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Mr. Greenbank

INSTITUTE FOR FISHERIES RESEARCH
DIVISION OF FISHERIES
MICHIGAN DEPARTMENT OF CONSERVATION
COOPERATING WITH THE
UNIVERSITY OF MICHIGAN

ALBERT S. HAZZARD, PH.D.
DIRECTOR

ADDRESS
UNIVERSITY MUSEUMS
ANN ARBOR, MICHIGAN

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PROGRESS REPORT ON WINTER-KILL STUDIES

1939-40

by
John Greenbank

Contents

Introduction

The study of the conditions for fish life under the ice in shallow lakes and ponds, on which a small start had been made in the winter of 1937-38, was continued during the period of ice cover of the winter 1939-40. This report is a summary of the work of the past winter and of the information obtained.

Inasmuch as the investigation presumably is to be continued and extended, this paper does not pretend to be a final report on, or a complete analysis of, the winter's data. Final deductions and conclusions will be deferred until much more investigation has been completed, since in the light of further data many of the conclusions which might be drawn now might well turn out to be invalid. Hence this is to be considered as a progress report only. Detailed tabular data are omitted, and there are included only such graphs as seem to present interesting or significant points.

It is difficult to determine just what is a "normal", and what an "abnormal", winter. However, the winter of 1939-40 definitely was abnormal, or at least unusual, in its prolonged duration. Ice strong enough to walk on persisted on the lakes of lower Michigan until the first few days of April, whereas it usually breaks up before March 15th or 20th. An opportunity was thus afforded of obtaining data over a relatively long and continuous time interval.

It might appear that the cumulative ill effects of decomposition processes over such an extended period would lead in the end to water conditions deleterious to fish life. On the contrary, and somewhat strangely, the worst condition for the season in each of the lakes under observation existed fairly early in the winter, and was followed by marked improvement. As will be demonstrated in more detail below, this shift in conditions was closely connected with weather conditions and changes in the amount of snow on the ice.

Actual winter-kill (to be described below) occurred in some of the waters studied this past winter, and varied from the death of a few dozen fish in one lake to the complete destruction of bluegills in a small pond. Reports named several other lakes in southern Michigan where mortality took place in some degree, mostly only moderately severe. On the whole the winter-kill apparently was somewhat greater than in 1937-38 or 1938-39, about equal to that of a hypothetically "average" winter, and much less than in the severe winter of 1935-36.

Lakes and Ponds Studied

(1) Mud Lake, near Waterloo, Lyndon Township, Washtenaw County. - This lake, about 60 acres in area, has a maximum depth of 5 feet. Its bottom is soft and mucky, with some marl. Both the inlet, from Sugarloaf Lake, and the outlet, into Waterloo Mill Pond, flowed from about one to five cu. ft./sec. all winter.

Samples were taken at four stations in the body of the lake, and at a station each in the inlet and outlet.

(2) Green (or Stoffer's) Lake, three or four miles northwest of Chelsea, on State Highway 92, Washtenaw County. - Green Lake has a maximum depth of 10 or 12 feet, but the depth throughout most of its area is less than 5 feet. There is no winter inlet or outlet of any consequence.

The one sampling station was near the middle of the lake where the depth is about $3\frac{1}{2}$ feet.

(3) Clear Lake, Waterloo Township, Jackson County. - This lake of about 140 acres reaches a depth of about 30 feet. Although in general the bottom is fairly soft, the water is much clearer and is less rich organically than that of the two lakes named above.

Two sampling stations were adopted.

(4) Pasinski's Pond, in Livingston County, about two miles east of Howell. - This private pond of about 4 acres has a maximum depth of 4 to 5 feet. The bottom is very soft and mucky.

I did some work on these four bodies of water in 1937-38. The following additional lakes were investigated in 1939-40.

(5) Unnamed acid bog lake (hereinafter called Bog Lake), Section 21, Lyndon Township, Washtenaw County. - This typical, brown-water, acid bog lake, with an area of $\frac{1}{2}$ acre or less and a maximum depth of about 6 feet, is bordered by a sphagnum mat. During the period of observation, its pH varied from 5.5 to 6.5, and its methyl orange alkalinity from 5 to 12 parts per million. It is completely isolated from any other body of water.

In the files of the Institute for Fisheries Research are maps or inventory cards, or both, for these five bodies of water.

(6) Hatchery Ponds. For some experiments described below, five of the small experimental ponds at the Drayton Plains Hatchery were used. These ponds are approximately alike. Each covers 50 x 100 feet, and is about 3 feet deep.

(7) Richmond Lake, Waterford Township, Oakland County. - This body of water, about 15 or 20 acres in extent, and with the greatest depth about

10 feet, has no distinct inlet or outlet. The bottom is very mucky, and the lake may be considered well advanced in senescence. The present margin of peat foretells the eventual fate of the lake basin.

Not on the list as initially scheduled, this lake was investigated after a report was received, from the personnel of the Drayton Plains State Hatchery, that fish were dying there in mid-February. Subsequently, several samples were taken.

Methods Used

Although some experiments (described below) were conducted, for the most part my time in the field and laboratory was taken up with periodic observations on the chemical conditions in the waters, in order to obtain a knowledge of how and when a situation dangerous to fish may arise. Samples from each body of water were taken at least once and often twice a week. An automobile was driven onto the lakes during the period of thickest ice, and at other times either a portable shanty or a hand sled fitted with a gasoline lantern, to keep samples from freezing was used.

Dissolved oxygen was determined by the unmodified Winkler method. The samples were fixed in the field, and titrated later in the laboratory. Alkalinity and pH tests were performed in the laboratory as soon as the samples could be brought in, before they warmed up. The pH tests were made colorimetrically, with a Rascher-Betzold comparator set.

Chemical Conditions in Lakes

1. Clear Lake.

The two stations at Clear Lake were in approximately the same locations as those used in 1937-38. The depth at Station 1 was about five feet, and the bottom was sandy mud. On each trip two samples were taken at this station, the one labelled "surface" at a depth of six inches, and the one labelled "bottom" at a depth of four feet, or about one foot off the bottom.

Station 2 was in about 22 feet of water, over a mud bottom. Samples for oxygen tests were taken at ½, 5, 10, 15, and 20 feet, and for alkalinity tests at ½, 10, and 20 feet.

Graph 1 shows the dissolved oxygen at the two depths of Station 1. A very gradual decline throughout the winter is indicated, but nothing approaching serious conditions was reached even after three months of ice cover.

The dissolved oxygen at Station 2 is shown in Graph 2. At the start of the ice cover (ice had been forming throughout the latter half of December, but not until December 31 was it safe to walk on, in order to get samples), the water was almost uniform in dissolved oxygen from top to bottom, presumably retaining such a condition from the fall turnover. Henceforth, however, not only was there a gradual decrease in the value for each depth, but there was a marked spreading of the curves; i.e., the development of normal winter stratification. In early March the dissolved oxygen at 20 feet had dropped to about 3.5 parts per million, while the water at the surface still carried about as much as it had in December, approximately 14 p.p.m.

The developing stagnation is also shown by the curves for pH (Graph 10). The sudden drop in pH of the surface sample in the first week of March obviously was due, not to stagnation, but to dilution with rain and snow water, which was relatively much less alkaline than the lake water. The curves (Graph 12) for methyl orange alkalinity likewise present the contrast between the relative constancy of chemical characteristics of the deeper water and the changeability of the surface water.

Clear Lake is well named. With the shanty to aid in cutting out extraneous light, I could easily see the top of the sampler, a 4-inch galvanized disc, at 20 feet. It is reasonable to suppose that with such a small proportion of suspended material, the water of the lake does not become dangerously stagnant, even in abnormally severe winters. It is recorded that the fish in this lake were not winter-killed in 1935-36, when a heavy toll was taken from many other lakes of the region -- some of them about as deep as Clear Lake.

2. Mud Lake

In Mud Lake I took samples at four stations (instead of only one as in previous work), plus a station in the inlet and one in the outlet, in the hope of determining whether a correlation exists between the condition of the water and the type of bottom and the rooted vegetation at the station. In examining the data, however, I have not found any definite evidence of such correlation. Probably other factors, in particular the shifting of the water mass by currents, effectively upset any relationship which otherwise might have been established.

At Station 1, where the depth is about three feet, the very soft, mucky bottom supports very little vegetation. Lying about the center of the deeper part of the lake, and just outside the channel of main inflowing current, this station responded more or less to changes in the condition of the inlet stream.

At Station 2, with a depth of about 1½ feet, the bottom is of marl and there is very little vegetation.

Station 3, about 1½ feet deep, has a soft, mucky bottom and a dense growth of pond-weed. This station was relatively near the outlet, and was somewhat subject to outflowing currents.

Station 4, about 2 feet deep, has a fibrous peat bottom and dense _Chara_. Stations 2 and 4 were in relatively quiet water, and were less affected by currents than were Stations 1 and 3.

One sample, at six inches depth, was taken at each of the stations; and a second sample, at two feet, usually was secured at Station 1.

Graph 3 shows the dissolved oxygen at the two depths at Station 1. For reference, the curve for the dissolved oxygen at the inlet station is superimposed on this graph. Graph 4 gives the dissolved oxygen at Stations 2, 3, and 4.

Because of proximity to the inflowing current, the oxygen at Station 1 followed rather closely that in the inlet stream. Furthermore, the curves for Station 1 and the inlet are decidedly flatter than those for the other stations. The water of the inlet, which carried a steady stream all winter, traverses only a short distance (about a quarter mile) between Sugarloaf Lake and Mud Lake. Since Sugarloaf Lake is a larger and deeper lake, its water presumably does not fluctuate so rapidly in dissolved oxygen as does that of Mud Lake. Since the stream was partly open most of the winter, there is a possibility of some oxygen exchange with the atmosphere.

It is interesting to note that in spite of the effect of inflowing water, and although the two sampling depths at Station 1 were only $1\frac{1}{2}$ feet apart, a very definite stratification in dissolved oxygen existed almost continuously. The curves for the two samples are remarkably parallel in their rises and falls; and yet, with the exception of one sampling date, when the water at the station apparently was well mixed, the upper water at all times was higher in dissolved oxygen than the water nearer the bottom. The incoming water may have flowed near the surface to produce this result, but it seems more probable that the higher oxygen value near the surface was due to ~~the~~ greater oxygen consumption in the bottom water, or to greater photosynthetic production of oxygen in the surface water, or to both factors.

Graph 5 indicates that, during almost all of the period during which observations were made, the water flowing into Mud Lake carried more dissolved oxygen than that flowing out. The difference is not subject to strict quantitative interpretation, because no measurements were made of the rates of flow of the inlet and outlet streams. Assuming, however, that these flows were fairly steady and that they were comparable in magnitude, then the water may be considered definitely to have lost dissolved oxygen in its transit through the lake. Such a consideration points toward the desirability of making a much more intensive series of measurements of dissolved oxygen in all parts of a lake, with a view toward arriving at a complete oxygen budget.

Mud Lake suffered a heavy winter-kill in 1935-36*, but there was no

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*Cooper, Gerald P. The effects of the 1935-1936 winter kill of fishes in the following lakes: Bateese in Jackson County; Mud, Stoffer's and Sugarloaf in Washtenaw County, and Park in Clinton County. Inst. Fish. Res. Report No. 351, April 9, 1936.

appreciable fish loss in Mud Lake, 1939-40, for I could find no dead fish along the shores when I visited the lake a few days after the ice went out. It would be a matter of pure conjecture to say whether or not the oxygen brought into the lake by the inlet stream was the redeeming amount that prevented a kill, but at any rate it probably had at least some beneficial effect.

3. Green Lake

In contrast to Mud Lake, Green Lake had very little inflowing water during the winter period, and its outlet during that time was a mere trickle. In many other regards the two lakes are similar. Green Lake has a somewhat greater average depth, perhaps; but even so it has a large area of shallow water. The bottom is soft, and has a considerable amount of rooted vegetation. The heavy mortality of fish in this lake during the severe winter of 1935-36 was studied by the Institute[*].

The time schedule did not permit the taking of a very extensive series of samples from Green Lake. Samples were secured at one station only, at least once a week, and toward the end of the ice-cover period about twice a week. The station was in about 3½ feet of water, over a soft bottom, and in moderately dense pondweeds. Two sampling depths were used, six inches and 2½ feet.

The two dissolved oxygen curves for the station in Green Lake are shown on Graph 6. Here again there is indicated a distinct tendency for the curves for the two depths to run parallel, but apart. Since wave

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[*] Cooper, Gerald P. The effects of the 1935-1936 winter kill of fishes in the following lakes: Bateese in Jackson County; Mud, Stoffer's and Sugarloaf in Washtenaw County, and Park in Clinton County. Inst. Fish. Res. Report No. 351, April 9, 1936.

action is prevented by the ice cover, and since diffusion of dissolved oxygen is extremely slow, it is possible for a distinct chemical stratification to develop in very shallow water.

The "peak" points, in the curve for the 6-inch sample, for the dates March 20 and March 31, represent, at least in part, sudden augmentations of dissolved oxygen by the running in of rain water or melting snow and ice.

Graph 11 shows that the pH of the water of Green Lake underwent an almost steady decline throughout the ice cover period. The resemblance of the pH curves to the dissolved oxygen curves is of course to be expected.

On March 3, Mr. Stoffer, who lives on the lake, cut a hole in the ice, about 3 feet square and about 80 feet from my sampling station. For about a week or ten days thereafter, he kept this hole free of ice, hoping to better conditions for fish life by maintaining this contact of water and open air. Samples taken in this open hole, however, showed the water there to be no higher in dissolved oxygen than at the sampling station.

After the ice had disappeared from the lake I observed perhaps a total of a hundred dead fish, at a few places along the shore and at the outlet dam. Since these fish probably drifted after the ice was gone, there is no way of knowing at what place or places in the lake they died.

4. Bog Lake

Samples were taken at depths of 4 inches, 1 foot, 2, 3, 4, and 5 feet at the one sampling station in Bog Lake. The dissolved oxygen curves for three of these depths are plotted on Graph 7.

Here is a really striking example of stratification within a small depth. For an 80-day period the dissolved oxygen at the 5-feet depth remained at less than one part per million; yet during that time the oxygen at the surface fluctuated from 14 p.p.m. to 0.6 p.p.m., and back to 15 p.p.m.

Further mention of the conditions in Bog Lake will be made in the theoretical discussion below.

5. Richmond Lake

Attention was called to Richmond Lake by a report of dying fish, and the first visit to the lake was made on February 18. At that time, although 12 inches of ice elsewhere covered the lake, there was a hole about 8 feet in diameter which had been kept open, presumably all of the time. Either the local entrance of spring water or the movements of fish might explain why this hole had not frozen over (it obviously had not been cut). Literally hundreds of golden shiners and dozens of bullheads, and a few sunfish, milled about at the surface in the open hole; and there were many dead fish, mostly shiners and a few sunfish, at the bottom. According to report, many hundreds of minnows had been dipped out by various people, for use as bait.

Dissolved oxygen tests suggest that the fish were to a large extent defeating their own purpose by congregating at the open hole. Samples taken at that time showed the water at 1-foot depth in the open hole to contain only 0.4 parts per million dissolved oxygen; while that at the same depth another place, where the ice was undisturbed, still had 1.9 parts per million. It might be assumed that the concentration of live fish in the open hole, and the decay of the dead fish, had consumed most of the small amount of oxygen which otherwise would still have been in the water, and of course used it much faster than it could be replaced by diffusion from the air. An alternative explanation of the low oxygen value in the open hole, however, would be the possible local inflow of oxygen-less spring water.

On February 22, there was little difference in the dissolved oxygen at the open hole and at the ice-covered station, the amounts (at the one-foot depth) being 1.1 and 0.7 parts per million respectively; and on March 4 the water in the open hole had 1.0 p.p.m., and that at the other station 0.6 p.p.m.

On March 9 the open hole had frozen over, with about ½ inch of ice. No live or freshly dead fish were in evidence. The water here still had only 0.3 p.p.m. dissolved oxygen, while the oxygen at the other station had increased to 2.8 p.p.m. Evidently those fish which were still alive had more or less dispersed themselves; and the most severe conditions had passed.

Unfortunately, no observation of the lake was made after the ice went out, but the total number of winter-killed fish probably was rather large.

Experiments at Hatchery Ponds

Early in December, 1939, I filled five of the small hatchery ponds (described above) with river water, to a depth of about 2½ feet. In order to maintain the water level, and to prevent bursting of valves, a small flow of water was left running into, and out of, each pond.

The intention was to use two of the ponds for experiments, and thus have three for controls. However, this plan went astray. Early in the winter the flow into one of the ponds ceased, and the water in that pond became somewhat erratic in its chemical characteristics, and quite different from that in the other ponds. On the other hand, the flow into another pond remained too large throughout the winter, so that water in that pond had almost the characteristics of river water at all times.

Thus only three ponds (Nos. 8, 9 and 10) remained, the data from which are at all comparable. Even in these three the flow of water was probably larger than might have been desired; for they behaved to some extent as running, rather than as standing, water. Since the flow through each of them was very nearly the same, and since the ponds were almost identical in dimensions, bottom, and other features, they may be considered to have been at least fairly good controls upon each other.

These three ponds were allowed to remain undisturbed, except for the taking of samples, until February 12. On that date the snow was shovelled cleanly off Pond 10, baring the ice. From that time on, the snow was removed from this pond soon after each new snowfall. On February 17 the ice on Pond 8 was completely covered with a layer of building paper, which was held in place by putting back on it the snow that had been on the ice. The paper stayed in place very well from then until the break-up of the ice. Pond 9 was left unmodified, as a control.

Periodically, dissolved oxygen samples were taken from these ponds, usually one sample at the outlet weir and one in the geometric center of each pond. The depth of sample was 1 foot. The curves representing the dissolved oxygen for the middle sample of each of these three ponds are shown in Graph 8.

In view of the fact that these curves stayed so closely together until the beginning of experimental conditions, their divergence after that time appears to be significant. Apparently the amount of light reaching the water did have a definite effect upon the amount of dissolved oxygen. Furthermore, it seems reasonable to suppose that this effect would have been much more striking had there not been a continuous partial displacement of water.

The water in the paper-covered Pond 8 at most times equaled, or slightly exceeded, in dissolved oxygen the water in the river itself. Thus it would seem that the differences between the curves for the three ponds ~~were~~ due not so much to diminution of oxygen in Pond 8 as to its production in Ponds 9 and 10. The amount of light reaching the water in Pond 9, through the snow-covered ice[*], apparently was enough to produce some photosynthesis; and the water in Pond 10, with the snow removed from the ice, did still better in oxygen production. In view of the fact that the river water coming into the ponds already was within a few parts per million of saturation in dissolved oxygen, the raising of the amount of oxygen within the ponds seems to have significance.

Experiments on Pasinski's Pond

Pasinski's Pond is of a certain special interest in that it furnishes the first instance in southeastern Michigan, of which I have knowledge, of the complete winter-kill of the entire population of a species of fish.

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[*] It must be remembered, also, that for a period of time in early March the ice of Pond 9 was bare, or nearly so.

Certain other bodies of water, as for instance Winnewana Lake, Washtenaw County, in 1935-36, supposedly have been completely "frozen out", only to have proved subsequently still to have left at least a few fish of each species. But in Pasinski's Pond, in the past winter, apparently every one of the bluegills present died; for rather intensive seining since then has failed to produce any.

This pond has, in the past, been the site of various activities of the Institute. It was poisoned three times in the fall of 1937 and spring of 1938, in an attempt to destroy the population of bullheads (Ameiurus nebulosus) which it then had. Although large numbers of the bullheads were killed, quite a few of them survived. The pond was stocked, in 1938, with several pairs of adult bluegills, at least a part of which spawned successfully that summer and again in 1939.

In the winter of 1939-40, then, the fish in the pond consisted of bullheads of various sizes, a large number of bluegills of one-year and young-of-the-year groups, and a very few remaining adult bluegills. During 1939 Beckman*, of the Institute staff, marked a number of the bluegills, in order to make a population estimate.

I made weekly visits to the pond during the period of ice cover of 1937-38; taking samples, however, at only one sampling station (roughly in the position of this winter's Station 15 - see below). The water of the pond remained in fairly good condition during that winter, and I did not observe any death of bullheads.

The pond is shallow, with a very soft, organically rich, bottom.

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*Beckman, W. C. Winter kill in Pasinski's Pond, Livingston County. Inst. Fish. Res. Report No. 594, April 16, 1940.

The water is fairly hard, with a usual methyl orange alkalinity of about 160-180 parts per million, and a normal pH about 8.0 or more. Vegetation is abundant. There is no steadily flowing inlet, but there is considerable surface run-in following storms. A small motor-driven pump, on the east shore of the north end of the pond, can deliver approximately 60 gallons per minute from a shallow well. This pump is used at times in the summer, to help maintain the water level in the pond. The outlet of the pond is small, and carries only intermittent overflow.

Although the pond is one simple basin, and has a total area of only about 4 acres, for purposes of interpreting certain data I have found it convenient to divide it, arbitrarily, into two parts, the north and south ends. The basis for this division is the kind, and to some extent the amount,of vegetation in each end. The north end has perhaps more rooted plants (chiefly pond-weeds), but the south end has a much larger growth of filamentous algae (mostly *Spirogyra* and *Cladophora*).

Starting early in January, I made weekly visits to the pond, taking samples at only one station (for reference purposes, this station is the same as Station 15 of the thirty or more numbered stations which I established later). This station was in about the center of the north end, and about mid-way across the pond from the pump.

By February 10, the dissolved oxygen in the north end of the pond, which had been steadily and rapidly dropping, had become dangerously low. On that date the pump was set into operation, and allowed to run continuously for seven days, in the hope that the water pumped in would carry enough dissolved oxygen to bolster the supply in the pond.

I thought at that time that the south end of the pond would afford an adequate experimental control on the pumping operations; since it would be unaffected by the pumped stream. However, as I soon discovered, the south end of the pond could not constitute a valid control, because the quantity of dissolved gases was quite different from that at the north end, at the start of the experiment. Probably this difference was due to the difference in vegetation, in that the algae in the south end were still producing some oxygen, so that the dissolved oxygen supply at that end was not so nearly exhausted.

On February 10 about twenty-five stations were established, in a sort of geometric pattern, in the north end of the pond, and three stations in the south end. Subsequently, on March 1, March 10, and other dates, about seven or eight stations were added to those in the south end. Samples were taken from nearly all of these stations at each visit -- once every three or four days until the break-up of the ice. The samples were taken at about $\frac{1}{2}$ foot depth.

The pump was turned off on February 17. It was started again on February 28, and ran continuously until March 6.

An effort was made to handle the dissolved oxygen data by drawing up maps, for various successive dates, showing lines of equal dissolved oxygen. These maps failed to present any clear-cut picture of the conditions, probably because slight currents and other local variations caused relatively large discrepancies from station to station.

Probably the most understandable, and at the same time perhaps the most valid, method of pictorially presenting the data is that employed in Graph 9. The single line running from January 7 to February 4 represents the dissolved oxygen at one place, Station 15. Joined to this by a dotted line, and then running to April 3, is a line representing, for each date, the highest dissolved oxygen value observed at any of the stations in the north end of the pond. Similarly, another line connects points representing the highest observed values at any station in the south end. Could it be assumed that the sampling was thorough (an assumption correct only to a certain degree), then the two lines would show the water highest in dissolved oxygen in the respective two ends of the pond at any one time. They do show, at any rate, that at any one time, in either end of the pond, there was water at least as high in oxygen as the value given by the curve. This point is somewhat vital, as will be pointed out below.

The peak values shown for March 8 and March 29 presumably were occasioned in part by run-in water from rain or melting snow.

It is difficult, with the data at hand, to prove either that the pumping did, or that it did not, have a definitely alleviating effect upon the condition of the water in the north end of the pond. Influencing factors were not well enough controlled to make the data entirely dependable. The first few days of running the pump seem to have brought about a slight increase in dissolved oxygen at some of the stations in the north end, or at least to have helped hold it at a fairly steady level. During the same period the amount of dissolved oxygen in the water of the south end was decreasing rapidly, probably because of decay of algae.

During the second period of operation of the pump the dissolved oxygen at certain stations in the north end increased rapidly, but at the same time it also was increasing rapidly in the south end, probably because of increased photosynthetic activity (see discussion below). In any event, the effect of the pumping seems not to have been manifest at any very great distance from the pump outlet. The pumped stream was, after all, rather small. Its oxygen content, as it came out of the pipe was about $1\frac{1}{2}$ - 2 p.p.m., but this was increased to about 4 - 6 p.p.m. by diffusion through mesh wire before entering the pond.

The inflowing water from the pump melted a hole through the ice at the edge of the pond, roughly 8 - 10 feet in diameter. This hole remained open during the time that the pump was running, and for a day or two after it was shut off. Figure 1 shows the pump discharge and aerating device. Figure 2 shows a view of the open hole at the discharge, and several of the stakes which marked sampling stations.

Figure 1. Pump discharge. Pasinski's Pond.

Figure 2. Open hole at discharge, and method of marking sampling stations.

On February 14, four days after the pump was first turned on, there were several bluegills in the open hole, still alive but not very active. On February 19, two days after the pump had been turned off, there were hundreds of dead bluegills in the open hole. At that time a sample of water taken in the hole, about 3 feet from the shore, had 0.9 p.p.m. of dissolved oxygen. Mortality struck rather suddenly; for on February 17 there had been very few, if any, dead fish. Apparently all or most of the bluegill population of the pond died within a few days, or at the most within two weeks; since I did not observe any dying or newly dead bluegills during March. Very few bullheads died in early February; but on February 28 I noticed many bullheads dead and dying at various stations. Altogether some 12,000 to 15,000 bluegills and over 1,000 bullheads died during the period of ice cover.*

A plausible explanation of the death of large numbers of bluegills in the open hole lies in their intense crowding. Attracted by the light, perhaps, these fish congregated at the open hole in such numbers that they used up most of the available oxygen supply, even though the pumped water was bringing in some oxygen. Once there, they remained, even until they died, rather than to move to better water (on February 19 there were 2.8 parts per million dissolved oxygen at a station only about 40 feet from the open hole). This instance is another bit of evidence that opening a hole in the ice is not, in itself, a means of preventing the suffocation of fish.

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*See Beckman, cited above, for estimates of numbers.

Theoretical Considerations

1. Snow, Light, and Dissolved Oxygen.

On each of the dissolved oxygen graphs is added at the bottom a graph showing the amount of snow present for each date. This graph is drawn up from data of the University of Michigan weather station, and shows the measured amount of snow on the ground at the station, in Ann Arbor, at any given time. Admittedly this amount may deviate somewhat, at times, from the amount on the ice on any one of the lakes which I studied. However, most of the snow-storms of southeastern Michigan are general. Furthermore, my measurements of snow on the ice were made at intervals of two or three days to a week (whereas those at the weather station were made twice daily); and were far from precise, because the depth of snow on the ice varied from place to place. So I believe that the curve as shown is a more satisfactory one than I could draw from my observed data, and that, in general and with only minor discrepancies, it presents a true picture of the amount of snow on the ice.

The snowfall of the winter came in frequent, but small, amounts. According to the weather record, it snowed at least a small amount on each of 59 of the first 90 days in 1940; yet the maximum recorded snowfall in any one day (from 7 P.M. to 7 P.M.) was only 4.3 inches, the greatest amount of snow on the ground at any one time was only 7 inches, and the total snowfall for the period was only 24 inches.

However, as the graphs demonstrate, even those small amounts of snow, as expressed in the fluctuations from time to time of the depth of snow on the ice, had a definite and at times a considerable effect upon the dissolved oxygen in the water. I shall point out, below, a few of the most apparent instances of this correlation.

In Graph 1, for Station 1, Clear Lake, shows no obvious connection between the amount of snow on the ice and the oxygen content of the water. The amount of dissolved oxygen remained high and fairly steady throughout the period of ice cover. I have as yet no explanation for the slight reaction of this water to changing light conditions, as contrasted to an apparently much greater (and at times almost immediate) response of the water in some of the other lakes.

Dilution with run-in water (which has been mentioned above) was largely responsible for the sharp drop, in late March, in the curve for the top sample of Station 1. This drop, however, did not bring the dissolved oxygen to anything near a dangerous value. The effect of the water brought in by rain or melting snow or ice was manifested, on several occasions in March, in rather abrupt changes in the characteristics of the upper layers of water of the several lakes and ponds studied. These changes must not be confused with trends of the undisturbed water.

The top sample at Station 2 of Clear Lake (Graph 2) behaved much as did the top sample at Station 1. The deeper samples at Station 2 showed a more or less steady decrease in oxygen during the winter, with no obvious correlation with light conditions. I do not have an explanation for the surprising rise in the curve of the 15-foot sample in late January.

In Graph 3 (Mud Lake, Station 1), each of the peaks of January 21 and March 8 closely follows a reduction in the amount of snow on the ice, and the low points of February 24 and March 3 follow snowfalls. The curves for Stations 2, 3, and 4 of Mud Lake (Graph 4) all show a definite tendency to be influenced by the amount of snow on the ice. During a period of bare ice in early March the oxygen at Station 4 reached a high point of 19.4 parts per million, or approximately 140% saturation.

In Green Lake (Graph 6) the drop in oxygen was fairly steady until it reached its low point in early March. It is conceivable that oxidation processes in the water, when once well started, were sufficiently consequential that their effects were not influenced to any great extent by photosynthetic activity. Also it is possible that the oxygen producers (plankton algae, or whatever they may be) were so disturbed by organic conditions of the water that they could not readily begin to function. By March 16, following a period of bare ice, there was some evidence of a slow recovery. The sudden rise to the peak value of March 20 (in the top sample), however, was partly brought about by run-in water. Here the effect of the run-in water was exactly the reverse of that mentioned above for the surface water in Clear Lake. The run-in water had a moderate amount of dissolved oxygen, and thus, in the one instance raised the amount in the lake water, and in the other lowered it.

The effect of snow in cutting off light, as reflected in changes in the dissolved oxygen of the water, is probably most strikingly demonstrated in Graph 7, Bog Lake. Even in early January there was a transitory rise in oxygen, following a reduction in the amount of snow on the ice. Then the sharp drop in oxygen continued until about February 11, reaching a low point during a time of relatively heavy snow cover. With the partial disappearance of the snow, the oxygen rose considerably, only to drop abruptly again during the period of snowfall of late February. Then the baring of the ice in early March was followed by a very rapid increase in oxygen, to a point (for the top sample) at or above the saturation level. During all of these changes in the upper water, the water near the bottom stayed consistently quite low in oxygen, presumably because very little light was able to penetrate the brown water to that depth, or because of the constant close contact of the bottom water with the organically rich bottom materials.

In the hatchery ponds (Graph 8), as has been pointed out above, normal pond processes of production and destruction of oxygen were to a large extent prevented from being displayed, by the flow of a certain amount of water through the ponds. Even so, during the period of bare ice in early and middle March there was a distinct production of oxygen in Ponds 9 and 10, which raised their dissolved oxygen values considerably above that of the darkened Pond 8.

In the oxygen curves for Pasinski's Pond (Graph 9) the relationship between snow on the ice and dissolved oxygen in the water is again evident. The oxygen in the south end of the pond (at least at the observed stations) declined very abruptly when the snow became relatively deep in mid-February. The oxygen in the north end already had reached a low level, probably because there was a smaller mass of algae to keep it replenished. A temporary rise in oxygen in both ends of the pond occurred during the period of bare ice in early March. The succeeding drop, which was under way even before the next snowfall, may have been induced in part by a slackening of photosynthesis, for some reason that is not apparent.

This cumulative evidence seems to indicate definite correlations between snowfall, light, and dissolved oxygen. If, as appears to have happened, a layer of only 3 to 6 inches of snow upon the ice can bring about appreciable changes in the oxygen content of the water of certain lakes and ponds, then it seems likely that a foot or more of snow on the ice for any long period could have quite a serious effect upon the condition of the water. Whether or not this effect is altogether the result of reduced photosynthesis by plants, is not at all certain. It may be that darkness favors some of the biochemical oxidation processes, and hence that actual utilization of oxygen is affected by light conditions. More investigation of these possibilities is needed.

2. Shallow and Deep Lakes Contrasted.

In a review of the differences in winter behavior of shallow and relatively deep bodies of water, certain points stand out. In general, dangerous conditions do not develop to nearly as great degree in deep lakes as they do in shallow ones, nor as abruptly. Changes in either direction apparently are started with more difficulty, in a deeper lake, and proceed more slowly. Perhaps a reasonable analogy is furnished by an object of comparatively great mass, the acceleration of which is more difficult to effect than that of a smaller body.

Differences in winter conditions are apparent even between comparable depths of water in shallow and deep lakes. According to the data obtained from Clear Lake, even the water just under the ice tends to fluctuate in dissolved oxygen much less in a deep lake than in a shallow one. And the deeper layers of water, although steadily losing oxygen throughout the winter, nevertheless do so at a slower rate, so that some dissolved oxygen may remain unless the winter is especially prolonged.

A possible explanation is that the water of a deeper lake, being in general somewhat less eutrophic containsless of the dissolved or suspended materials conducive to the process of oxidation.

It is obvious that in winter the water in the best condition, in a deep lake as well as in a shallow one, is that nearest the top. The withdrawal of oxygen is accomplished to the greatest extent next to the bottom; and the bottom water of even a deep lake may become foul in time. In a sense it may be said, then, that a deeper lake is much less subject to winter-kill not because of the deep water as such, but because a larger proportion of its water is not in close proximity to the bottom.

3. Peculiarities of an Acid Bog Lake.

The data of this winter's work show that the water of a bog lake responded much more readily and more quickly to changes in light than did the water of the other and more alkaline lakes studied. At the same time it probably was more dependent upon light for maintenance of conditions fit for fish life, for its deeper layers became stagnant quite early in the winter. There was a remarkably distinct and stable stratification in the bog water, presumably because its color permitted very little light to reach the bottom water, even though the total depth was only about 6 feet.

As will be mentioned below, the bottom water in Bog Lake became not only low in dissolved oxygen, but also rather high in free carbon dioxide, hydrogen sulfide, and possibly other gases of decomposition. This condition had developed fairly early in the winter, and persisted rather steadily. It thus seems to be indicated that, in the absence of compensating oxygen production, the processes of decay in bog water may go on at a comparatively fast rate.

4. Dissolved Oxygen—Carbon Dioxide Relationships.

It is well established that there is an interrelationship between the amount of dissolved oxygen in the water and the amount of free carbon dioxide, that is all important to the respiration of fish (of course, many other factors, such as temperature, species of fish, and so forth, must be taken into consideration). One of the most intriguing methods of portraying that relationship is the one used by F. E. J. Fry in a recent paper.[*] For a given species of fish, with other conditions controlled, the lethal curve is plotted on a plane, the vertical ordinates of which represent dissolved oxygen and the horizontal ordinates carbon dioxide. Thus any point on the curve represents a value of carbon dioxide at which the fish cannot utilize oxygen below the pressure indicated for that point. The curve is different for each species of fish, and there is a definite order of sensitivity and of toleration. The curves for the various species of fish are roughly parallel.

In Graphs 13-18, I have attempted to use the same set of coordinates to show the relationship of the amount of dissolved oxygen and of free carbon dioxide in the water of various lakes. Any point upon one of the graphs represents the oxygen and carbon dioxide values for one particular time. The points are connected by a continuous zig-zag line, showing the course of the conditions from time to time. In order to avoid confusion, I have omitted most of the dates represented by the various points; but the trend throughout the period of ice cover may be observed by following the line from its initial to its final end.

I have set down on these graphs only relative, and not absolute, values

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[*] Fry, F. E. J. The position of fish and other higher animals in the economy of lakes. Problems of Lake Biology; published by the American Association for the Advancement of Science, The Science Press, 1939. pp. 132-142.

for carbon dioxide; because I believe that the values which I have are not exact. I placed what now seems to have been a mistaken confidence in the accuracy of two methods of calculating carbon dioxide from pH and alkalinity determinations, and did not make enough check determinations by titration.* It must be pointed out, however, that although the calculated values may not be correct in absolute quantity, they probably are rather accurate in relative or comparative amount.

Thus the graphs for the different waters must be used as having only a relative meaning, useful for comparing one water with another. Considered from this standpoint, the graphs have considerable significance.

The smooth curve which is superimposed upon each graph is a hypothetical curve of the type described above as used by Fry. Since the carbon dioxide scale is relative, and not absolute, this curve cannot be taken to be that of any specified species of fish. Rather it must be considered to be that of a hypothetical species of fish under hypothetical conditions of temperature and so forth. Any point below or to the right of this curve represents conditions under which this theoretical fish could not live. The danger point in fish welfare has therefore been reached when this curve is crossed, either downward or to the right, by the line showing the changing content of dissolved oxygen and carbon dioxide in the lake.

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*The mathematical mechanics by which the calculations were made, as well as those which pointed out the faults in accuracy, are too long and involved to be included here. Naturally the data have been kept; for I believe that check determinations made in the future will provide the necessary correction factors whereby the calculations can be revised and made reasonably accurate.

In comparing these various graphs there are several points of interest. The water in Clear Lake (Graphs 13 and 14) stayed at all times well on the "safe" side of the arbitrary reference line. Even though the water at the 20-foot depth did become at times somewhat low in dissolved oxygen, it did not accumulate any great amount of carbon dioxide.

In Green Lake (Graph 15) conditions for a time became perilously near to those hypothetically lethal. That the arbitrary lethal curve may be fairly accurately placed on these graphs (in regard to some of the species of fish found in these waters) is suggested by the indication of a small winter-kill of fish in Green Lake, as described above. Similarly, the heavier kill in Pasinski's Pond probably is correlated with the more severe conditions, as shown in Graph 16. On this graph, the line representing oxygen and carbon dioxide actually does cross the reference curve.

Altogether the most severe conditions were those of Bog Lake (Graphs 17 and 18). The top water fluctuated sharply between very good and very bad conditions. The water near the bottom consistently stayed in a putrescent state, quite beyond the bounds of endurance of the hypothetical fish mentioned above.

Previous sampling has shown Bog Lake to contain mud minnows (Umbra limi), and probably no other species of fish. No evidence of any winter-kill of the mud minnows was found this winter. Furthermore, since the lake is entirely isolated from any other body of water, it is only reasonable to suppose that these fish may have survived many winters in the past which were much more severe than that of 1939-40. The inference, therefore, is that either the species, or this particular race or population of the species, is adapted to endure conditions which would be fatal to many other fish.

Summary

I collected a considerable amount of data concerning conditions under the ice, in the winter of 1939-40, in three shallow lakes and one comparatively deep one, in a small acid bog pot-hole lake, and in a small private pond. On this pond I performed an experiment in trying to add dissolved oxygen by pumping in a stream of aerated ground water. In some experiments on small hatchery ponds, light was excluded from one pond by means of a paper covering, and more light was admitted to another pond by the removing of the snow from the ice.

The water in Clear Lake (a fairly deep lake) stayed in rather satisfactory condition throughout the winter, although there was a steady diminution in dissolved oxygen in the lower layers of water.

Dissolved oxygen in Mud Lake became rather low at times and at certain stations; but apparently both photosynthesis and the inflow of a steady stream of comparatively good water figured in keeping the oxygen partly replenished. No winter-killed fish were observed in Mud Lake.

The water in Green Lake steadily declined in dissolved oxygen until about March 10, and its recovery from the perilous condition of that time was rather slow. This lake apparently was not as greatly affected by changes in light conditions as were some of the other waters studied. There was a small mortality of fish.

The water in Bog Lake became quite putrid, for a time, apparently with no ill effect upon the population of mud minnows. This water was very responsive to changing light conditions, and underwent wide fluctuations in amounts of dissolved gases present.

Richmond Lake offered an example of the winter conditions that may exist at certain times in an extremely eutrophic body of water. Many fish suffocated in the water under the ice in this lake.

Apparently the pumping at Pasinski's Pond produced no tangible results, probably because the amount of oxygen thus introduced was comparatively small. It certainly did not prevent the kill, apparently total, of bluegills. The entire pond developed deleterious conditions for a while; but the behavior of the two ends of the pond was dissimilar, probably because of differences in the amount and kinds of vegetation.

The experiments in artificially changing light conditions in the small ponds produced apparently significant results. The water with the most light maintained the best dissolved oxygen supply, in spite of continuous partial replacement of water.

Changes in the amount of snow on the ice (even increases or decreases of only a few inches) often are reflected in distinct changes in conditions in the water.

Water from rains, melting snow, or run-off from the surrounding land, may have a very noticeable effect upon the conditions in the water under the ice. The oxygen if low may be raised considerably (as shown in Graph 9), or if high may be lowered somewhat (Graphs 1 and 2, on March 23). This effect is rather transitory, and usually is manifest in only the top foot or two of water. If it happens to occur at a critical time, however, it may partly alleviate conditions harmful to fish.

Oxygen utilization takes place to the greatest extent in the water nearest the bottom; and a deep lake is in less danger of developing dangerous conditions because a larger part of its volume is not in contact with the bottom.

Brown bog water may develop and maintain stagnant conditions at only a few feet depth, presumably because light penetrates it but poorly.

Some interesting relationships between oxygen and carbon dioxide are shown by a method of graphing which gives the simultaneous values for these factors at various times, and compares them with a curve representing hypothetically dangerous conditions.

Plans for Further Study

Tentative plans for future studies include:

A continuation of the work of an observational nature. Possibly I shall make this work somewhat less extensive, and more intensive, concentrating on one or two bodies of water. Under consideration is the idea, mentioned above, of drawing up a sort of balance sheet of oxygen gains and losses in a small lake. However, because of the large number of factors involved, this might prove to be too cumbersome an undertaking.

Investigation of plankton, light, and oxygen relationships. The main difficulties (and they are appreciable ones) to be overcome here are those connected with getting and evaluating plankton samples, and with measuring light intensities.

Studies of oxygen production and oxygen consumption, probably to take the form largely of experimental determinations of oxygen demands of waters, sediments, and other materials. It is hoped that some preliminary studies may be made to determine the possible role of factors other than reduced photosynthesis in the loss of oxygen that takes place in darkened waters.

Experiments in oxygen replenishment, by means of aerators or pumps; and further experiment in promoting photosynthesis by snow removal.

Physiological experimentation on tolerances of fish to conditions of stagnation.

INSTITUTE FOR FISHERIES RESEARCH

John Greenbank

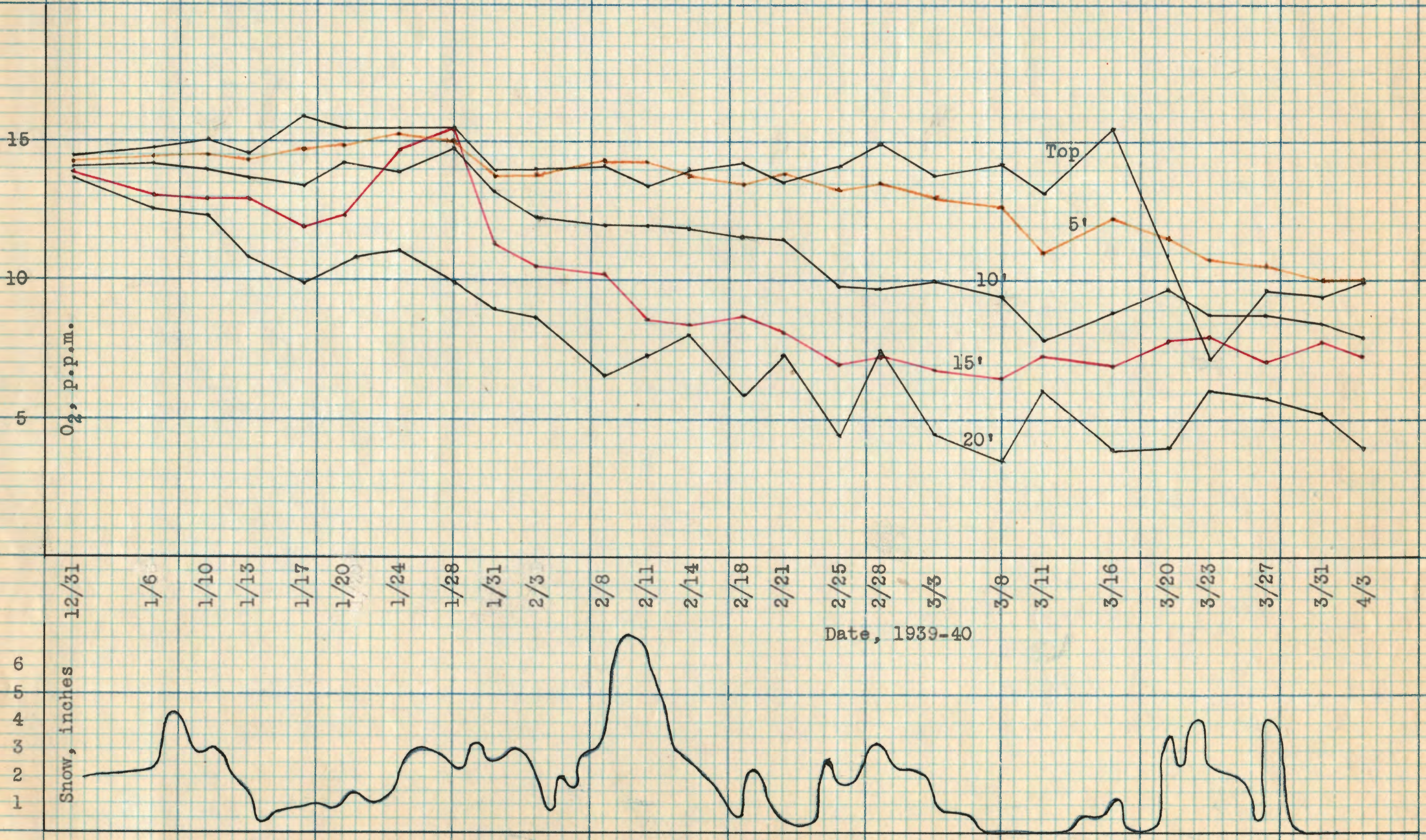
Typed by: Alma Hartrick
Approved by: A. S. Hazzard

Graph 1. Dissolved Oxygen

Clear Lake - Sta. I

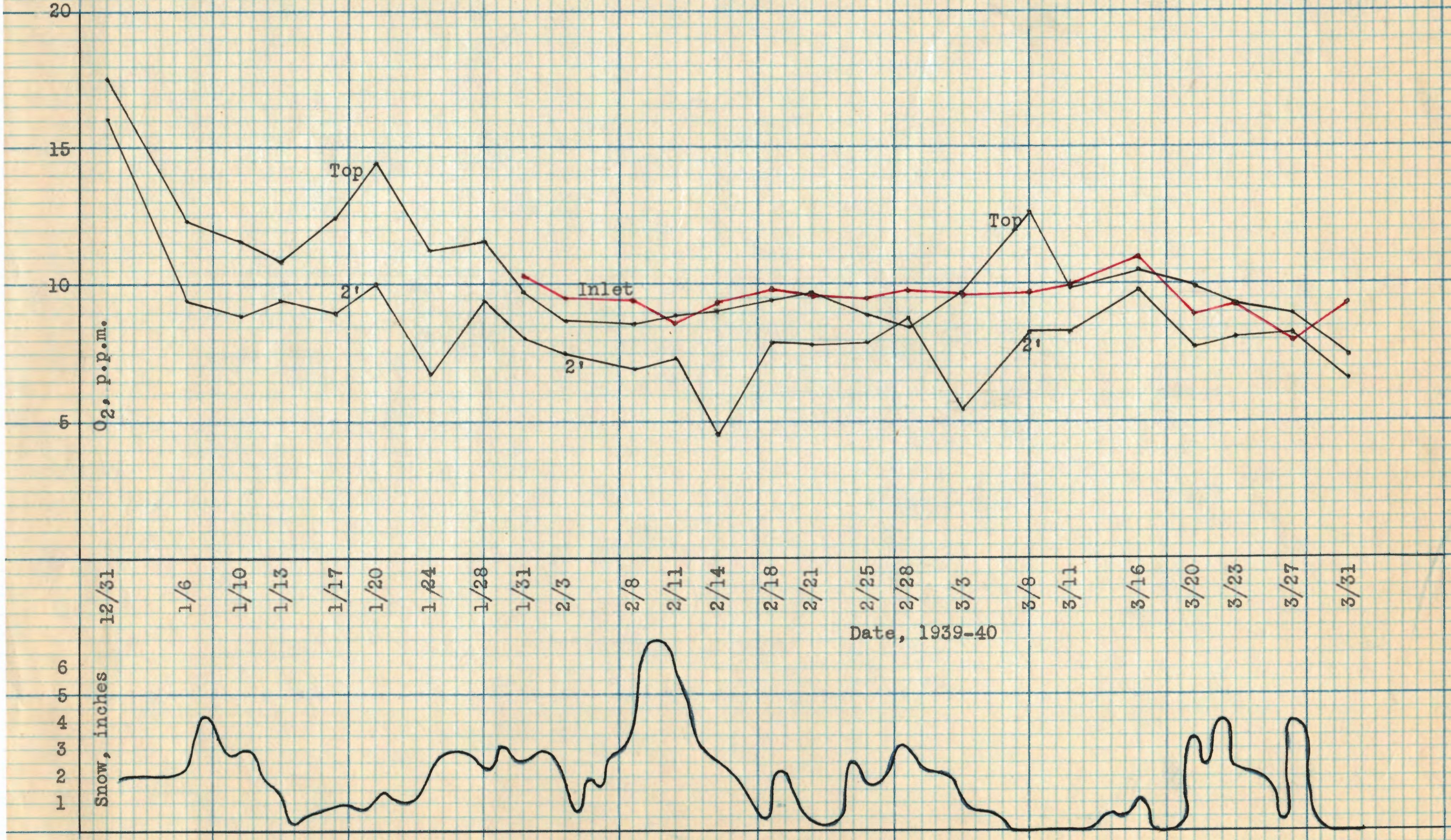
Graph 2. Dissolved Oxygen

Clear Lake - Sta. 2

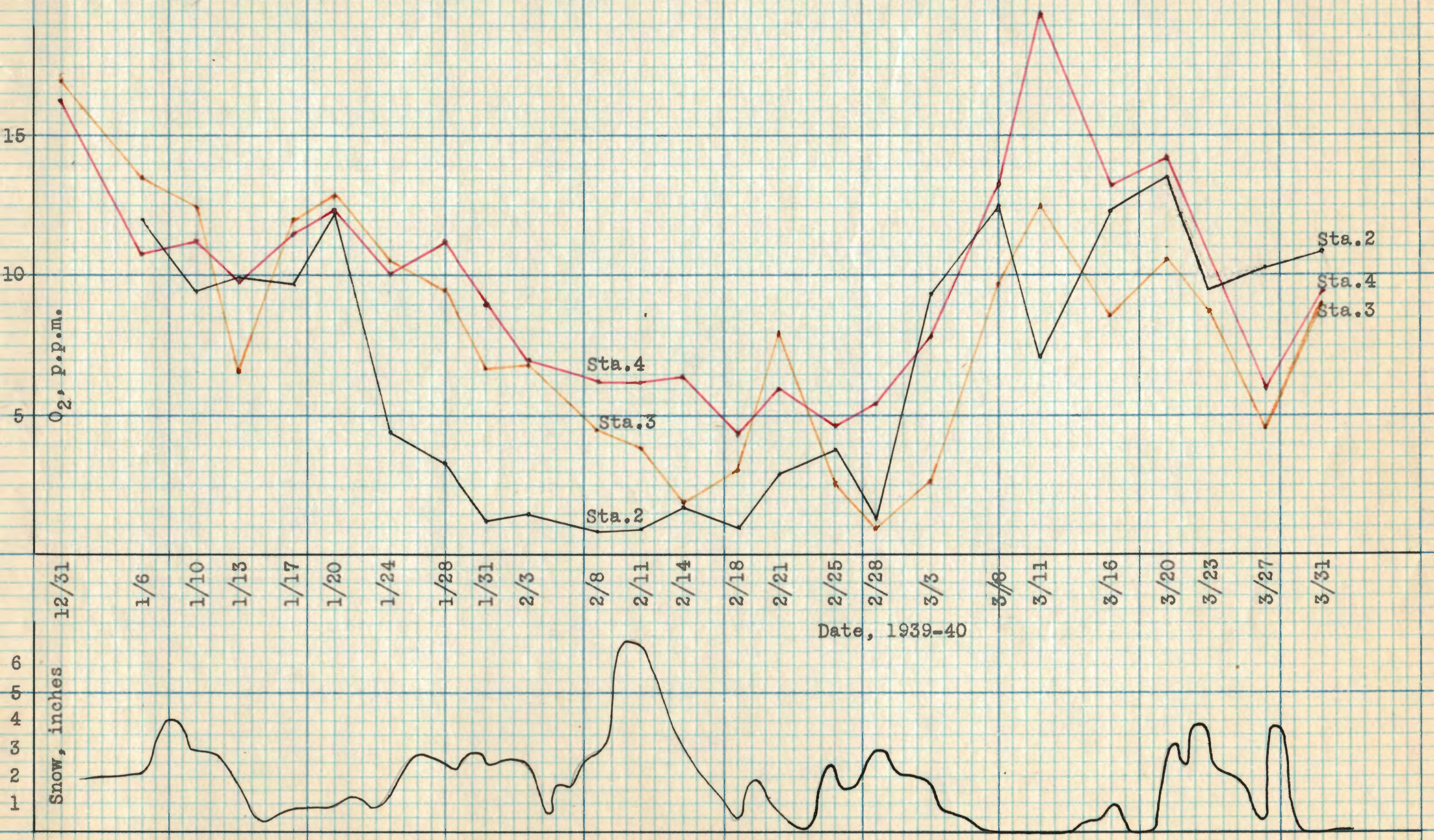


Graph 3. Dissolved Oxygen

Mud Lake - Sta. 1
and Inlet

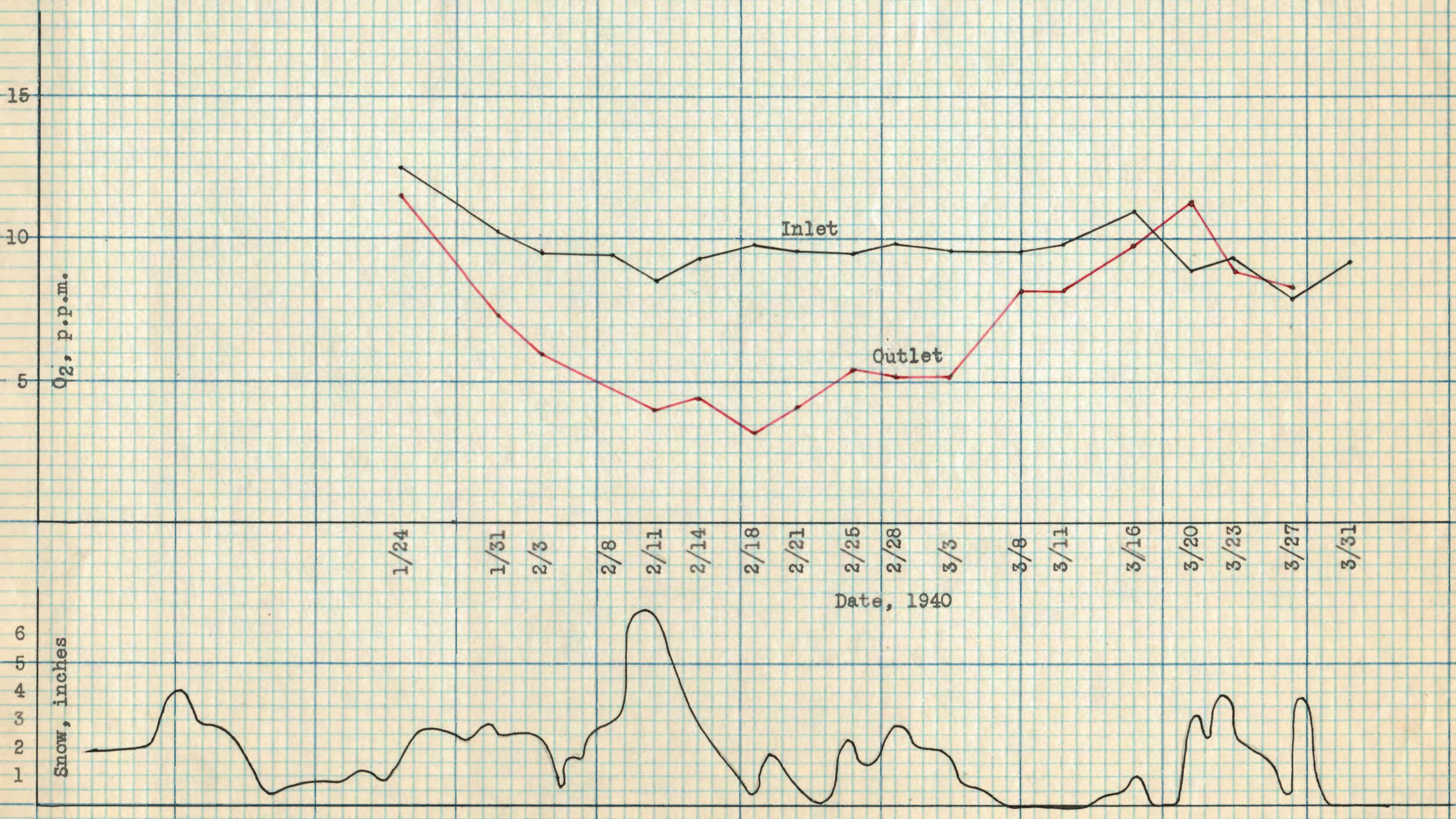


Graph 4. Dissolved Oxygen
Mud Lake



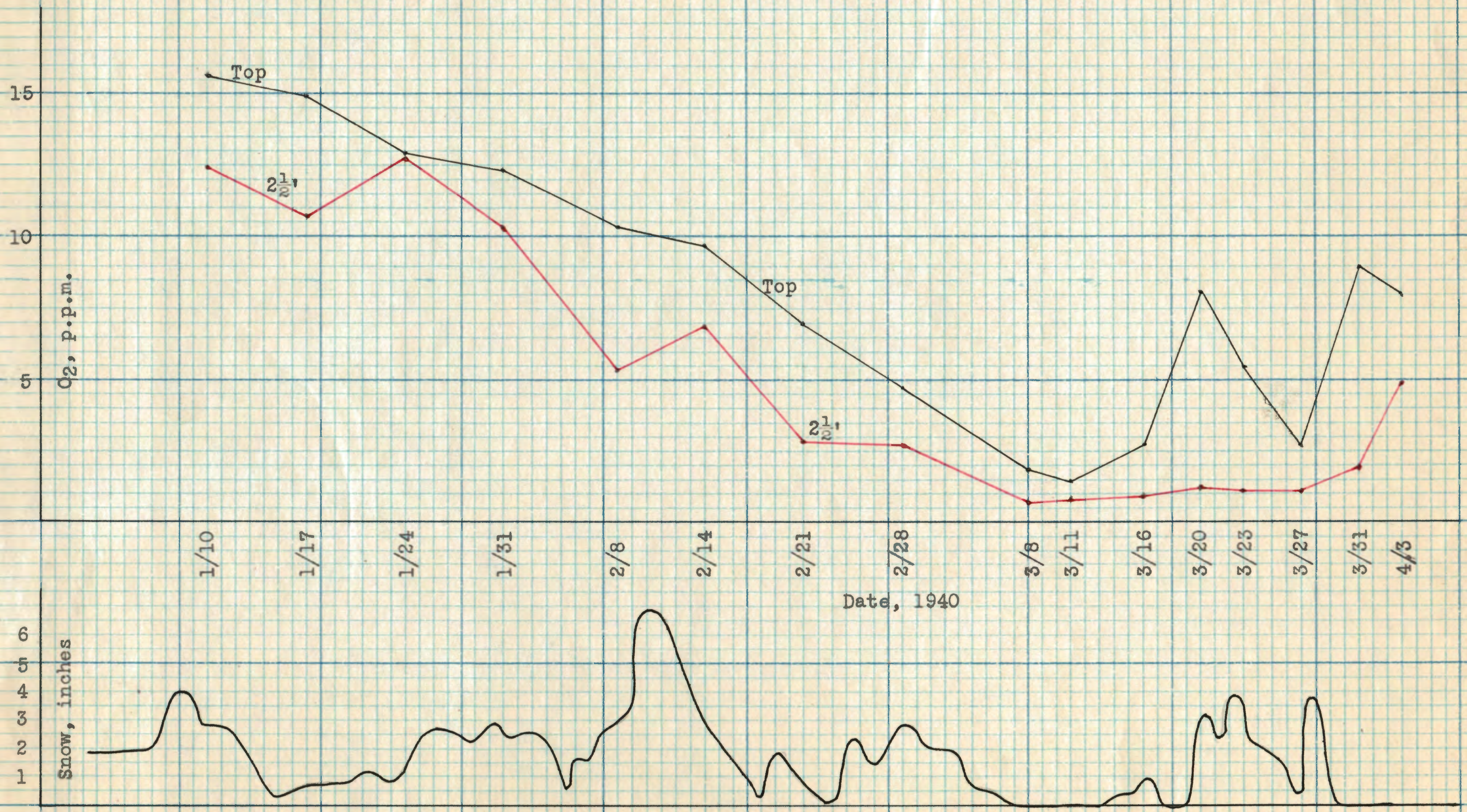
Graph 5. Dissolved Oxygen

Mud Lake



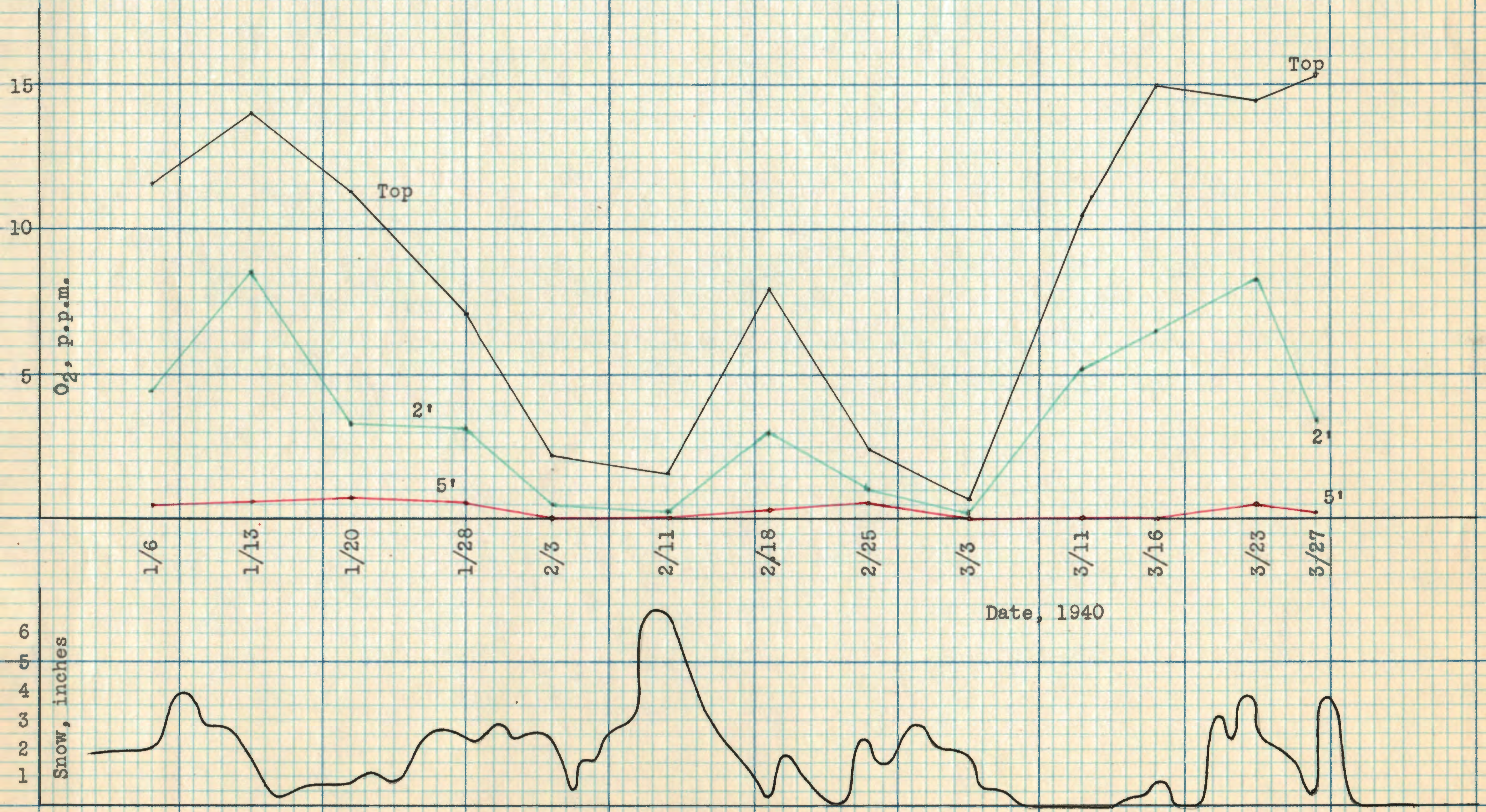
Graph 6. Dissolved Oxygen

Green Lake



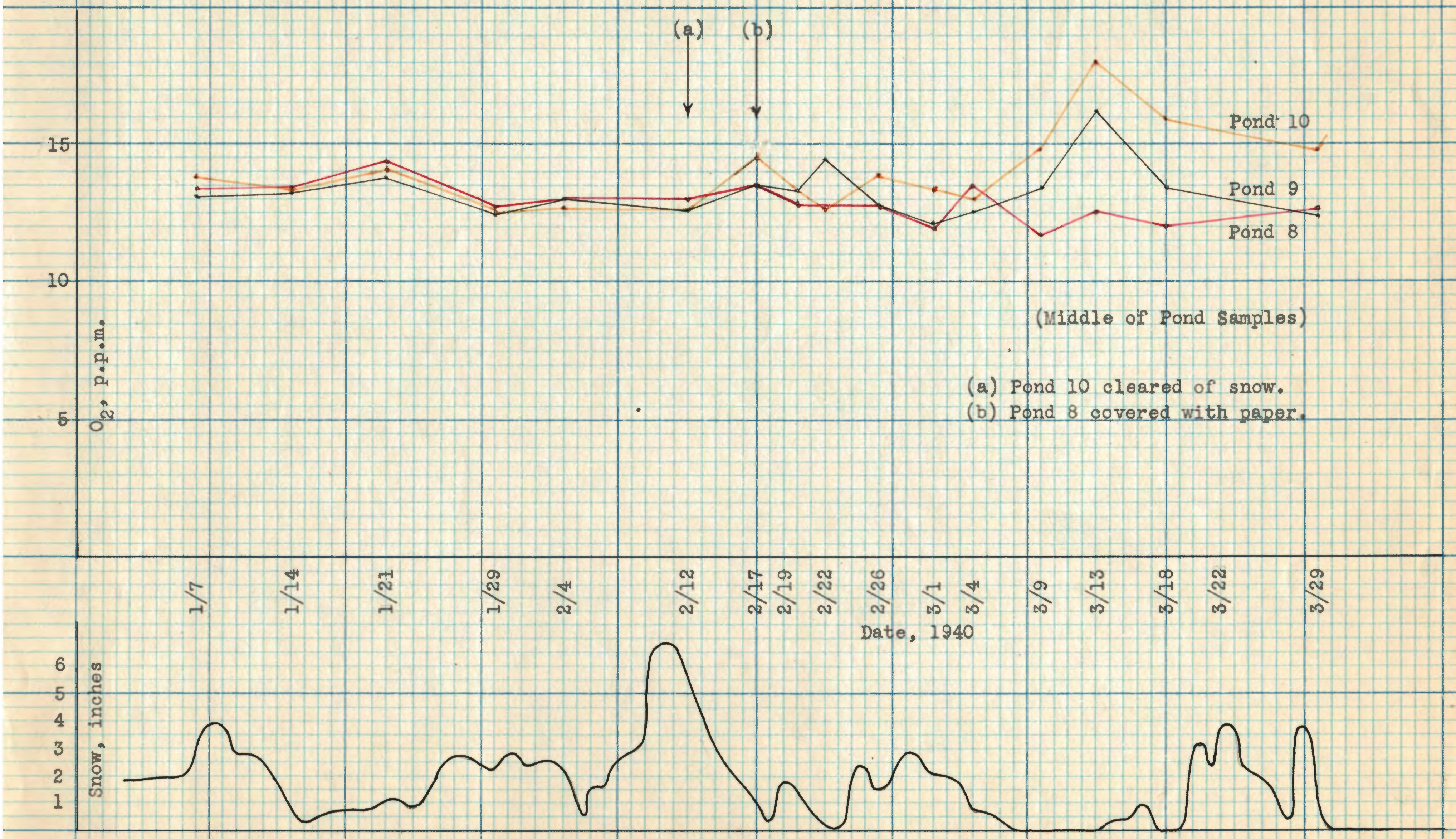
Graph 7. Dissolved Oxygen

Bog Lake



Graph 8. Dissolved Oxygen

Hatchery Experimental Ponds

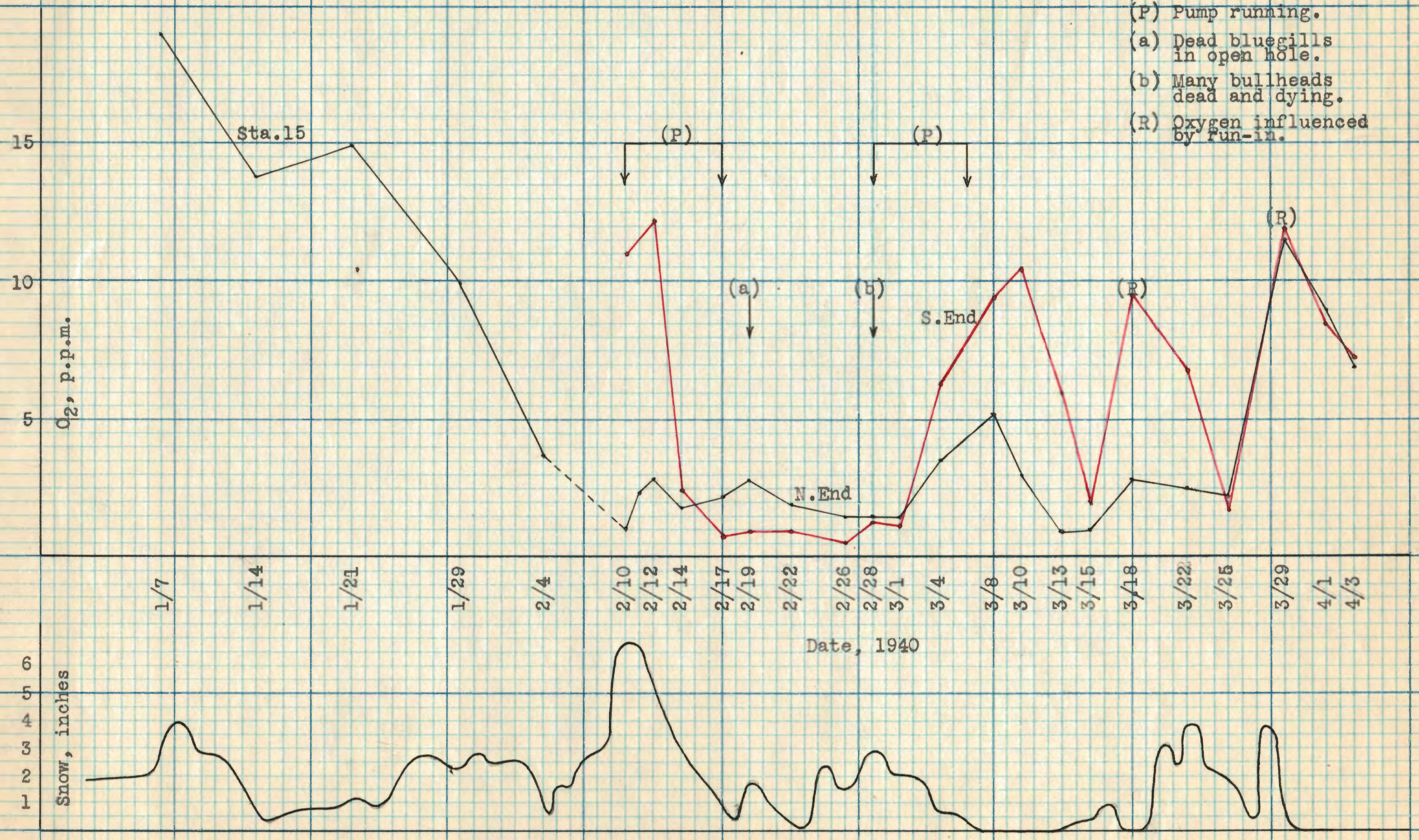


(Middle of Pond Samples)

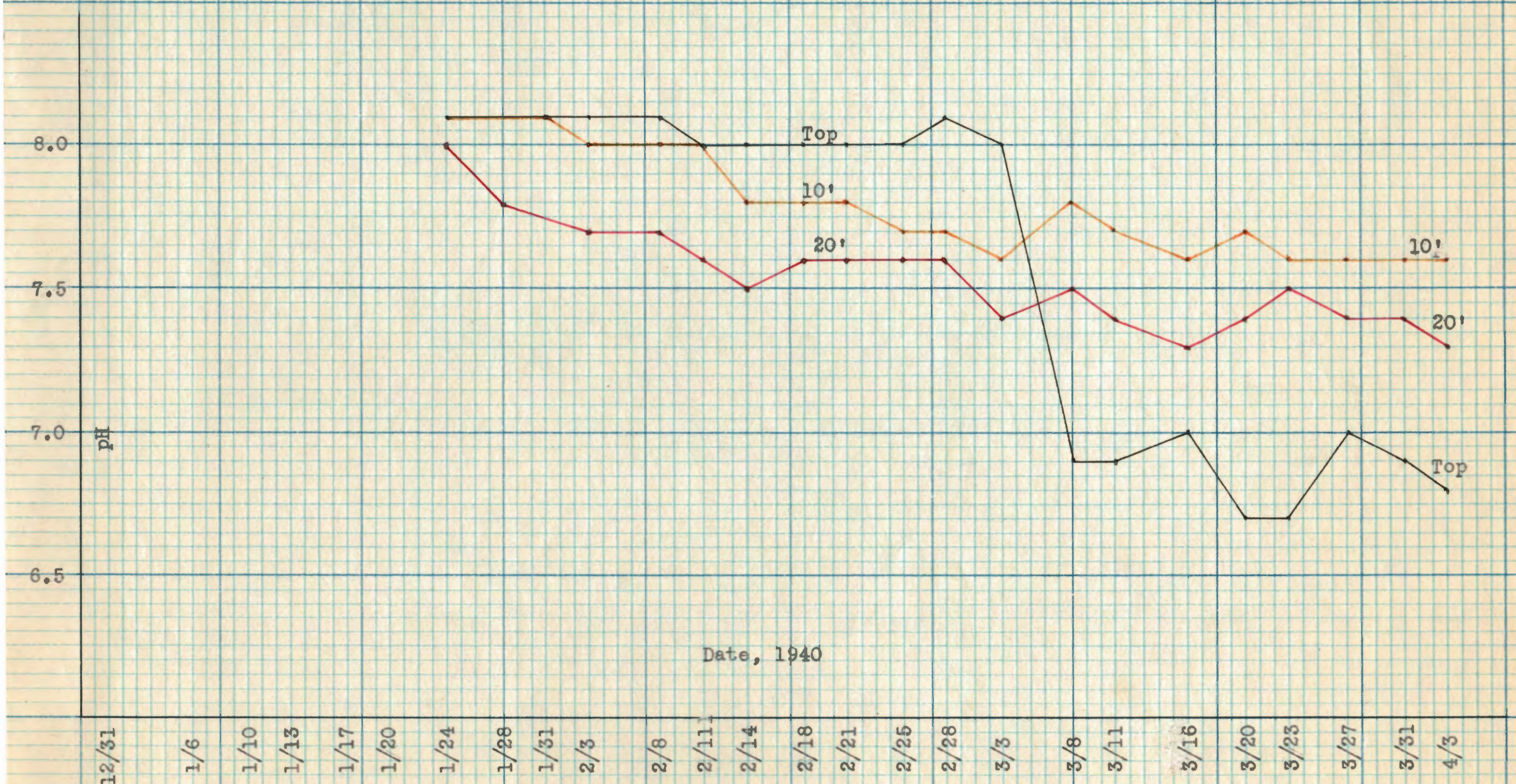
(a) Pond 10 cleared of snow.
(b) Pond 8 covered with paper.

Graph 9. Dissolved Oxygen

Pasinski's Pond

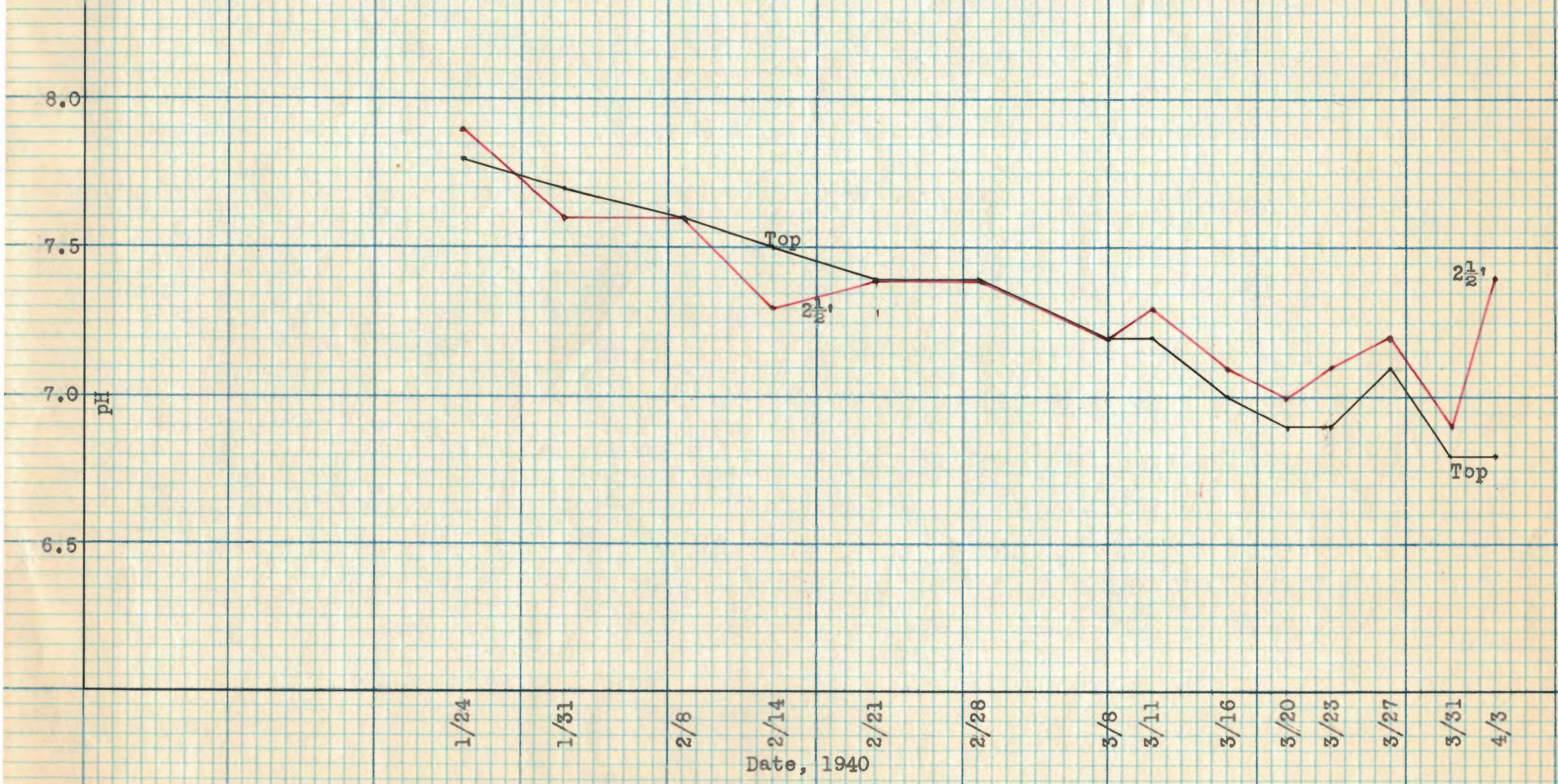


GRAPH 10
pH
Clear Lake, Sta. 2

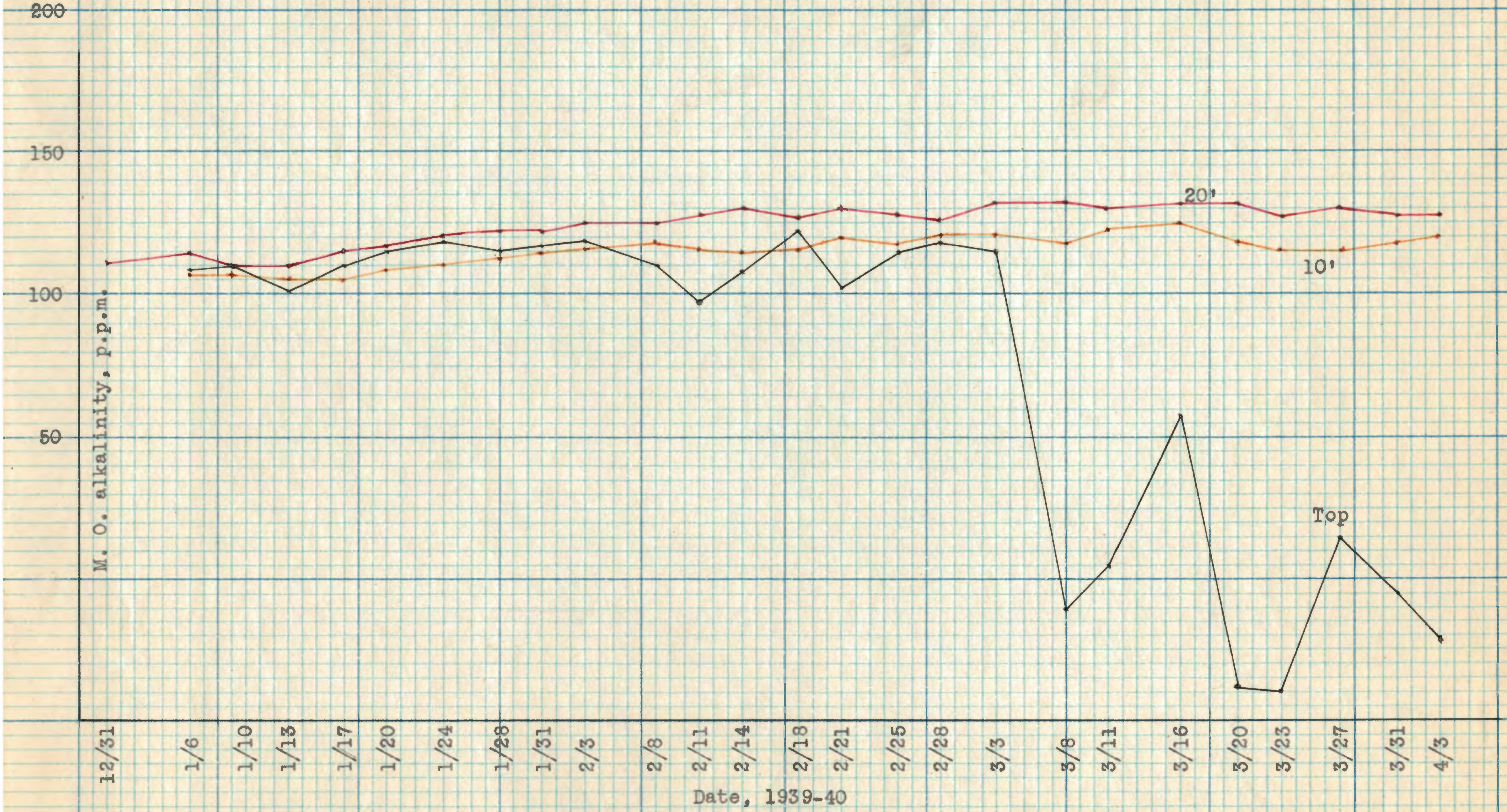


GRAPH 11

pH
Green Lake

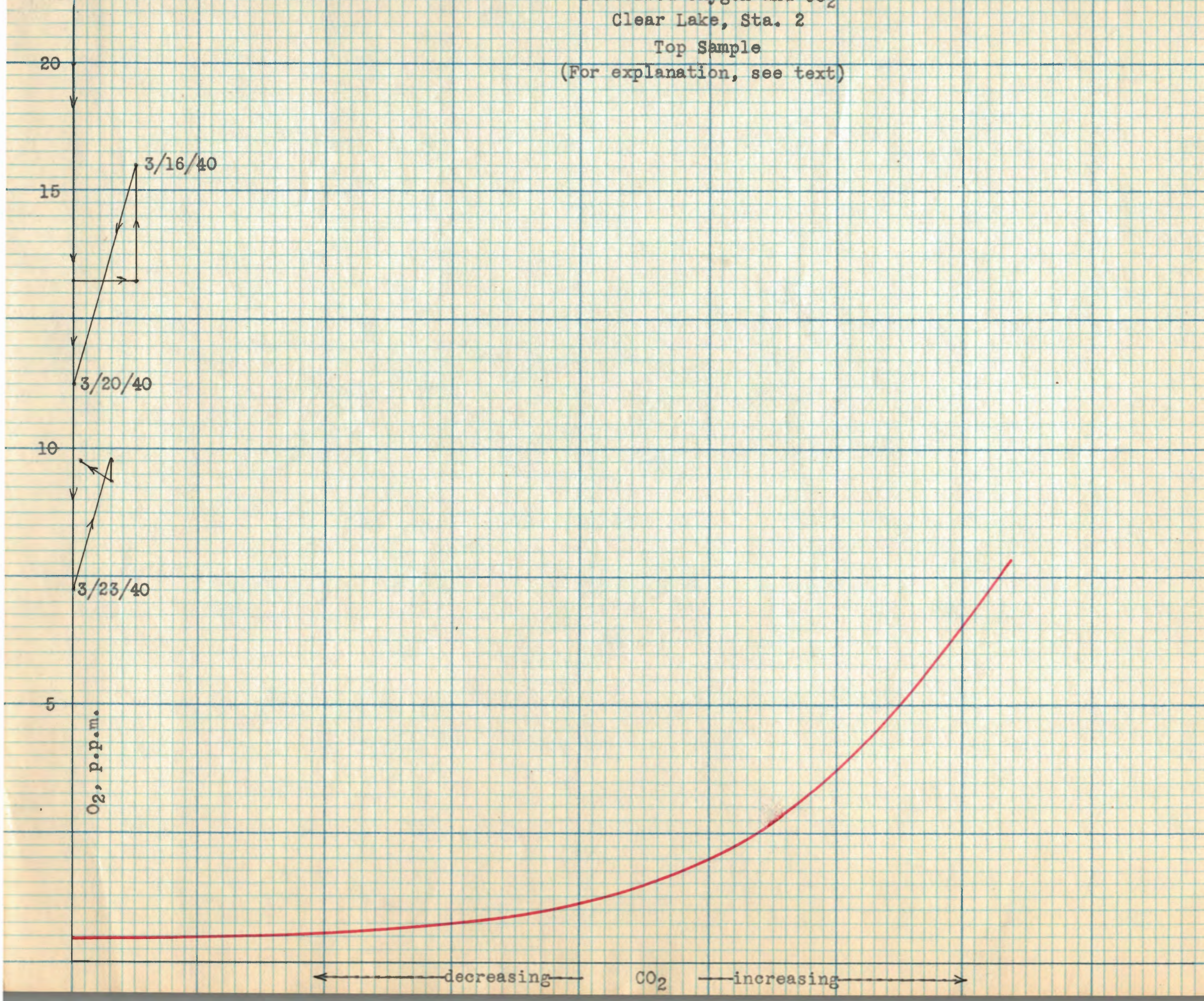


GRAPH 12
Methyl Orange Alkalinity
Clear Lake, Sta. 2



GRAPH 13

Dissolved Oxygen and CO_2
Clear Lake, Sta. 2
Top Sample
(For explanation, see text)



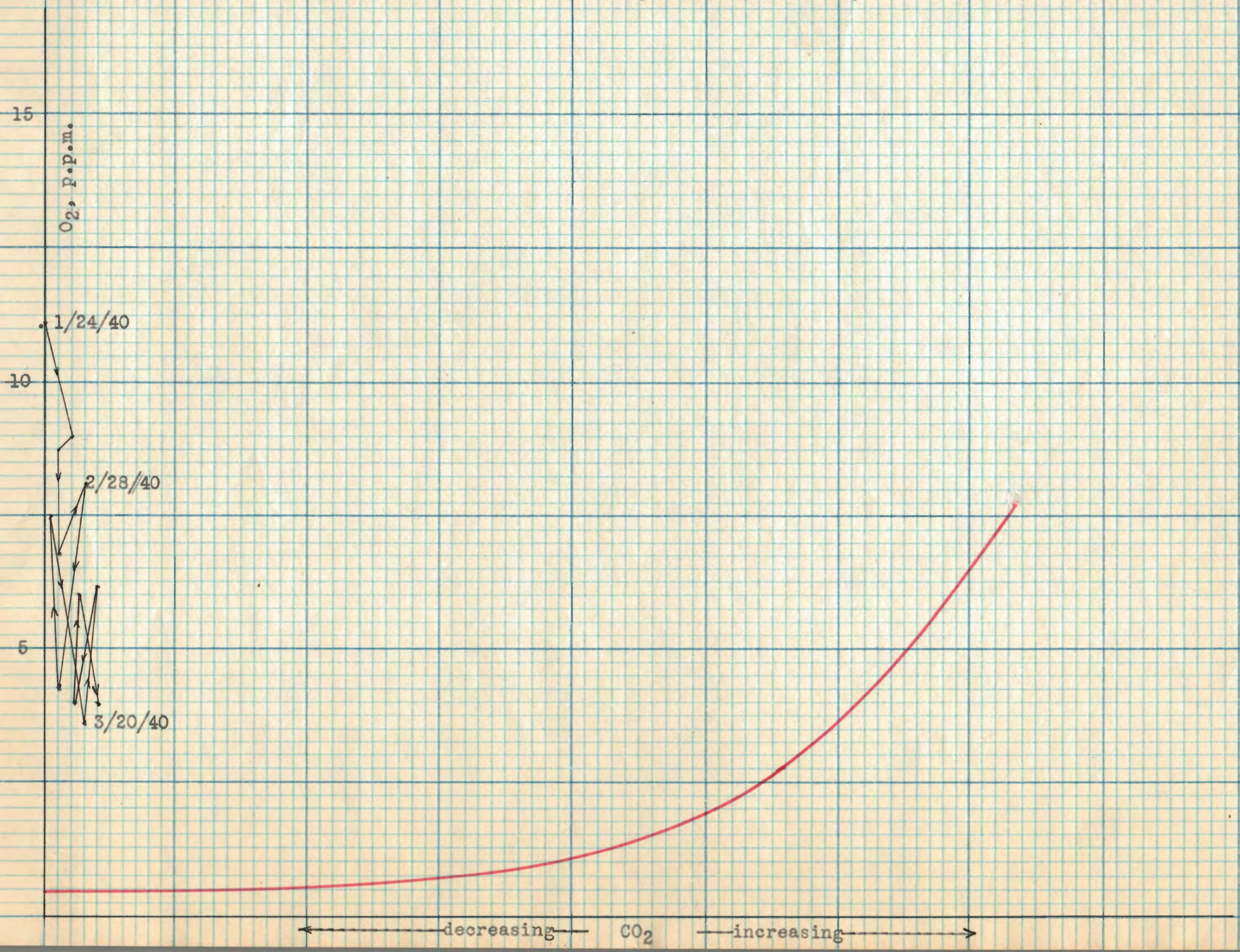
GRAPH 14

Dissolved Oxygen and CO_2

Clear Lake - Sta. 2

20' sample

(For explanation, see text)



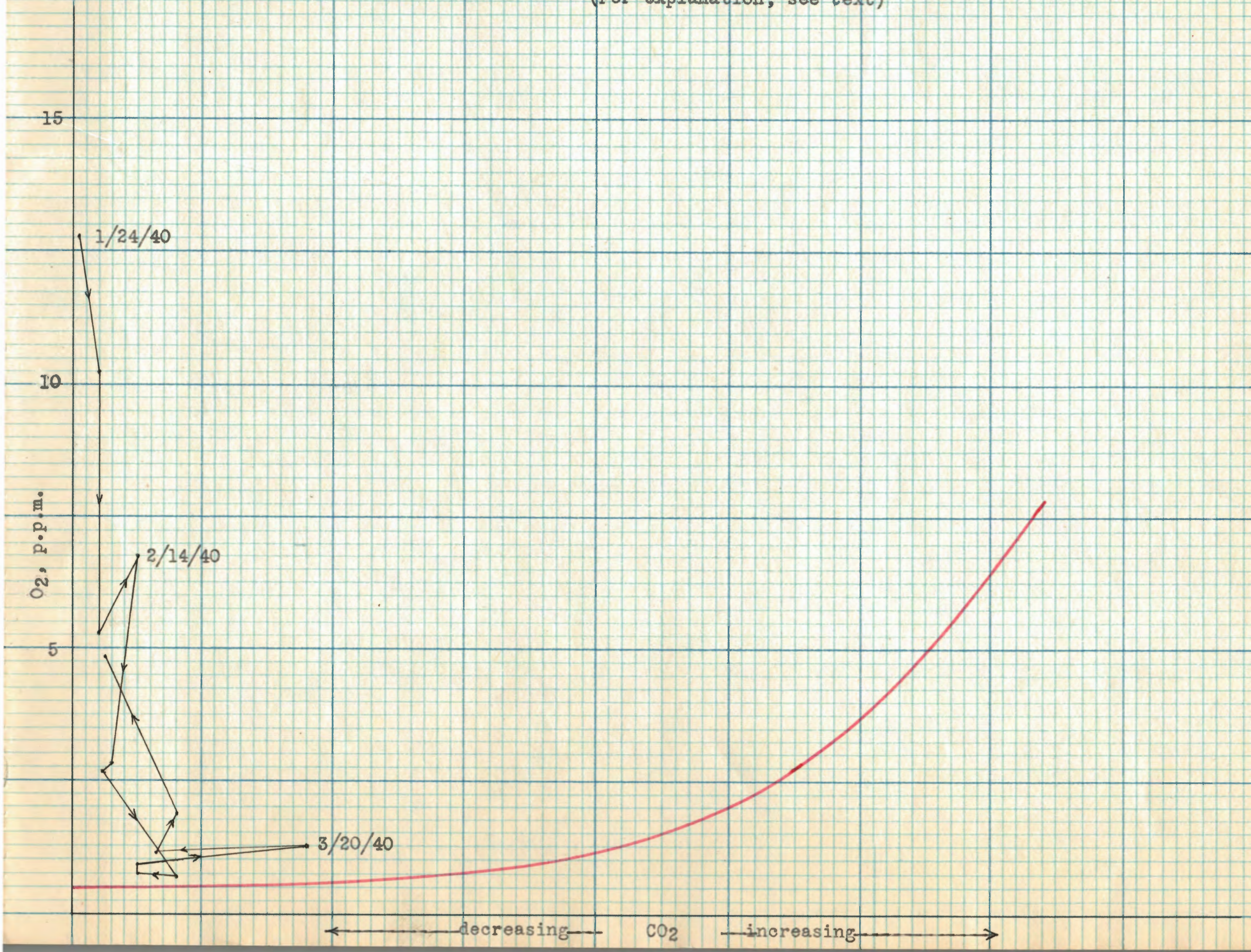
GRAPH 15

Dissolved Oxygen and CO_2

Green Lake

2½' sample

(For explanation, see text)



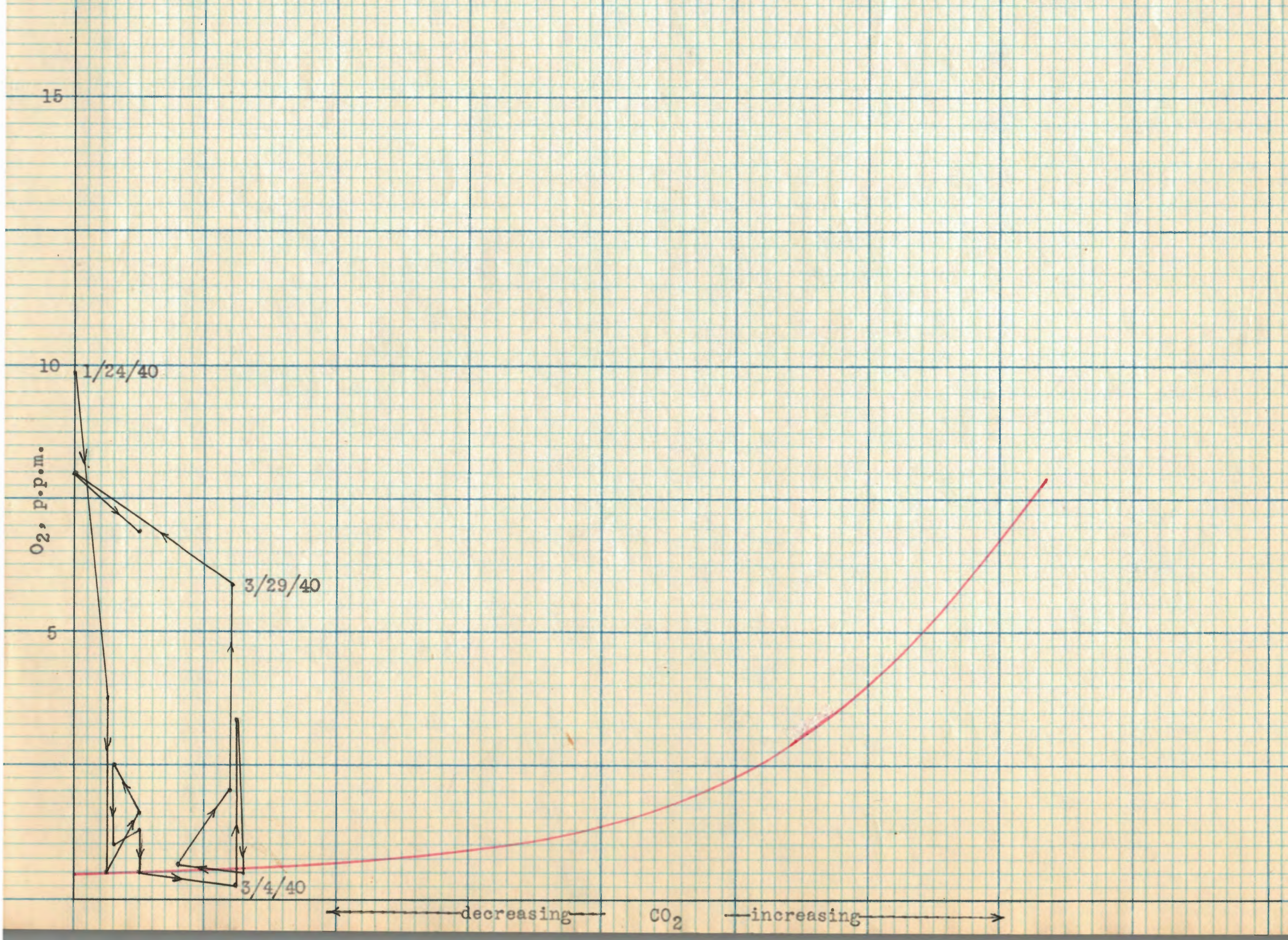
GRAPH 16

Dissolved Oxygen and CO_2

Pasinski's Pond

Sta. 15

(For explanation, see text)

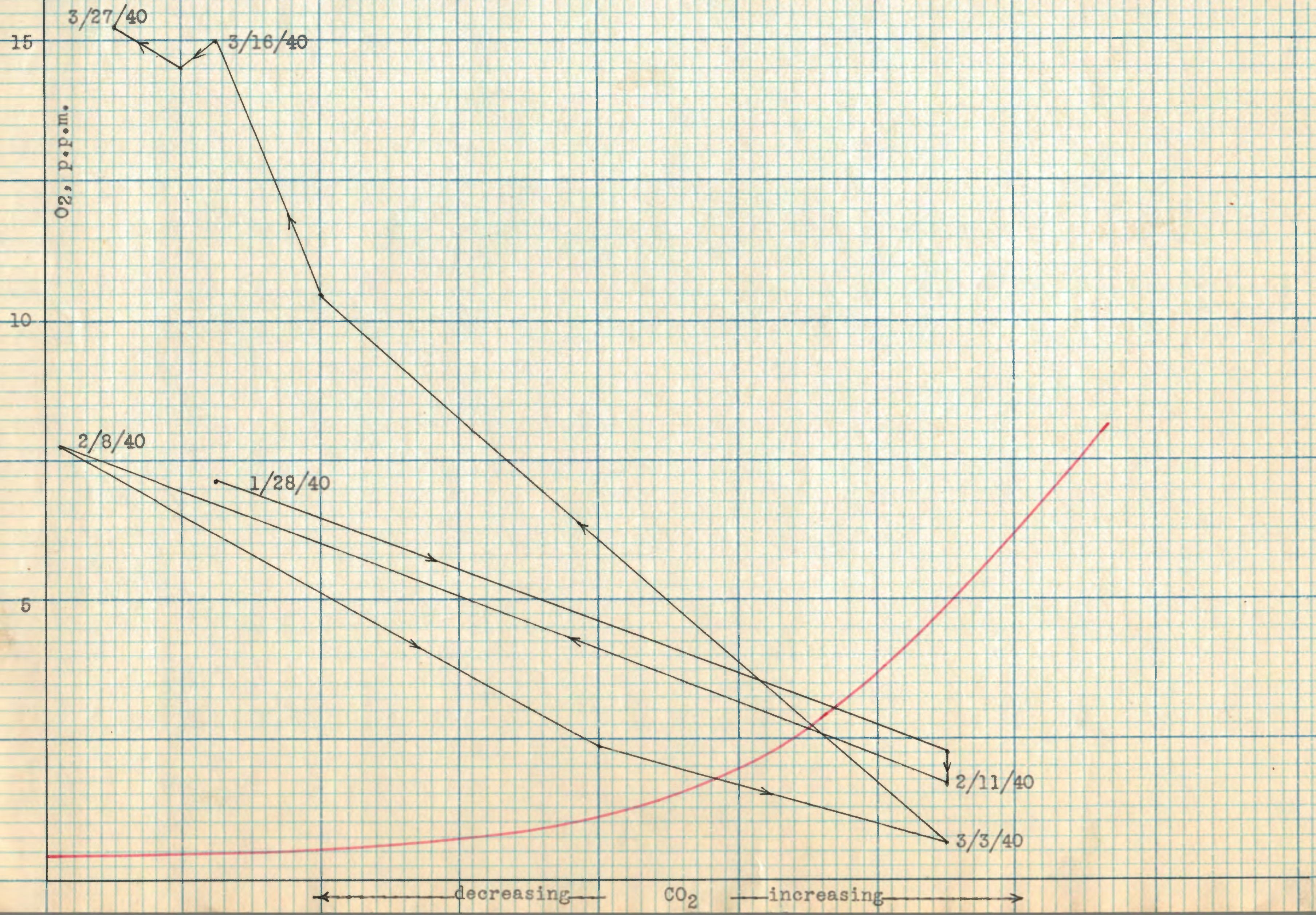


GRAPH 17

Dissolved Oxygen and CO_2

Bog Lake - Top Sample

(For explanation, see text)



GRAPH 18

Dissolved Oxygen and CO_2

Bog Lake - 5' Sample

(For explanation, see text)