.5 | 11.4 | 16 | 2.8 | 5.0 | ... |
| 4.1 | 10.4 | 11 | 3.9 | 5.6 | ... |
| 4.3 | 10.9 | 12 | 4.3 | 7.4 | ... |
| 4.3 | 10.9 | 13 | 3.2 | 5.2 | ... |
| 4.5 | 11.4 | 15 | 2.7 | 8.4 | 9.7 |
| 4.4 | 11.2 | 14 | 3.5 | 5.9 | ... |
| 3.9 | 9.9 | 9 | 3.4 | 5.4 | ... |
| 4.0 | 10.2 | 11 | 2.2 | 5.0 | ... |
| 4.0 | 10.2 | 12 | 3.4 | 6.4 | ... |
| 4.3 | 10.9 | 14 | 3.2 | 5.1 | ... |
| 4.6 | 11.7 | 17 | 2.7 | 5.2 | ... |
| 4.3 | 10.9 | 13 | 2.2 | 5.1 | 7.9 |
| 4.0 | 10.2 | 11 | 2.0 | 4.5 | ... |
| 4.7 | 11.9 | 19 | 2.4 | 5.8 | ... |
| 3.9 | 9.9 | 12 | 2.9 | 5.9 | ... |
| 4.3 | 10.9 | 15 | 2.4 | 4.5 | ... |
| 4.3 | 10.9 | 14 | 4.3 | 6.1 | ... |
| 4.2 | 10.7 | 12 | 3.1 | 5.7 | ... |
| 4.1 | 10.4 | 10 | 3.7 | 6.4 | ... |
| 4.0 | 10.2 | 12 | 2.5 | 5.0 | ... |
| 4.1 | 10.4 | 10 | 2.5 | 4.9 | ... |
| Mean length at each annulus in centimeters | | | | | |
| | | | 3.12 | 5.8 | 8.8 |

Figure 37. Length versus age of yellow perch in Stoner Lake.


Centimeters in Length
Ages
0
1
2
3
4
5
6
7
8
9
10
11
12
13
1
2
3
4
1953
1963

The apparent rate of growth may also be due to more than one factor. Pike were introduced into the lake in fairly small numbers by the residents around the lake. Pike would prey upon the perch and tend to reduce the population size with a resultant increase in growth rate of individual perch, but, we have no accurate estimate of the numbers of pike so their effect upon the perch population cannot be determined. Winterkills have been reported in the past few years and a reduction in population by this means would also cause an increase in the rate of growth. If production of bottom organisms was increased by addition of lime, this also could result in an increased growth rate for perch, especially if increase in food production happened at the same time as a decrease in fish population size due to pike introduction or winterkill. An increase in standing crop of bottom organisms was indicated but not shown conclusively.

# SUMMARY

Calcium compounds were applied to Stoner Lake in June, 1952, by T. F. Waters at the rate of 26.5 pounds of hydrated lime ($Ca(OH)_2$) and 6.2 pounds of ground limestone ($CaCO_3$) per acre-foot of water. In the summer of 1953 Waters added lime in a slurry to Starvation Lake at a rate of 50 pounds per acre-foot and to Timijon Lake at the rate of 37 pounds per acre-foot. The lime was added with the expectation that it would bring about chemical changes in the lake waters which would result in a higher rate of biological productivity for the lakes. In order to determine the effects of lime addition, Waters conducted a series of chemical and biological tests upon the three limed lakes and three unlimed control lakes both before and after lime application. Significant changes were noted (Waters, 1953, 1956) so the present study was undertaken in 1963 to determine whether the effects noted shortly after lime addition were still evident after a ten-year period. In order to answer this question the original methods of chemical and biological sampling were followed as closely as possible.

Apparent long-range effects of lime application are as follows:

## Chemical and Physical

1. Dissolved oxygen--No effect upon dissolved oxygen levels was noted either immediately after liming or in 1963.

2. Light penetration--No effect upon light penetration was noted.

3. Hardness and alkalinity--Alkalinity in Stoner Lake rose from 6 parts per million $CaCO_3$ before liming to 15 parts per million after lime application in 1952. By 1963 alkalinity had declined to 9 parts per million, still very low but 50 percent higher than before lime application.

Total hardness and alkalinity in Timijon Lake rose with lime application in 1953 from about 5 parts per million $CaCO_3$ to a level 15 times that high. By 1963 alkalinity and hardness had dropped to 20 to 35 percent of the highs reached just after liming but they are still two or more times as high as before lime was added, with greatest concentration found just off the bottom.

In Starvation Lake, from an initial concentration of about 5 parts per million $CaCO_3$, total hardness and alkalinity underwent four- or five-fold increases in the upper layers and increases of 12 times or more near the bottom when lime was added. By 1963, concentration of $CaCO_3$ had fallen to about 50 percent of the highest levels. In the upper levels this means a continued 100 percent increase over pre-lime concentrations. But, in the water just off the bottom the $CaCO_3$ concentrations in 1963 were nearly six times as high as pre-lime levels. No significant changes were found in alkalinity or hardness in the control lakes.

4. pH--Rise in pH closely parallels the rise in total hardness and alkalinity. In Stoner Lake lime addition brought about an increase in pH from 6.8 to 8.0 in both basins. By 1963 pH had decreased to an average of 7.0, nearly the original level. In Timijon Lake pH increased from about 5.5 to over 7 at the three upper layers and from 5.5 to over 9 at level 4 just off the bottom. By 1963, pH had decreased from 1955 levels but was still at least one pH unit higher than before liming except at level 4 near the bottom where it was only 0.6 units higher than pre-liming values. In Starvation Lake pH was increased from an initial value of about 5.4 to an average of 6.6 at the top three sampling levels and increased to 8.1 at the lowest level just off the bottom. By 1963, pH had decreased at all sampling levels but was still one unit above pre-lime values at the upper two levels and one-half unit higher than pre-lime values at level 4 just off the bottom. No changes were noted in pH in the control lakes.

5. Conductivity--No previous data were available on conductivity in Stoner Lake so no changes could be noted. Conductivity in both Starvation and Timijon Lakes increased greatly with lime application. Six-fold increases were

noted at the upper three sampling levels and a ten-fold increase was found near the bottom of both lakes. By 1963, conductivity was about 50 percent as high as just after liming but was still two to five times as high as before liming. No changes were noted in the control lakes.

6. Color--Waters found no significant decrease in color with lime application but got a temporary increase in color in Starvation and Timijon Lakes. In 1963, Stoner Lake was slightly less colored but the other five, including controls, had color increases. Since the controls changed also, this could not be attributed to effect of lime application.

7. Phosphorus--No pre-lime data are available for Stoner Lake so no comparisons could be made. Waters found that liming did increase phosphorus concentration in Starvation and Timijon Lakes and increase was especially great at the lower level just off the bottom. By 1963, phosphorus concentration was about at the pre-lime level except in the deepest water where phosphorus values were twice as high as pre-lime levels in Timijon Lake and three times as high in Starvation Lake. Even unlimed lakes fluctuated quite widely in total phosphorus concentration, a phenomenon which other workers have found to be quite common, especially during plankton blooms.

8. Adsorbed calcium--Waters was unable to claim an increase in adsorbed calcium in Stoner Lake but did find

increased calcium deposits in the mud of Timijon and Starvation Lakes. The 1963 data, available only for Stoner Lake, show that calcium in the bottom mud was about nine times as high as before liming and four to five times as high as it was just shortly after liming. So, a buildup of $CaCO_3$ in the bottom mud is indicated but it is not possible to say this is all due to adsorbed calcium since some may be due to calcium carbonate particles settling out of the water.

## Biological

1. Bottom organisms--No change in community composition was detected in Stoner Lake. There appeared to be a great increase in numbers and weights of insects between 1953 and 1963 but it was not possible to show statistical significance due to the small sample size and extreme variability between samples.

2. Fish--Yellow perch collected in Stoner Lake appeared to be smaller for their age than in 1963 and to have a faster rate of growth. The small size may be accounted for by bias in both 1953 and 1963 sampling methods. The faster rate of growth, if it is real, may be due to population reduction due to winterkill, or pike introduction, or to increase in food supply. All fish caught were small and stunted.

Information obtained in 1963 does indicate that the initial chemical changes brought about by lime addition to soft-water bog lakes in 1952 and 1953 are still evident after a ten-year period and, in some cases, are quite substantial. Sufficient data are not available to show an increase in biological productivity due to lime application.

# APPENDIX

Table 13. Volumes of plankton sampled in 1963--average of two samples per station

| Lake | Volume in ml/liter of Water Sampled | Volume in ml/Sample* |
|---|---|---|
| Starvation | | |
| Level 1 | 0.013 | ... |
| 2 | 0.015 | ... |
| 3 | 0.010 | ... |
| 4 | 0.005 | ... |
| Timijon | | |
| Level 1 | 0.050 | ... |
| 2 | 0.010 | ... |
| 3 | 0.015 | ... |
| 4 | 0.010 | ... |
| Stoner | | |
| P-1 | ... | 1.60 |
| P-2 | ... | 1.50 |
| P-3 | ... | 4.25 |
| P-4 | ... | 7.50 |
| Juanita | | |
| Level 1 | 0.020 | ... |
| 2 | 0.045 | ... |
| 3 | 0.008 | ... |
| 4 | 0.008 | ... |
| Irwin | | |
| Level 1 | 0.080 | ... |
| 2 | 0.070 | ... |
| 3 | 0.013 | ... |
| 4 | 0.010 | ... |
| Grant's | | |
| Level 1 | 0.013 | ... |
| 2 | 0.020 | ... |
| 3 | 0.018 | ... |

*Plankton samples in Stoner Lake were taken by pulling a 12 cm diameter Wisconsin plankton net through the water for twenty feet at a speed such as to just keep the upper rim of the net below the water surface. Station designations for Stoner Lake refer to sampling spots illustrated on Figure 13.

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