A STUDY OF TWO LIMESTONE QUARRY POOLS

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INTRODUCTION

Very little work has been done in the United States on the chemical and plankton conditions in pools and ponds. Scott (1910) made a study of the fauna of a solution pond. Reed and Klugh (1924) studied the hydrogen ion concentration of a granite and a limestone pool near Kingston in the Province of Ontario. In Europe, more attention has been given to this field. Griffiths (1916, 1922) and Atkins and Harris (1924) have studied the heleoplankton and chemical factors in quarry pools and ponds. Among the many other workers are Alexander, Rylov, Nordqvist, Scähferna, Fric, Diefenbach, and Sachse.

This paper is based upon a study of the physical, chemical, and plankton conditions of two limestone quarry pools near Milwaukee, Wisconsin. The larger of the two, which shall be called the Wauwatosa pool, lies near the western city limits of Milwaukee, in a recently annexed portion of land, adjacent to the suburb of Wauwatosa. It is the site of an old limestone quarry, in which operations ceased about thirteen years ago, and which, since then, has been slowly filling with water as there is no outlet, until it is now 23 meters (75 feet) deep. It is roughly rectangular in shape with the long axis in an east-west direction, and covers an area of approximately 1.36 hectares (3.36 acres). The walls on all sides are precipitous, and rise on the south side of the pool to a height of about 5 m. The height of the walls decreases toward the north side where it is only about 1 m. above the surface of the water. On all sides the walls descend abruptly to a depth of 5 m. except for a few recently submerged shallows, which are small in extent. The limestone about the pool is overlaid by glacial gravel, which forms a moraine on the south side, the crest of which is about 200 m. from the quarry. The other sides are com-

paratively low. The drainage into the pool is primarily from the moraine to the south. Except for dwellings on the crest of the moraine, there is little contamination from civilization. Much carbon, however, settles on the pool, from smoke of a railroad a few city blocks to the north, and from factories nearby. The pool receives plenty of sunshine due to its east-west position, and to the lack of vegetation along the eastern and western shores.

Along the sides is a ledge about 5 m. below the surface of the water. This ledge is very narrow along the eastern three-fourths of the quarry, but forms the entire floor of the quarry at its western portion. From this ledge the bottom descends abruptly again to a ledge at a depth of 15 m., which is the depth of the larger portion of the pool. In the northeastern portion, at the site of the former "quarry hole" is a large area, about one-fifth the area of the pool, which is 23 m. deep. The bottom of the pool to within a year ago was comparatively free from ooze. A sample of the bottom brought up with a mud dredge showed the greater part to consist of coal dust or carbon, and to be approximately about two inches in thickness. In September 1926, clay was emptied into the pool. Within a comparatively short time, it became distributed over the bottom of the pool.

The rise of the water level of the pool during the time it was studied is of interest. A photograph taken of the pool in May 1921 shows the water level to be about 9 m. below the level of August 1925 when this study was begun. Between August 1925 and March 1928 the water level rose about 2.1 m.

The study of the second pool was begun in September 1926. This also is an abandoned limestone quarry, about five miles to the northeast of the one just described. This pool is on the south limits of North Milwaukee, and will be called the North Milwaukee pool. This body of water is about one-third the size of the Wauwatosa pool, and is also well isolated from contaminating sources. The walls rise vertically from the bottom on all sides. The average depth is about 4.5 m. The deepest place in the pool is 5.5 m. The water level is less than 1 m. below the level of the solid rock. This is covered with glacial gravel, overgrown on all sides

with grass. On the western side (the pool's long axis is in a north-south direction) the gravel forms a ridge about 3 m. high, with steep sides. There is little vegetation on the shores except for a clump of trees in the southeast corner and a few low wild crab trees near the center of the west shore. The other shores are low. The eastern side has a low dike to prevent a creek about 5 m. distant from overflowing into the pool in times of flood. The level of the creek is slightly lower than that of the pool and lies in solid rock. The bottom of the pool is composed of soft black ooze, but its depth is not known. About five years ago almost all of the water was pumped from the pool after the creek had overflowed into it. At this time the dike was built. In winter ice is harvested from this pool, but not from the Wauwatosa one. The smaller pool is about eight to ten years old.

METHODS

Practically all of the samples from the Wauwatosa pool were taken in the open water at the spot where it was deepest (23 m.) and about 10 m. from shore. This was made possible by the use of a small flat-bottomed boat kindly loaned by Mr. W. Manegold, who lives on the property, and with whose kind permission and hearty cooperation this work was made possible. At times it was impossible to use the boat, and samples were then taken from the southwestern portion where the wall was vertical for about 5 m. Samples were taken as far from shore as was possible by pushing the line from the shore with the aid of a plank a little more than a meter long. Samples from the North Milwaukee pool were taken in the same manner from a point near the middle of the west shore. During the winter, samples of the North Milwaukee pool were taken from the center of the pool. So far as possible samples were taken during the same time of the day. This was between nine and twelve a. m.

All of the limnological apparatus was loaned by the Wisconsin Geological and Natural History Survey, through the courtesy of Professor C. Juday, under whose supervision and guidance this work was done.

The net plankton was collected by means of a closing net

with No. 25 bolting cloth (Juday 1916). Hauls were made from 0 to ½ m., ½ to 1 m., then 1 m. hauls to generally 5 m. and in the Wauwatosa pool further hauls of 5 m. each to 20 m., and from 20 to 23 m. During 1927 horizontal surface hauls were made. One was just below the surface while the second haul was made about 10 m. below the surface. Each of these hauls of the net was for a distance of 2 to 3 m. The catch was killed and preserved immediately, and before counting, was diluted to 20 cc.

A Sedgwick-Rafter counting cell was used in making the plankton counts. The plankton in the entire cubic centimeter contained within the cell was counted by the aid of a mechanical stage, for such organisms as were not found in great numbers. The abundant organisms were counted by enumerating twenty squares with a Whipple micrometer (Whipple, 1927). Entomostraca, when in small numbers, were counted by looking at the total catch with a hand lens. All of the counts were computed on the basis of the number of organisms per liter.

Temperatures were taken with a Negretti and Zambra deep sea reversing thermometer. It was generally found necessary to take temperatures for every meter to 5 m., and often this procedure had to be continued to 10 m. Then readings were made at 5 m. intervals to the bottom, and intermediate readings were taken whenever necessary.

The turbidity of the water was taken with a Secchi disc 10 cm. in diameter, and the depth at which it disappeared was noted.

Dissolved oxygen was determined according to the modification in Standard Methods of Water Analysis (1925) of the Winkler Method (Winkler, 1888). Carbon dioxide was determined by the Seyler method as given by Birge and Juday (1911).

The hydrogen ion concentration was determined colorimetrically using cresol red (pH 7.2 to 8.8) and thymol blue (pH 8.2 to 9.8) as indicators and making a comparison with the Clark Color Chart of Indicators (Williams and Wilkins Co. 1922).

Nitrogen determinations were made as directed in Standard Methods of Water Analysis. Free ammonia, organic

nitrogen, nitrates, and nitrites, were determined. Nitrogen determinations were not begun until May 1927.

All of the chemical work other than oxygen, carbon dioxide, and hydrogen ion concentration was done in the laboratory of the Wisconsin State Laboratory of Hygiene, and thanks are due to Dr. W. D. Stovall and to Dr. M. S. Nichols for permission to use the laboratory. To Dr. B. P. Domogalla, Biochemist for the City of Madison, the author is much indebted for guidance and assistance in all of the chemical analyses in the laboratory, and also in assisting in the transportation of the samples of water to Madison.

Soluble and total phosphorus were determined by the modification by Domogalla of the method of Juday, Kemmerer and Robinson (1927).

Chlorides were determined as directed in Standard Methods of Water Analysis.

Soluble silica was determined by the Atkins modification (1923) of the colorimetric method of Dienert and Wandenbulcke (1923).

The organic matter of the centrifuge plankton was determined by centrifuging one liter of water in a Foerst electric centrifuge (Juday 1924 and 1926). The organisms from a liter of water (concentrated to 4.5 cc. of water left in the bowl of the centrifuge) were transferred to weighed platinum dishes of 8 cc. capacity. After drying at 60°C. for 24 hours, the dishes were cooled in a desiccator and the dry weight was ascertained. They were then ignited in an electric furnace and after cooling were again weighed and the loss on ignition was determined. Since the centrifuge bowl contained 4.5 cc. of water, the amount of volatile matter in solution in the water must be deducted from the loss on ignition. This factor was found by determining the loss on ignition of 10 cc. of the centrifuged water, and the amount of such "blank" volatile matter in 4.5 cc. was subtracted from the loss on ignition of the centrifuged plankton.

In addition to the liter of water centrifuged for organic matter, 500 cc., or sometimes 250 cc., were centrifuged and diluted to 10 cc. for counts of the nannoplankton organisms which escape through the meshes of the closing net.

TEMPERATURES

A comparison of the temperatures of the surface water with the monthly meteorological tables issued by the Milwaukee office of the United States Weather Bureau shows that the water temperature increases more rapidly than that of the air, and that it cools more slowly. The high specific heat of water also prevents its showing as great variations as are shown by the air. In the spring the heat absorbed during warm periods is not dissipated to any great extent during the cool spells so that the water continues to increase in warmth at a comparatively uniform rate.

In the fall the water continued to cool until it reached a temperature near 0°C. This temperature was not reached in the Wauwatosa pool until early in December; but in the North Milwaukee pool, since there was a smaller volume of water to be cooled, the temperature reached this point as much as two weeks earlier. On the first quiet, cold night, ice formed on the pool. This occurred for the Wauwatosa pool on December 18, 1925, on December 4, 1926, and on December 20, 1927. The smaller pool froze on November 13, 1926, and on December 8, 1927.

The ice left the smaller pool earlier than it did the large one for there was less water to be warmed. Ice left the North Milwaukee pool on March 13, 1927 and on March 20, 1928. The large pool was free of ice on April 17, 1926, March 17, 1927, and March 28, 1928. The maximum temperatures at the times the pools were visited was 24.0° on July 10, 1926 for the Wauwatosa pool, and 25.7° on July 16, 1927 for the North Milwaukee one. The minimum surface temperature for the large pool was 1.5° on January 3, 1926 while for the smaller pool it was 0.4° on January 2, 1927.

The Wauwatosa pool in 1925–1926 showed typical lake conditions in regard to temperature. At the beginning of August, 1925, the thermocline or layer of rapid change of temperature began at about 5 m. On August 22 when the boat was used for the first time, the top of the thermocline was at 6.5 m. The thermocline continued to 12 m. with a temperature change from 21.5° to 5.7°. On September 3 the temperature in this layer did not change to any extent.

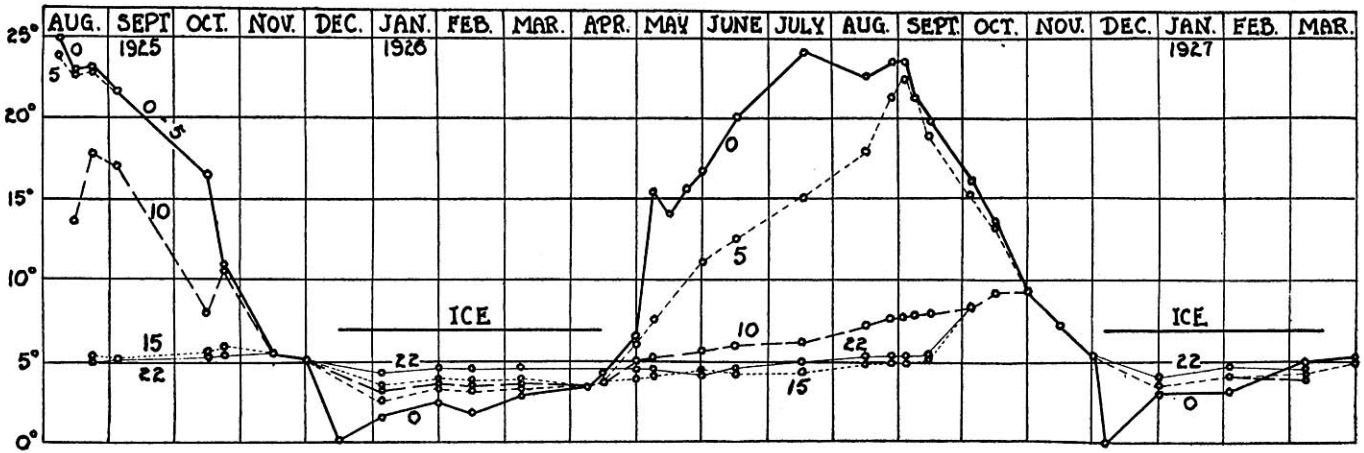

FIG. 1. Seasonal changes in temperature, expressed in degrees centigrade, at various depths in the Wauwatosa pool. The depths are indicated in meters by the figures attached to the curves.

The epilimnion, or layer above the thermocline, had cooled a degree (21.0°). The hypolimnion or layer below the thermocline began at 12 m. as before, with a temperature of 5.7° which was uniform thence to the bottom (23 m). By October 10 the surface had cooled to 16.5° bringing the epilimnion down to 8.5 m. The thermocline continued as before to 12 m. with the same temperature. On October 24 the surface layers had cooled uniformly to 10.9°, down to a depth of 11 m. at which level the temperature was 10.4°. This marked the lower limit of the epilimnion. Since the temperature of the hypolimnion remained constant, this narrowed the thermocline to only one meter with a fall in temperature of 4.5°. On November 14 the temperature was uniform from the surface to the bottom, namely 5.5°. On November 26 it had further cooled one-fourth of a degree. Ice formed on December 18, to a depth of one inch or 2.5 cm. By December 24 the ice was 2½ inches or 6.3 cm. thick and on January 2, 1926 it was 6 inches or 15 cm. thick. During the time observations were made, the ice reached a maximum thickness of 15 inches.

During the winter the water at a depth of 23 m. maintained a temperature between 4.0° and 5,0°. At 10 m. and 15 m. the temperature remained near 3.5°, while at 5 m. the temperature slowly rose until in February, 1926 it was almost the same as that for the 10 and 15 m. levels. The surface in the meantime had also become warmer, so that by the second week in April, when the ice left the pool, the surface water was practically the same as that for the rest of the levels. (Fig. 1).

With the increase in the length of the day in spring and a consequent increase in the number of hours of sunshine, the surface water warms very rapidly. At this time the temperature of the water is slightly more than 5.0°, and, being of a lower density than the water beneath it (which is close to 4°), tends to float on the surface. This prevents winds and convection currents from mixing it with the lower water so that the warm surface layer, or epilimnion, is formed. (Birge 1908). This layer was not clearly marked off until May. On May 9 it was only 1 m. thick. Below it came the thermocline which extended to 5 m. with a fall in temperature from 7.7° to 3.7°. On May

29 the upper layer was still one meter in thickness but the thermocline extended to 7 m. By June 22, 1926 the surface water had warmed to 20.0° and the epilimnion extended to 4 m. The thermocline had its lower level at 10 m. with a temperature of 8.2°. The hypolimnion had been warming up slightly. This condition continued for the summer with the epilimnion increasing in depth and warming slightly. The coldest water was near the 18 m. level where the temperature was below 4.9° at all times. (Fig. 2).

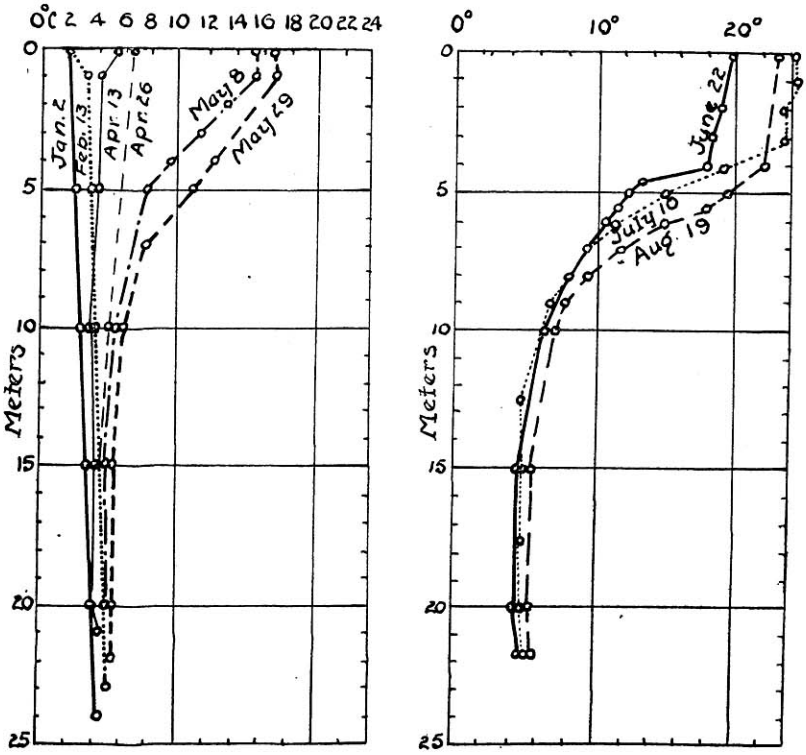

FIG. 2. Diagrams showing the changes in the temperature of the upper water between January 2 and August 19, 1926 in the Wauwatosa pool.

After September 16, 1926, clay was emptied into the pool as already stated, which warmed the entire hypolimnion and raised its upper level to 8 m. The entire water of this lower layer had a temperature of 8.4°, and it steadily

warmed so that the overturn, or period of uniform temperature, was brought on much earlier than usual. (October 30).

During the summer of 1927 the boat could not be used so that bottom temperatures of the deep water were unavailable. When it was used again in September 1927, the bottom temperature was the same as that for the 5 m. level. This was probably due to the fact that clay was still being emptied into the pool and continued to keep the lower water at a temperature higher than usual.

The temperatures of the North Milwaukee pool were substantially the same from surface to bottom, since the pool showed no stratification. This condition is typical for small, shallow lakes.

TURBIDITY

The turbidity of the water as measured by the Secchi disc, corresponded in general with the plankton growths at the time. In the case of the phytoplankton, an increase in numbers will increase the turbidity and so cut off the penetration of the sun's rays to the deeper waters and thus limit the growth of these organisms to the upper water. Since the North Milwaukee pool had at nearly all times a heavier growth than the large pool, the turbidity was also found to be higher than that for the Wauwatosa pool. The deepest level at which the disc disappeared in the North Milwaukee pool was 2 m. in July and September 1927, and in February 1928. This was the minimum turbidity. The greatest turbidity occurred in October 1927 and March 1928 when the disc disappeared at 0.5 m. The Wauwatosa pool had a much clearer water, in spite of the fact that clay was emptied into it. The minimum turbidity was found in August and September 1926, before the clay altered conditions. At this time the disc disappeared at 10 m. Immediately afterward, the disc was lost to sight at 6 and then 3 m. in October. Coincident with this, however, was an increase in the growth of plankton. The greatest turbidity in the large pool was found on November 30, 1926 when the disc disappeared at 0.75 m. At this time there was a heavy diatom growth and clay was still being dumped into the pool.

Chemical Results

Oxygen. The story of dissolved oxygen for the Wauwatosa pool is very similar to that of the temperature, and is very much in accord with the findings of Birge and Juday and of other workers on Wisconsin Lakes. (Fig. 3).

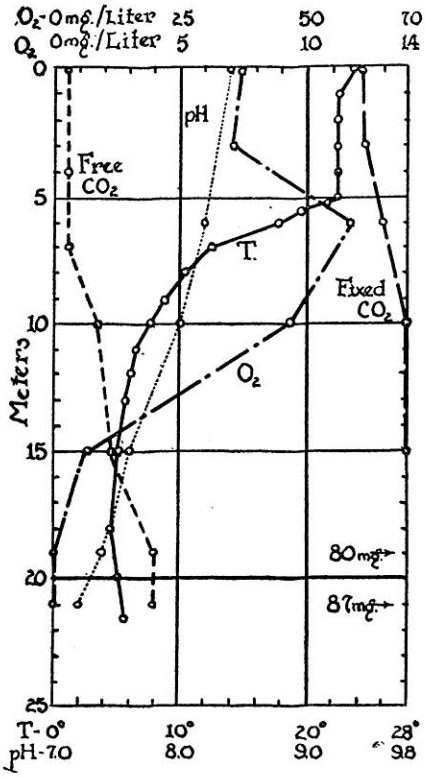

FIG. 3. Vertical distribution of the dissolved gases in the Wauwatosa pool on September 2, 1926.

Oxygen determinations were made in October 1925 and were then resumed in March 1926. In October 1925 the bottom water contained no free oxygen. The March determination showed no oxygen to be present in the bottom water, so that whatever had been acquired by the overturn of the fall had been used in the process of respiration and oxidation. Since the covering of ice prevented the circulation of water, the lower water remained without oxygen

until the spring overturn. By April 26, 1926, the bottom water had acquired slightly more than 2 mg. per liter of oxygen or 2 p.p.m., and this steadily rose until May 8 it reached its maximum of 3.3 p.p.m. By this time the epilimnion had formed, effectively cutting off the lower water from contact with the air, and in this manner depriving it of further oxygen. The oxygen in the lower water was gradually consumed until by July 10, it had again disappeared in the water below 19 m.

With the dumping in of clay in the latter part of September, oxygen was brought to the lower water, probably partly by absorption to particles of clay and partly by carrying down some of the surface water. The amount of oxygen at the lower levels at once rose and soon was the same as that at 10 m. With the overturn in the fall, all layers contained oxygen, ranging from 80 to almost 100 per cent saturation. The bottom water now continued to be supplied with oxygen due to the dumping of clay, which continued for a few weeks after the ice had formed. In this way the amount of oxygen did not decrease in the bottom water as it had during the winter of 1925–1926. During the spring of 1927 and during most of the summer the bottom water could not be investigated due to the leaky condition of the boat. When a test was made on October 10, 1927 before the fall overturn, the bottom water contained 5.5 p.p.m. of oxygen as compared to 1.0 p.p.m. the year before. It must be remembered that clay was continually being emptied into the pool about 150 m. from the deepest portion.

The North Milwaukee pool presented no such conditions. It was found that the temperatures varied little between the surface and bottom. The same was true for oxygen. The greatest difference between the surface and the bottom was on March 12, 1927 when the surface held 14.7 p.p.m. of oxygen in solution as compared with 6.0 p.p.m. for the bottom water. Unlike the larger pool, the North Milwaukee pool reached and even exceeded saturation with oxygen, several times during the year. The maximum surface saturation was on November 26, 1926 with 138.1% saturation or 18.7 p.p.m. of oxygen. A similar high value was reached on December 7, 1927 with 135.3% or 19.3 p.p.m.

The minimum saturation percentage was found in October of both years—63.9% or 6.62 p.p.m. in 1927 and 44.9% or 4.5 p.p.m. in 1926. The maximum saturation is not unusual, for Birge and Juday (1911) report a saturation for Knight's Lake, Wisconsin of 364.5% and others have found similar conditions to exist at times.

Carbon dioxide. With regard to the carbon dioxide, the Wauwatosa pool is again found to be comparable to some lakes. With the spring overturn the amount of fixed carbon dioxide was practically the same from surface to bottom. As the stratification of the water progressed, the amount of fixed CO_2 increased in the bottom water because of the accumulation of free CO_2 which permits a greater degree of solution of the carbonates. In August and September, 1926 the bottom water contained 85 and 87 p.p.m. of fixed CO_2, respectively, while the surface water at this time had 57 and 52 p.p.m., respectively. (Fig. 3) With the dumping of clay in the latter part of September the free CO_2 disappeared from the bottom water and the amount of fixed carbon dioxide decreased as a result. With the fall overturn, the water again became uniform from surface to bottom with respect to fixed CO_2. During the winter the bottom water contained a larger amount of fixed CO_2, but the increase was not more than 2 p.p.m.; before the ice had left the pool a decrease in the amount of fixed CO_2 at the bottom was found, so that there was no real gain during the winter. The difference between the surface and bottom during the winter was very slight.

The free CO_2 followed in a general way the course of the fixed CO_2. This was particularly true for the bottom water, when in August 1926 there were 30 p.p.m. of free CO_2, which was the maximum for the year. This corresponded with the maximum of 85 p.p.m. of fixed CO_2. The amount of free CO_2 in the surface water gradually diminished until neutrality to phenolphthalein was reached in September. After clay was emptied into the pool, the surface water contained no free CO_2 except in December 1927 and March 1928 when 5.5 and 4 p.p.m., respectively, were present.

The North Milwaukee pool as a whole contained more fixed CO_2 than the Wauwatosa one. The maximum was

reached on December 11, 1927 with 94 p.p.m. of fixed CO_2. The variations throughout the year were also much greater in extent, reaching a minimum of 40 p.p.m. in October 1927. Determinations of the fixed CO_2 in the bottom water of the North Milwaukee pool were not made during the summer. In October 1927 when they were made, the amount was the same for the surface and bottom, namely 85 p.p.m. During the summer of 1927 there was no free CO_2. in the surface water. This was probably due to its utilization by algae during the process of photosynthesis.

Hydrogen ion. The study of the hydrogen ion concentration has played an important part in ecology. Shelford (1923) and Jewell and Brown (1924) studied the reactions of fish to varying concentrations of the hydrogen ion. Juday, Wilson, and Fred (1924) studied the hydrogen ion concentration in various lakes deep enough to permit stratification. The lower levels were found to have a lower pH than the upper, due to decomposiiton in the former and photosynthesis in the latter. Noland (1925) found that ciliates exhibit a tolerance to rather a wide range of pH. He also found decided diurnal variation due to photosynthesis during the daytime. Philip (1927) also found a wide diurnal variation in a Minnesota lake and a horizontal variation depending on the proximity to clumps of plants and on the distance from the littoral region. Reed and Klugh (1924) found a variation of pH from 7.6 to 9.2 in a limestone pool in October and a biota distinct from that of a neighboring granite pool with a variation of pH from 6.2 to 6.8.

In the Wauwatosa pool the pH of the surface water varied from 7.8 to 8.8, being highest in September 1926, and lowest in March 1927 under the ice. In March 1928 the same value was reached with 4 p.p.m. of free CO_2. present, although for the previous year there was no free CO_2. in March. The bottom water varied between pH 7.2 and 8.6. The low value was found in September 1926 when there were 20 to 25 p.p.m. of free CO_2 and no free O_2 present. (Fig. 3). The high value came in 1926 just after the overturn on November 30. After the ice was formed the pH of the bottom water became lower, but did not vary more than pH 0.2 from that of the surface water. During 1927 the

lower water did not reach as low a pH value as it had in 1926 because clay was dumped in as stated above.

The surface of the North Milwaukee pool varied between pH 7.6 and 8.9; the greatest variations were found in the spring and fall. The maximum was found on October 30, 1926 and the minimum on March 30, 1927. The lower water, except during the spring and fall overturn, had a lower pH value than the surface and varied between 7.4 and 7.8.

Chloride. The Wauwatosa pool had uniformly about 20 p.p.m. of chloride during the summer of 1927. The determination of the chlorides was started in February 1927. The high values in the larger pool may be attributed in part to the chlorides brought in with the clay. (This may also be true for the soluble silica, next to be discussed.) During the winter the chlorides rose to 21 p.p.m. Just before the ice melted the chlorides in the surface water decreased. In March 1927 and 1928 there was a decrease of 7 to 8 p.p.m. This seems to be due to the melting of the ice and a consequent dilution of the water under the ice. A sample of the January ice on melting was found to contain only 25 per cent of the amount of chloride found in the water just beneath it. The bottom water had a lower chloride content than the surface during the summer, but with the fall overturn it approached the same concentration. Throughout the winter it remained lower than the surface except in February 1927 when it was 4 p.p.m. higher than the surface.

The North Milwaukee pool did not show such a high chloride content, averaging about 12 p.p.m. However, during the summer, it exhibited a greater variation; in July 1927 it reached a maximum of 17 p.p.m. The two increases in the amount of chlorides in July and September were perhaps due to additions as a result of drainage after heavy rains; or they may have been due to a concentration as a result of evaporation, for the water level fell about 27.5 cm. during the summer, and only a small part of this reduction in level was probably due to seepage through seams in the rock. The minimum, as is the case for the large pool, appeared in March, both in 1927 and 1928, just before the ice melted. In March 1927 there was a decrease

of 4 p.p.m. from that of the February value and in 1928 a decrease of 8.5 p.p.m. from the February reading with the minimum value of 6.5 p.p.m. The bottom water showed a slightly higher chloride content during the latter part of the winter and during the summer; after the fall overturn, both surface and bottom had the same concentration.

Silica. Birge and Juday (1911) found a periodicity in the silica content of the water in Wisconsin lakes, correlated with the seasonal variations in diatom numbers. They found that the silica content of the upper waters decreased during the summer due to its utilization by diatoms. The sinking of the dead diatom shells to the lower water and their subsequent decomposition increased the silica content of the lower water during the summer. With the fall overturn the dissolved silica was uniformly distributed from surface to bottom, thus furnishing favorable conditions for the multiplication of diatoms. Pearsall (1923) found that the increased diatom growth was associated with heavy rains in spring and fall which brought dissolved silica and nitrates into bodies of water by drainage.

The amount of dissolved silica in the surface water of the Wauwatosa pool varied from minima of 2.8 p.p.m. in March 1928 and 3.0 p.p.m. in October 1927, to a maximum of 7.5 p.p.m. in February 1928. The bottom water was about 0.5 to 1.5 p.p.m. higher than the surface in silica content before the overturn, but after the overturn in November it had less than the surface. During the winter the silica accumulated in the bottom water until it had about 0.5 p.p.m. more than the surface water. The amount of soluble silica fell in March in a manner similar to the fall in chloride content described above, and may have been due to the same cause.

The amount of silica in the North Milwaukee pool was less than that in the large pool. The surface water was low in soluble silica during the summer, with about 0.7 p.p.m. Both the surface and bottom increased in silica content after the fall rains. The maximum for the surface was reached in November 1927 with 5 p.p.m. During the winter the silica increased in both the surface and bottom

waters. The maximum for the bottom was reached in March 1928, with 5.5 p.p.m.

Nitrogen. No definite correlation could be found between the various forms of nitrogen in the pools. In general the various forms of nitrogen tend to run parallel to each other. In the Wauwatosa pool the maximum organic nitrogen was found on October 31, 1927 with 3 p.p.m. A minimum of 0.35 p.p.m. preceded this. The maximum is correlated with a maximum crop of plankton, but the minimum is not so correlated with a minimum crop of plankton. The higher organic nitrogen values seem to be coincident with high counts of entomostraca. The high point of the nitrate curve was the same for both pools and fell on October 31, 1927. It is not due to nitrates brought in by rains for there was no rain for the fortnight preceding this date. The nitrates were low in the summer in the Wauwatosa pool, due to the demand made upon them by the phytoplankton. The ammonia nitrogen was also low during the summer. During the winter the bottom water of the Wauwatosa pool contained from 0.13 to 0.03 p.p.m. of ammonia nitrogen less than the surface, although soon after the overturn in November it had 0.5 p.p.m. more.

A similar condition was found for nitrogen in the North Milwaukee pool. The variations between the surface and bottom were not as great as they were in the Wauwatosa pool. The nitrates were much lower than any of the other forms of nitrogen, and agree with the findings of Domogalla and others for Wisconsin lakes. The nitrites in the Wauwatosa pool varied between 0.0015 and 0.0095 p.p.m. while those for the smaller pool varied between a trace and 0.0195 p.p.m.

Phosphorus. There is a discussion in regard to the role of phosphorus in the economy of plankton growth. The studies of Atkins (1923, '24, '26) and Atkins and Harris (1925) introduced the theory that phosphorus is a limiting factor in the growth of phytoplankton. The whole question is discussed by Juday et al (1927) in a study of lakes of northeastern Wisconsin. They find no correlation between the soluble phosphorus and the phytoplankton, nor do they find any correlation between the amount of centrifuge plankton and the organic phosphorus.

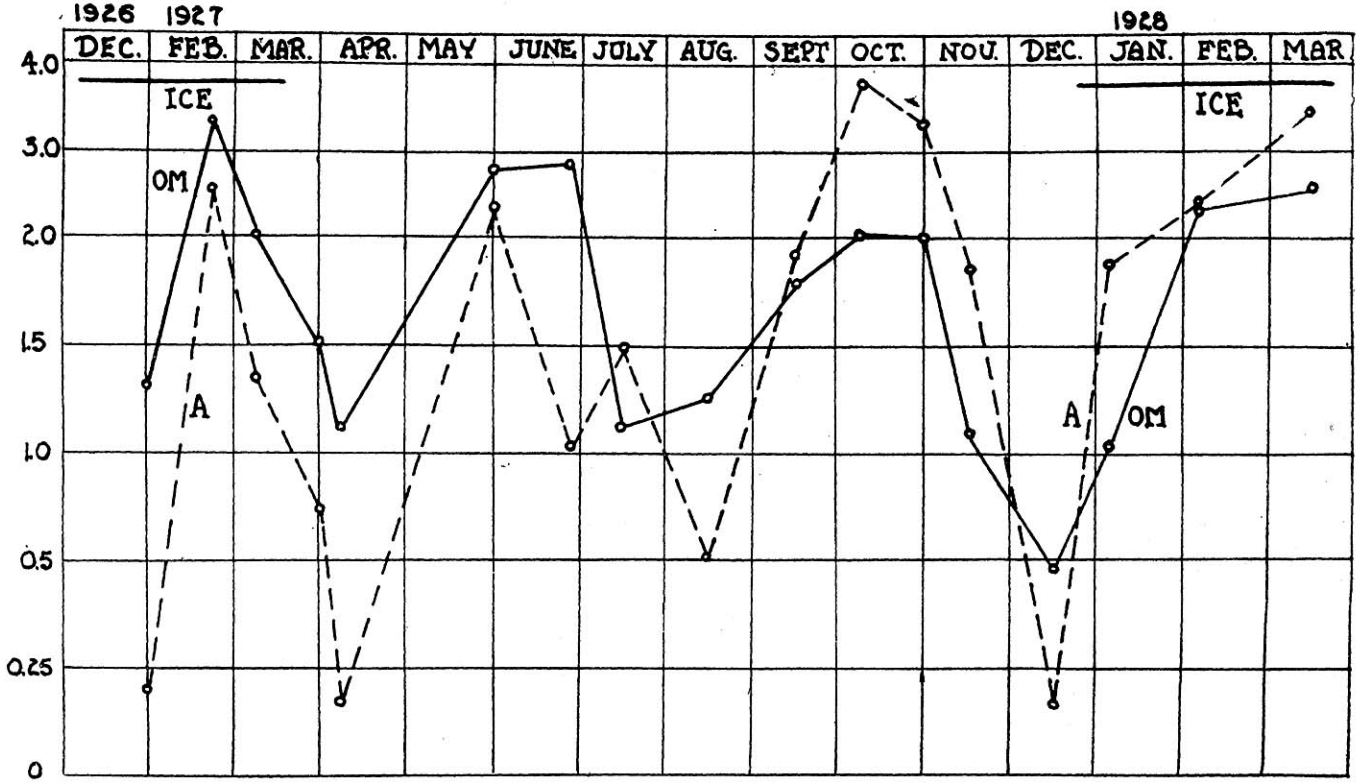

FIG. 4. Organic matter (curve marked OM) and ash (A) of centrifuge plankton of Wauwatosa pool, indicated in milligrams per liter of water.

A similar condition appears to maintain for these pools. The maxima of the soluble phosphorus came in September and February in the large pool when the soluble phosphorus reached 0.12 and 0.14 p.p.m. respectively. The average was generally about 0.03 p.p.m. The bottom water held less soluble phosphorus than the surface and there was no accumulation of it at the bottom during the winter. The organic phosphorus was not correlated with the net plankton or with the centrifuge plankton counts.

The soluble phosphorus in the North Milwaukee pool was lower than that of the Wauwatosa pool. Its average was about 0.003 p.p.m. and the highest points were found in September and January when 0.08 and 0.06 p.p.m., respectively, were reached. Here, again, except for the high peak in the curve in March 1928, there was no correlation between the organic phosphorus and the plankton. In March 1928 there was a coincident rise in the nannoplankton.

Organic matter. A study of the volatile or organic matter obtained by ashing the centrifuge plankton shows this to correspond very well with the net plankton counts as well as with the counts of the centrifuge plankton. (Fig. 4) The Wauwatosa pool had a maximum of organic matter in February 1927 with 3.32 mg. per liter. February 1928 showed 2.43 mg. per liter of organic matter present. The minima came in April and July, 1927 with slightly more than 1.1 mg. of organic matter per liter. The influence of diatoms as the dominant portion of the plankton crop is seen by the increase in ash at such times.

The North Milwaukee pool, except for July 1927 with a minimum of 0.75 mg. of organic matter per liter, showed higher values than the large pool. This was due to the greater abundance of plankton in the small pool. Here, too, the organic matter followed the trend of the curve for the plankton. The curve also shows the two annual maxima, the one in spring, and the other in the fall. (Fig. 5).

PLANKTON

In addition to the physical and chemical factors, there are the complex interrelations between the various inhabitants of the pools. The Wauwatosa pool had a deficiency

and at times a complete lack of oxygen in the lower levels, while the North Milwaukee pool was well supplied throughout its depth at all times. Atkins and Harris (1924) found that bodies of water with the bottom waters low in oxygen, have diatoms and Peridinieae, while those with a plentiful supply at all times support Chlorophyceae and Protoccales, primarily. Pearsall (1921, 1922) found that, in bodies of water where the value of the ratio Na

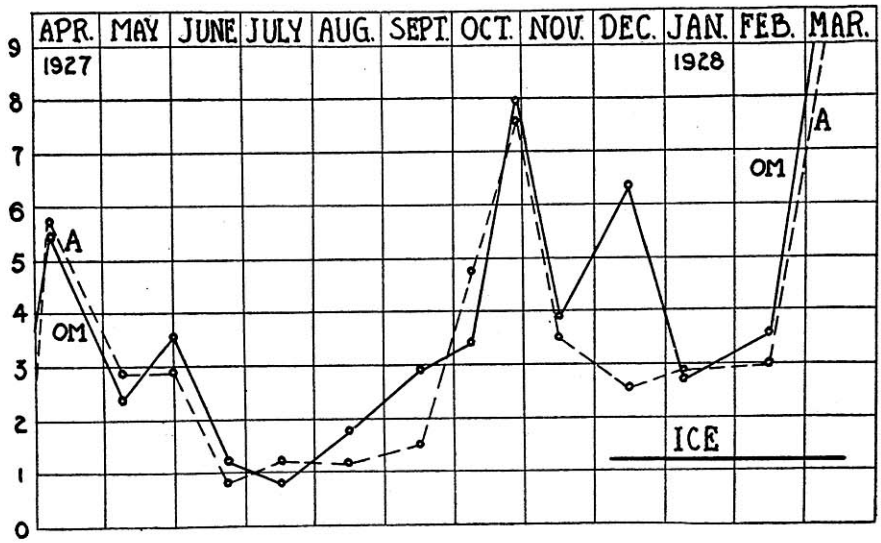

FIG. 5. Organic matter (curve marked OM) and ash (A) of centrifuge plankton of North Milwaukee pool, indicated in milligrams per liter of water.

and K to Ca and Mg was high, a desmid flora predominated, while a diatom flora predominated in bodies of water with a low ratio and where the silica and nitrates were present in sufficient quantities.

The Wauwatosa pool had low oxygen in the bottom water and had a predominant diatom and dinoflagellate plankton. Both pools had a large amount of Ca and Mg, consequently a low value for the Na and K ratio, and the diatoms predominated at certain seasons of the year. In the North Milwaukee pool, with oxygen at all levels at all times, the Chlorophyceae predominated during the summer.

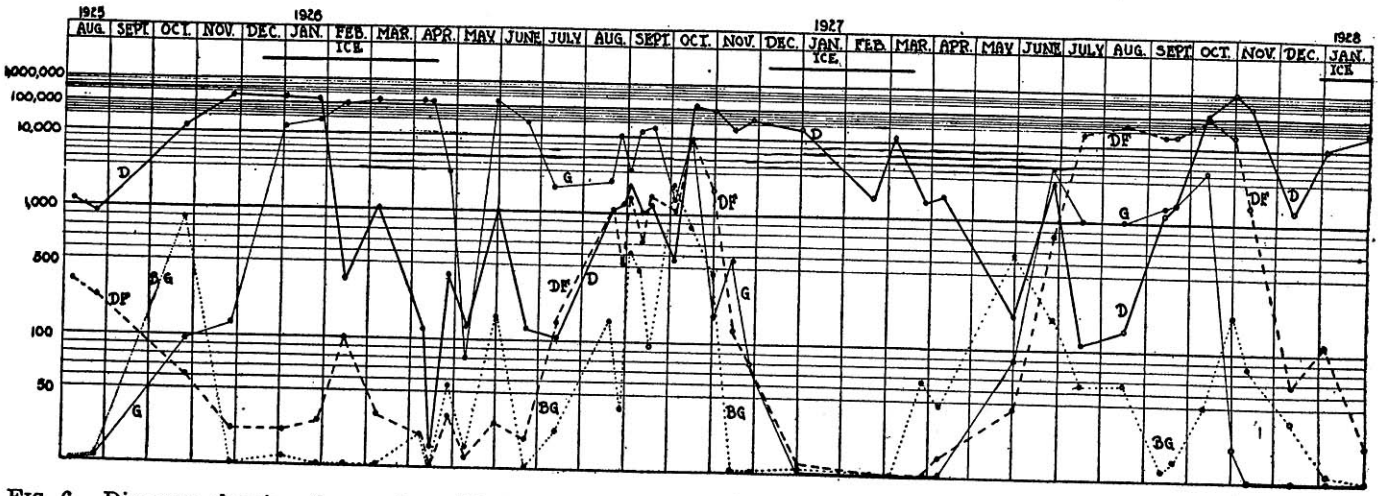

FIG. 6. Diagram showing the number of individuals and colonies in the net phytoplankton of the upper meter of water in the Wauwatosa pool. D—diatoms; G—green algae; BG—blue green algae; DF—dinoflagellates.

In the Wauwatosa pool the diatoms were abundant in spring and fall, with the latter as the greater of the maxima. (Fig. 6). The growth of diatoms begins in the late summer and the maximum is reached in October or November. Two genera are dominant, one succeeding the other. Fragilaria appeared first and was followed by Asterionella in greater numbers, which continued to be dominant for varying periods, often into March. The maximum of diatoms was reached on October 31, 1927 with 1,000,000 colonies of Asterionella per liter in the net plankton. In the early months of 1926 Eudorina became the dmoinant plankton organism, and continued so through April, reaching a maximum of 250,000 colonies in March. This was its only appearance in numbers in the pool during the time it was studied. After the decrease in the number of Eudorina, Sphaerocystis began to appear and increased in numbers, overshadowing the diatoms in the spring. During the latter part of summer Oocystis took the place of Sphaerocystis and reached its maximum number in September with 40,000 colonies and individuals per liter. In October this organism was surpassed in numbers by diatoms again. In 1926, Ceratium, which is dominant in early fall, did not reach as great numbers as it did in 1927. During the summer of 1927 there was a very meager plankton population. In the latter part of the summer the dinoflagellates became the dominant organisms, with two pronounced peaks in their numbers. The first peak came in August with 70,000 cells per liter and the maximum came in October, just before encystment, with 100,000 individuals, chiefly Ceratium. Peridinium numbered a few hundred cells per liter. After the cool weather of the second week of October, Ceratium decreased in numbers and began to encyst. On October 31, 1927 the cysts numbered 1,000 per liter as compared to 30,000 encysting individuals.

At this time, also, several cases of abnormalities in the number of horns or spines of Ceratium were found, similar to those described by Huber-Pestalozzi (1927). These abnormalities consisted of unusual twistings of the spines, especially one or more of the spines of the hypovalve. In about ten cases, seen in the course of the plankton counts, a doubling of one or more of the hypovalve spines was ob-

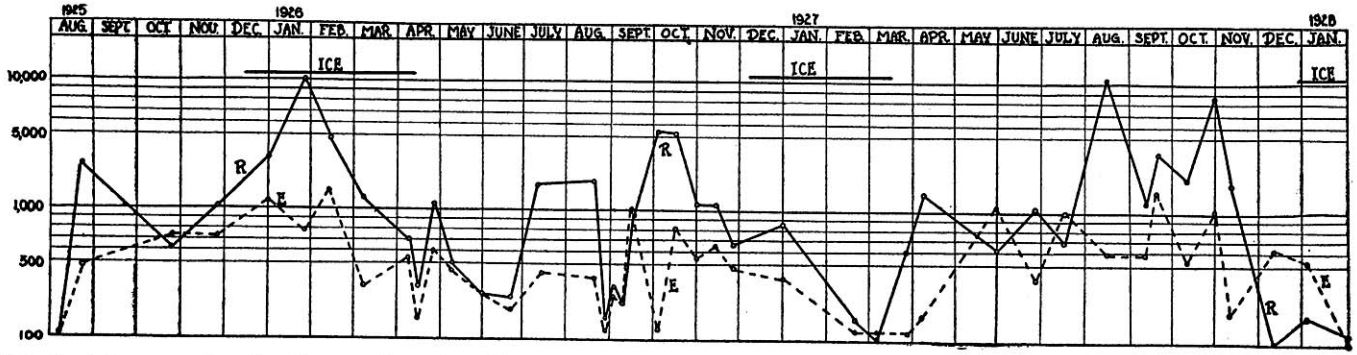

FIG. 7. Diagram showing the number of rotifers (R) and entomostraca (E) in the net plankton of the upper meter of water in the Wauwatosa pool.

served, similar to that shown in fig. II (No. 8) of Huber-Pestalozzi's paper. In one case each of the three hypovalve spines was duplicated and in another, two extra spines were present. In each case the spines were well developed and not mere stumps.

Among the less abundant forms, the blue greens reached their highest numbers in October, May and June. In the fall, the common ones were Oscillatoria and Anabaena, while in the spring and early summer Chroococcus was most common.

The rotifers were abundant in the late summer. At this time Polyarthra was the most common rotifer. In 1926 the maximum occurred in January, with 1,000 per liter consisting of almost equal numbers of Polyarthra and Anuraea. In 1927 the maximum came in August, with 1,600 per liter, the most common being Polyarthra. (Fig. 7).

The entomostraca were found in greatest numbers in the fall, although there were a few exceptions to this; small increases were found during the summer. Since the seasonal variations were studied primarily in the upper meter of water, where the entomostraca are rarely found in great numbers, the curve for them may be somewhat misleading. The greater part of the entomostraca in the upper meter of water consisted of nauplii. There seemed to be no definite cycle in the numbers of the nauplii. This is also the condition found by Birge and Juday (1922). Daphnia, Cyclops, and Diaptomus were the most common of the entomostraca. These forms show a diurnal migration. (Juday 1904). In samples of water collected during the day, Daphnia and Diaptomus were most abundant between two and four meters, where at times 50 Daphnias and over 100 Diaptomi per liter were present. On July 15, 1927 samples were taken at the surface at 9:00, 9:30, 10.00, and 11:00 p. m. An almost full moon rose at 10:00 p. m. At 9:30 the surface water yielded the greatest number of entomostraca—about 200 Diaptomus and 75 Cyclops. Daphnia were present in very small numbers—1 adult and 11 young individuals. The following noon another sample was taken and no entomostraca, other than several nauplii were present. (Fig. 7).

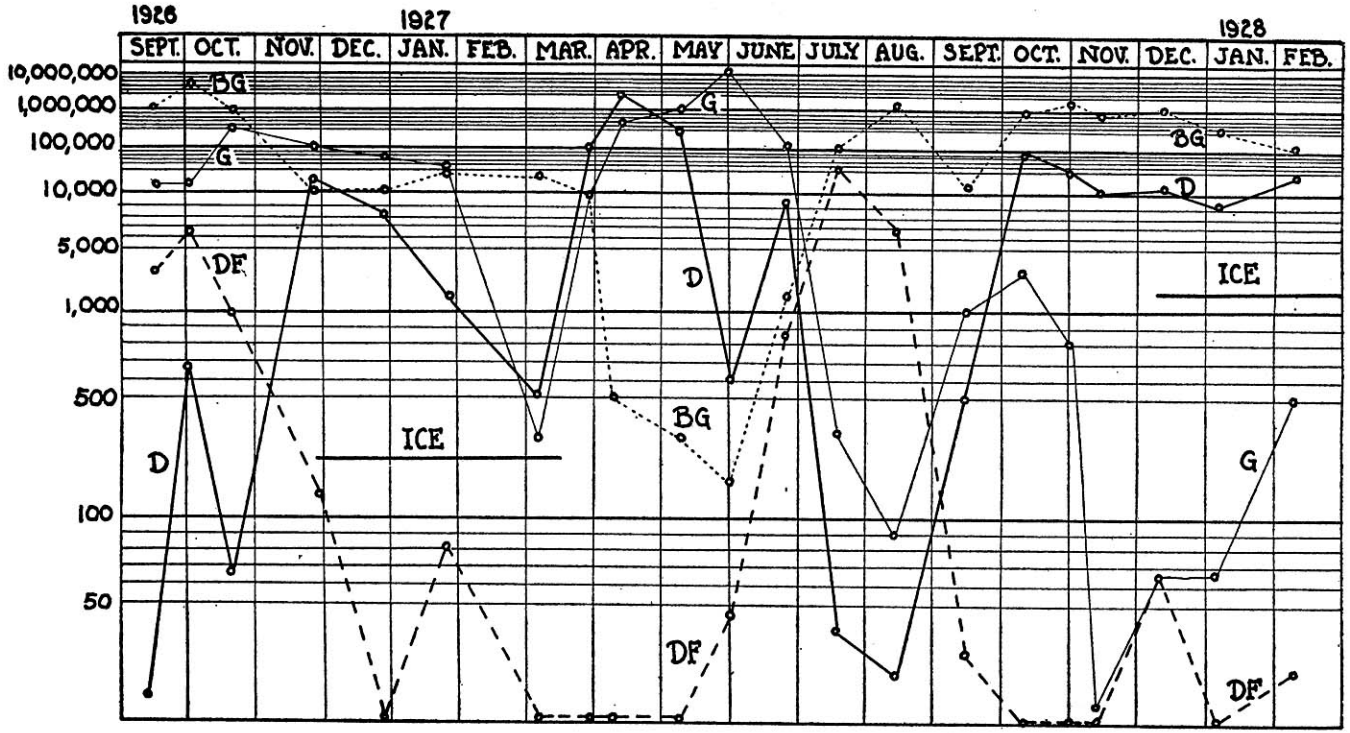

FIG. 8. Diagram showing the number of individuals and colonies in the net phytoplankton of the upper meter of water in the North Milwaukee pool. D—diatoms; G—green algae; BG—blue green algae; DF—dinoflagellates.

The North Milwaukee pool shows a much greater wealth of organisms. The number varies between 40,000 and over 29,000,000 per liter in the net plankton. The maximum growth of plankton came in the spring instead of in the fall as was the case for the Wauwatosa pool. The dominant forms were different from those in the large pool.

The diatoms were not the dominant plankton forms, except early in the spring, when Synedra and Diatoma were most abundant for a short time. In the late summer and fall the blue greens (Aphanizomenon and Anabaena) were the most common organisms. In the fall of 1926, Synura was next to the blue greens in numbers, reaching a total of 500,000 colonies per liter in October. Synura did not appear in the fall of 1927, leaving the diatoms second in number of individuals. (Fig. 8).

Toward the early part of the winter of 1926 Synura gave way to a crop of Dinobryon of which, in January 1927, there were 50,000 colonies of about 20 cells each. The number of Dinobryon then decreased, but in May rose again, and then were completely overshadowed by a heavy crop of monads which in the net plankton numbered 29,000,000 per liter.

The dinoflagellates were not as conspicuous in the North Milwaukee pool because other forms were more numerous. The greatest number was found in July 1927 when 65,000 Ceratium and 2,000 Peridinium per liter of water were present. The Ceratium in this pool was larger and broader, with heavier spines than that in the Wauwatosa pool. This form was followed in August by a slender and smaller type, often with only two spines on the hypovalve.

The protozoa were more abundant in the smaller pool than in the larger one. In October 1926 the protozoa reached the highest point, with over 60,000 cells per liter. The greatest number of them consisted of Codonella, although free swimming Vorticellas of several species numbered over 2,000 per liter. In 1927 the crop of protozoa was not as large, amounting to 2,000 per liter. The protozoa were most numerous in October and March with a slight rise in numbers also in June.

The rotifers also were more numerous than in the Wauwatosa pool, reaching a maximum of over 50,000 per liter

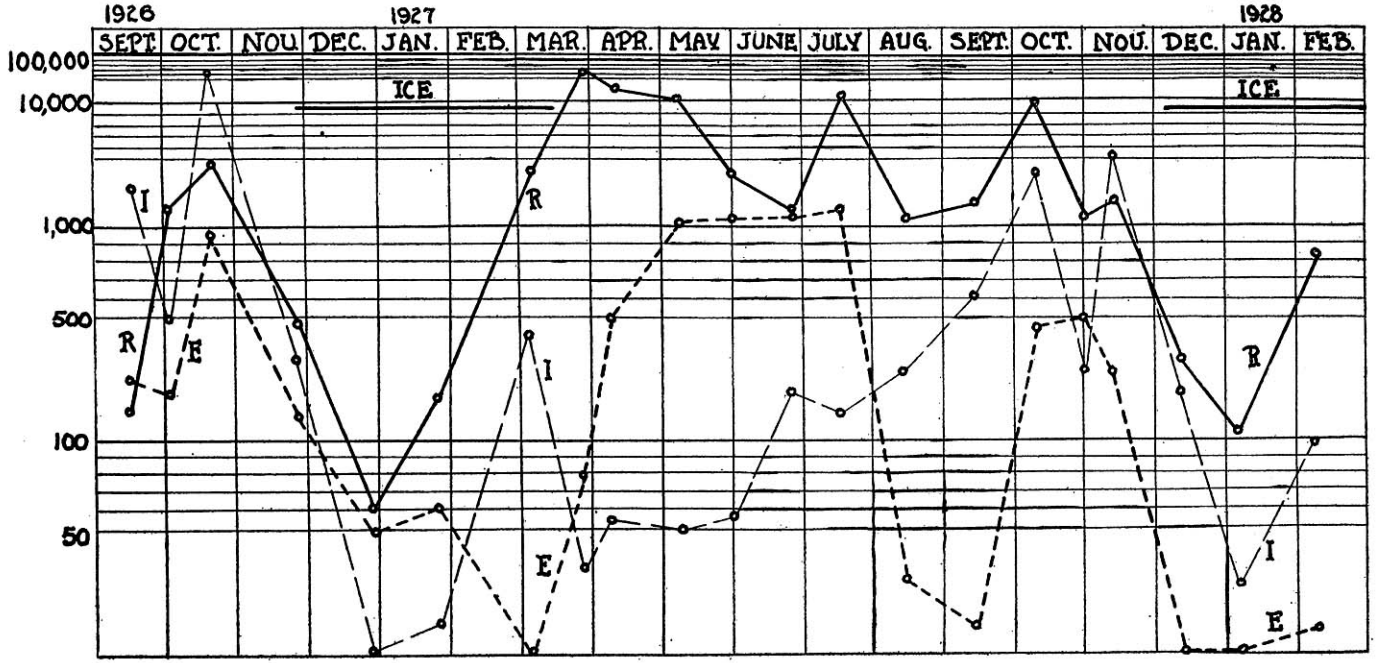

FIG. 9. Diagram showing the number of infusoria (I), rotifers (R) and entomostraca (E) in the upper meter of water in the North Milwaukee pool.

on March 27, 1927. This is about thirty times the maximum number found in the large pool. This maximum consisted mainly of Polyarthra (22,000), *Anuraea aculeaea* (20,000), *A. cochlearis* (6,000) and Triarthra (2,000). A second peak in the rotifers was found in July, when they numbered 25,000 per liter with *A. cochlearis* as the common form. In October 1927 a third peak was found when they reached 14,000 per liter with *A. cochlearis* var. *tecta* most common. (Fig. 9).

The entomostraca were represented by Cyclops, primarily, and nauplii formed the greatest contribution to their number. The maxima were found in late fall, late spring and early summer. The following table will give some idea of the numbers of entomostraca in the surface water at the periods of greatest abundance.

	Oct. 1926	*May* 1927	*July* 1927
Diaptomus	50 per liter	600	60
Cyclops	700	100	60
Nauplii	200	500	1200
Daphnia	25	—	35
Bosmina	80	100	700

This study of the plankton of the two pools shows that they are very different with respect to the kinds and the numbers of organisms they maintain. The increase in phytoplankton does not seem at all times to be due to the increase in the intensity of light in the spring, for at times some phytoplankton organisms reach their maximum when the light conditions are poor, (Eudorina in the Wauwatosa pool in March). In the North Milwaukee pool there is an increase in the number of phytoplankton organisms in the spring and this appears to be due in part to the increase in actinic power of the light at this time as suggested by Lloyd (1926). The greatest growth of diatoms takes place when the water is between 10° and 15°C. and at a time when the light is not too intense. (Whipple, 1927). In general, the protozoa occur in greatest numbers when certain of the phytoplankton forms are most numerous, and similar relations seem to hold between the rotifers and entomostraca. Of the Cyanophyceae, Aphanizomenon is more tolerant of a wide range of temperature than most

algae, Whipple (1927). It occurred in greatest numbers when the temperature of the water was near its highest point (24°) in August, and persisted throughout the fall and winter, in December reaching as many as 1,000,000 filaments per liter under the ice. In fact, the growth of Aphanizomenon was so heavy that the ice became greenish and was not harvested because of the discoloration. Whipple (1927) cites a similar case.

At various times, samples were taken at different stations to study the horizontal distribution of the plankton. Although some small variations were found at times, they were not of sufficient magnitude to enable one to draw conclusions. With very little wind, the plankton organisms probably had a fairly uniform horizontal distribution. Whipple (1927) believes that the horizontal distribution is quite uniform.

The vertical distribution is, to a certain extent, dependent upon the wind. Some of the diatoms tend to sink in quiet water, while a circulation of the water by the wind will keep them in the upper stratum. Aphanizomenon tends to float on the surface of the water, but a wind would carry some down to the lower water. (Whipple 1927). The vertical distribution in the North Milwaukee pool was fairly uniform. The greatest growth was found within the upper meter. The greatest number of organisms may be found in either the first or the second half-meter of water. From one meter downward, there was a gradual diminution in numbers, with the smallest number at the bottom. In the Wauwatosa pool uniform distribution was noted only when the temperature was uniform and the water was in full circulation. When stratification was pronounced there was an abrupt change in the number of plankton organisms at different levels. As in the North Milwaukee pool, the greatest number of organisms was found in the first meter of water, except for the entomostraca as noted above.

The nauplii were most abundant at the surface, while Diaptomus and Cyclops were most common in the second half-meter of water. Daphnia were most abundant between two and four meters. Of the rest of the forms there was a gradual decrease toward the bottom. When strati-

fication is present there is no such gradual fall in numbers from the surface to the bottom. At such times the entomostraca were still found in greatest numbers between two and five meters, the nauplii and Cyclops at higher levels than the Daphnia.

Table 1 gives the numbers of the various organisms at the different levels of the two pools during the four important seasonal periods of the year. The first column in May, shows the vertical distribution when the temperature is almost the same from surface to bottom, during the period of the spring overturn in the Wauwatosa pool. The summer period of stagnation and stratification is seen in the column for August. The fall period of uniform temperature and overturn comes in November, while the winter condition is seen in February.

SUMMARY

1. Physical, chemical and biological observations were made on two limestone quarry pools in the vicinity of Milwaukee, Wisconsin.

2. The temperature of the surface water of the two pools followed that of the air in a general way, rising somewhat more rapidly in the spring and falling more slowly in the autumn. The Wauwatosa pool was thermally stratified during the summer. With a maximum depth of only 5 m., the North Milwaukee pool was substantially uniform in temperature from surface to bottom.

3. The North Milwaukee pool contained an abundance of oxygen at all depths throughout the year; dissolved oxygen entirely disappeared from the bottom water of the other pool in summer and in winter. There was no definite correlation between the various forms of nitrogen in the two pools; in general there was a correlation between the organic nitrogen and the plankton crop. Nitrates were low in summer. No correlation was found between the phosphorus and the plankton.

4. Diatoms and dinoflagellates were dominant in the Wauwatosa pool, and Chlorophyceae and Cyanophyceae in the North Milwaukee pool. The latter pool had a greater number of plankton organisms per liter and also a greater

variety of species. The maximum crop of plankton was found in the spring in the North Milwaukee pool, but it came in the fall in the Wauwatosa pool. Protozoa and rotifers were more abundant in the North Milwaukee pool than in the Wauwatosa pool. With the exception of the entomostraca, the largest number of plankton organisms was found in the upper meter of water in both pools. The vertical distribution of the summer plankton in the Wauwatosa pool was similar to that of stratified lakes.

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TABLE 1. *Summary of the vertical distribution of the various plankton organisms in the two pools. The results are stated in the average number of individuals per liter between the depths given.*

Plankton	Depth	Wauwatosa Pool				North Milwaukee Pool			
		May 29, 1927	Aug. 11, 1927	Nov. 11, 1927	Feb. 4, 1928	May 31, 1927	Aug. 14, 1927	Nov. 12, 1927	Feb. 5, 1928
Entomostraca	0–½	156	44	----	----	1,178	16	270	----
	½–1	100	78	33	----	1,611	22	324	22
	1–2	66	50	50	5	517	72	111	11
	2–3	35	61	83		288	806	129	----
	3–4	91	38	44	15	452	----	100	5
	4–5	----	39	66	----	55	289	----	16
	5–10	----	11	13	7	----	----	----	----
	10–15	----	5	7	9	----	----	----	----
	15–20	----	1	----	7	----	----	----	----
Rotifera	½	67	1,875	346	11	4,018	5,304	3,580	1,218
	1	55	1,532	135	----	3,885	2,104	1,789	391
	2	41	1,072	56	2	1,151	627	675	245
	3	16	335	78	----	1,035	252	535	993
	4	11	117	11	5	1,052	1,121	483	507
	5	----	16	28	----	1,732	----	----	375
	10	----	5	6	1	----	----	----	----
	15	----	8	1	----	----	----	----	----
	20	----	1	----	----	----	----	----	----
Protozoa	½	----	1,141	33	----	11	884	9,217	89
	1	----	1,126	----	----	100	134	2,676	111
	2	----	313	----	2	6,216	837	1,027	27
	3	----	28	5	----	5,580	694	954	189
	4	5	22	----	----	2,374	291	763	79
	5	----	11	----	----	542	----	----	66
	10	----	1	1	----	----	----	----	----
	15								
	20	----	----	4	----	----	----	----	----
Total Zooplankton	½	223	3,060	379	11	5,207	6,204	13,067	1,307
	1	155	2,736	168	----	5,596	2,260	4,718	524
	2	107	1,435	106	9	7,884	1,536	1,813	283
	3	51	424	166		6,903	1,752	1,618	1,182

TABLE 1. *Summary of the vertical distribution of the various plankton organisms in the two pools. The results are stated in the average number of individuals per liter between the depths given*—Continued.

Plankton	Depth	Wauwatosa Pool				North Milwaukee Pool			
		May 29, 1927	Aug. 11, 1927	Nov. 11, 1927	Feb. 4, 1928	May 31, 1927	Aug. 14, 1927	Nov. 12, 1927	Feb. 5, 1928
Total Zooplankton—Continued	4	102	177	55	20	3,878	1,701	1,346	589
	5		66	94		2,329			457
	10		17	20	8				
	15		13	8	9				
	20		2	4	7				
Blue Greens	½	884	89			235	2,100,616	1,322,484	353,600
	1	420	44	179		189	3,200,626	678,470	153,680
	2	621	44	44		8,924	1,361,830	758,554	60,112
	3	610	11	16		7,477	142,386	690,360	110,922
	4	627		33		224	309,724	528,688	134,368
	5		5	44		22			89,708
	10			10					
	15			1					
	20			14					
Diatoms	½	224	111	919,449	61,243	648	11	21,700	76,136
	1	267	268	235,222	48,841	492	11	21,758	30,020
	2	83	116	146,055	36,378	167		11,178	7,698
	3	228	93	99,946		212		20,445	19,150
	4	395	56	81,826	32,818	30		25,142	5,332
	5		33	154,800		246			7,100
	10		5	104,795	26,607				
	15		3	42,293	19,654				
	20			77,888	21,087				
Greens	½	99				30,744,620	44		671
	1	133				28,747,847		11	380
	2	71			5	9,835,898	99	11	21
	3	110	5	11		6,632,239	167	5	
	4	38	16		5	1,805,846		8	44
	5					1,076,666			33
	10			1					
	15								
	20			18					

TABLE 1. *Summary of the vertical distribution of the various plankton organisms in the two pools. The results are stated in the average number of individuals per liter between the depths given*—Continued.

Plankton	Depth	Wauwatosa Pool				North Milwaukee Pool			
		May 29, 1927	Aug. 11, 1927	Nov. 11, 1927	Feb. 4, 1928	May 31, 1927	Aug. 14, 1927	Nov. 12, 1927	Feb. 5, 1928
Dinoflagellates	½	67	97,240	4,061	11	22	27,404	----------	44
	1	22	53,924	996	33	66	7,850	----------	----------
	2	----------	28,735	1,127	102	39	5,357	----------	----------
	3	11	8,840	482	----------	11	5,000	----------	----------
	4	21	9,293	234	38	----------	4,502	----------	----------
	5	----------	1,500	296	----------	----------	----------	----------	----------
	10	----------	286	171	57	----------	----------	----------	----------
	15	----------	11	44	30	----------	----------	----------	----------
	20	----------	25	30	6	----------	----------	----------	----------
Total Phytoplankton	½	1,274	97,440	923,510	61,254	30,745,525	2,128,075	1,344,184	430,451
	1	842	54,236	236,397	48,874	28,748,594	3,208,487	700,239	184,080
	2	775	28,895	147,226	36,485	9,845,028	1,367,286	769,743	67,831
	3	959	8,949	100,455	----------	6,639,939	147,553	710,810	130,072
	4	1,081	9,365	82,093	----------	1,806,700	314,226	553,868	139,744
	5	----------	1,538	155,140	32,861	1,776,934	----------	----------	96,841
	10	----------	291	104,977	26,664	----------	----------	----------	----------
	15	----------	14	42,338	19,684	----------	----------	----------	----------
	20	----------	25	77,950	21,093	----------	----------	----------	----------
Temperatures	½	12.2°C.	22.3°	11.5°	5.0°	12.7°	24.0°	7.4°	1.2°
	1	12.2	22.0	11.0	5.1	12.5	23.0	7.4	2.0
	2	12.2	22.0	10.7	5.1	12.5	19.0	7.4	----------
	3	12.2	20.0	10.7	5.2	12.5	----------	7.4	3.2
	4	10.0	16.0	10.6	5.2	11.5	18.0	7.4	----------
	5	8.2	14.5	10.6	5.2	10.2	17.0	7.4	5.0
	10	----------	14.5	10.6	5.2	----------	----------	----------	----------
	15	----------	14.5	10.6	5.2	----------	----------	----------	----------
	20	----------	14.5	10.6	4.9	----------	----------	----------	----------