A STUDY OF SEDIMENTATION OF WINONA LAKE[1]

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Introduction

This paper describes the distribution of the sedimentary deposits in the main body of Winona Lake (except the portion labeled Little Eagle in Figures 3 and 4) as determined by 75 borings through the accumulated organic sediment, i. e., down to gravel or sand. The borings were numerous enough and distributed in such a manner that there could be constructed not only six cross sections of the lake but also a fairly accurate contour map of the original bottom. These diagrams have made it possible to estimate the total volume of sediment in the lake and to determine its location with reference to the original shape of the lake basin. The study has thrown some light on the nature of the so-called "marl islands", mounds of sediment rising almost to the water surface. Further studies of the same type are contemplated on other and different types of lakes in the hope that more accurate and precise generalizations may be made as to the manner in which lakes fill and become extinct.

Acknowledgments

The author is indebted to Dr. Will Scott, director of the Indiana University Biological Station, for granting the use of the facilities of the station, for furnishing the special equipment for the work, for suggesting the method of drilling used, for permitting the use of the contour map of the present lake basin hitherto unpublished, for permitting the author access to his literature, and for constant suggestions and advice during the progress of the work. Acknowledgment is due also to Richard Stoner, Richard Hotz, Robert Bruce, John Niehoff, and Robert Wilson, who assisted in the field work at various times without compensation. Members of the Biological Station staff helped the progress of the work in many ways.

General Description of Winona Lake

Winona Lake is located in Kosciusko County, Indiana, near the city of Warsaw. It lies on the western border of the Packerton moraine, which is the interlobate kettle moraine between the Huron-Erie and Saginaw lobes of the Wisconsin ice sheet.[2] It is of the kettle-hole type of glacial lake. Its greatest length is 1.7 miles; it averages slightly more than .5 mile in width and is 80 feet deep at the deepest point.

Physiographically the shore line of Winona Lake is in late youth, although the youthfulness may be partly due to rejuvenation brought about by the lowering of the lake at an earlier period. A wave-cut terrace lying along the eastern shore, 5 to 8 feet above the present lake level, indicates such a condition.

Two streams, Cherry Creek and Sugar Creek, enter Winona Lake, and there is one outlet. The two marl islands near the south end of the lake form conspicuous features of the contour map (Figs. 2 and 4).

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[1]Contribution from the Biology Department of Heidelberg College and contribution 247 from the Zoology Department of Indiana University.

[2]Malott, C. A., 1922. The physiography of Indiana. Handbook of Indiana Geology, Pt. 2. Indiana Dept. Cons. Publ. 21:59-256.

The features noted make it apparent that Winona Lake is particularly well adapted to the present study inasmuch as it offers an averge set of glacial lake conditions.

Method of Study

Location of Borings.—The borings that form the basis of the present study are numbered and their locations shown on Fig. 2. During the field work their locations were determined by the depth of water and by drilling along lines between two conspicuous points on shore that could be located on the map. These lines are labeled on the map as A-A, B-B, etc. The locations of the borings are placed along these at the depth at which they were made, as shown by the contour lines of the map.

FIG. 1. The float from which drilling in water was done. The force pump is shown in the foreground at the left; the casing between the two middle figures; the tubing, with rubber hose attached, between the arms of the derrick. A block-and-tackle is shown suspended from the derrick and attached to the tubing, and a length of tubing, not in use, is shown projecting above the derrick.

The Boring Apparatus and Its Use.—The borings were made by a technique somewhat after the manner in which sulphur is recovered from wells. A casing of iron pipe, 1¾ inches in diameter, was driven into the sediment and a half-inch pipe (herein referred to as the tubing) placed inside the casing. The tubing was then connected to a force pump by a rubber hose and water was forced down the tubing to wash the sediment from the lower end of the casing. Since the casing was sealed at the bottom by the sediment, the water and sediment were forced to the top between the casing and tubing.

In the water, the work was carried on from a float (Fig. 1), which

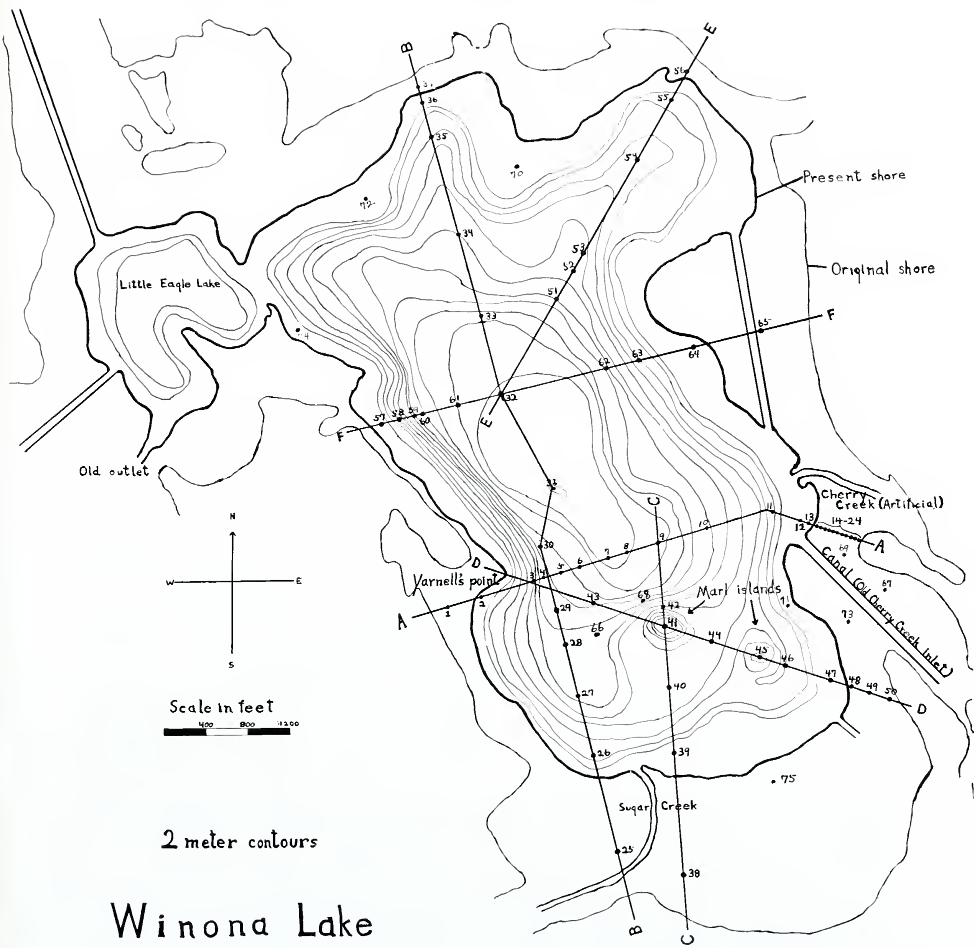

FIG. 2. Contour map of Winona Lake (made by Dr. Will Scott and hitherto unpublished), showing the lines (A-A, B-B, and etc.) along which borings were made. The numbered dots along the lines indicate the locations of the borings. The scattered borings 66 to 75 are also shown. The outermost line represents a close approximation of the original shore of the lake; it was added to the rest of the map from a map by Allen A. Norris.

was securely anchored. A derrick, block and tackle, windlass, and sometimes an automobile jack were used to facilitate the mechanical operations of lowering and raising the pipes, pulling the anchors, and many other processes. Depths were easily determined by keeping account of the amount of pipe used in the drilling operations. Holes in 80 feet of water and penetrating more than 50 feet of sediment were drilled without difficulty by this method, and no doubt it could be used for much greater depths.

Method of Sampling.—Samples of the sediment were taken at approximately 10-foot intervals in each boring. The method used to secure the samples was to put the casing down to the desired depth, then wash out all the sediment that had come up into the casing during its descent, by forcing water through the tubing as described above. When this had been accomplished, the tubing would be forced or allowed to drop into the undisturbed sediment below the casing to a distance of 2 to 5 feet, depending on the nature of the deposit, so that a plug of sediment was forced into the lower end of the tubing. Next, the tubing would be withdrawn from the casing and the sample discharged into a pint fruit jar, appropriately labeled, and sealed. This method gave ample and uncontaminated samples from a known level.

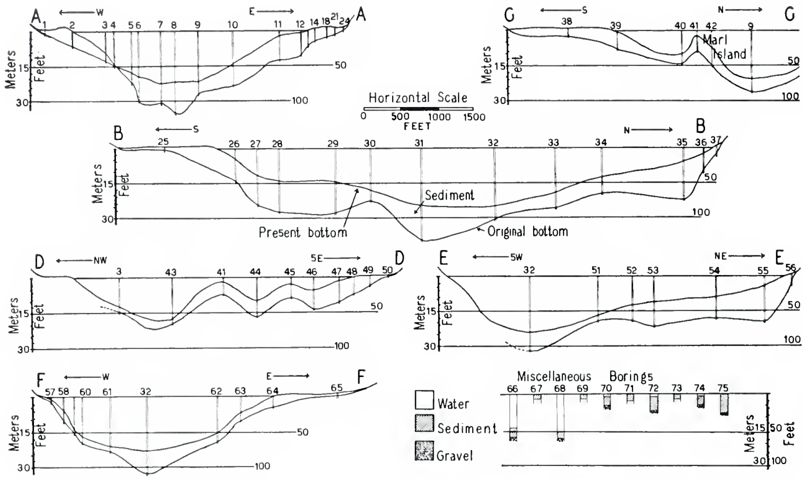

FIG. 3. Profile diagrams of the original and the present lake basins. The space between the two lines represents the sediment in the lake. The vertical scale of the diagrams is ten times the horizontal. Borings are shown as double vertical lines and numbered as in Figure 2.

It was found that the two quarter-inch holes drilled four feet from the lower end of the tubing greatly facilitated the securing of samples in the soft sediment, inasmuch as they permited the water in the lower end of the tubing to escape easily when the sample was entering instead of having to move the whole column of water. They also permitted the water above the holes and the sample to escape when the tubing was being raised in order to recover the sample. Without these holes the soft samples would be forced out by the extra pressure created by raising the tubing full of water above the lake level.

A detailed report of the mechanical and chemical analyses of the samples will be made in a subsequent paper. The samples were valuable, insofar as this report is concerned, in determining the depth of the organic deposits and the original bottom of the lake.

Field Notes.—The depth and location of each sample were recorded on a card, and these records provided the data from which the cross section profiles (Fig. 3) and the contour map (Fig. 4) of the original bottom are based.

Construction of the Profile Diagrams and Contour Maps.—In the construction of the profile diagrams and the contour maps the present water level was used as the reference point for depths of both the present and the original bottoms. The location of the six sections shown in Figure 3, together with the location of the borings upon which they are based, are shown on the contour map (Fig. 2). The locations of the borings on the profile sections are indicated by the vertical double lines labeled from 1 to 65. Both of the figures (Figs. 2 and 3) are labeled by the same letters and numbers. In order to accentuate the irregularities of the present and original bottoms, the vertical scale has been made ten times the horizontal.

In Figure 4 the contour map of the original bottom (red lines) is superimposed upon a contour map of the present bottom (black lines); the contour interval is two meters. The map of the original bottom was made by marking on the lines along which the borings were made the points where the depth was any multiple of two meters, as revealed by the profiles, and then drawing the contour lines through all points recorded for each depth. The scattered borings, 66 to 75 inclusive (Figs. 2 and 3), were of value in drawing the contour lines of the original bottom between the lines of the main cross sections.

Calculations of Volumes.—The calculations of the volumes of the present and original lake basins were made by the usual method of considering the basins as inverted cones and the contour lines as the perimeters of the bases of frustra of the cones. Since the present lake basin is 24 meters deep, it is composed of 12 frustra, while the original basin, 38.8 meters deep, is composed of 20 frustra. By tracing the contour lines on the map with a planimeter the areas of the two bases of each frustrum were determined, and the product of the average of these two by the altitude (2 meters) was regarded as a sufficiently close approximation of the volume. The sum of the volumes of all the frustra of each basin is its total volume. The difference between the volume of the original basin and that of the present basin represents the total volume of sediment, and by the same method the volume of sediment in any frustrum may be determined (Table I).

Description of Findings

General Description of Profiles and Contour Map.—The cross section profiles were located along lines (Fig. 2) which, it was thought, would best reveal the nature and shape of the original bottom; that is, they run across as many varieties of conditions as possible. For example, profiles A-A, B-B, F-F, and E-E all run from shore across or to the deep portions of the lake. The east end of A-A and the south end of B-B run across the deltas of Cherry and Sugar Creeks. Profiles C-C and D-D cross the marl islands in two directions. The miscellaneous scattered borings, 66 to 75, are located on points and in bays in such a manner as to determine whether or not the superficial conditions obtained all the way down to the original bottom of the basin. The map of the original bottom (Fig. 4) helps to visualize in three dimensions features shown only in two dimensions on the cross section profile diagrams.

An examination of the profiles and the contour maps shows that the original bottom is very much more irregular than the present bottom. In the present basin, except at the marl islands (profiles C-C and D-D), there is everywhere a progressive deepening from the shore toward the deepest part, while in the original bottom there are, besides the marl islands, many ridges between deep holes; for example, note the ridges at borings 30 and 34 on profile B-B (Fig. 3). The map of the original bottom shows five such holes (Fig. 4, A, B, C, D, and E) as contrasted with only one in the present bottom. Even where such ridges do not rise high enough to produce a hole, as in the cases referred to above, they often produce shoulders and shelves as shown best on the profiles (Fig. 3) near borings 4, 5, 7, 9, 11, and 14 on section A-A and near borings 57, 59, 61, and 63 on section F-F.

Further examination of the original bottom in the profiles (Fig. 3) and the contour map (Fig. 4) shows that, except for the marl islands, the deepest sediment occurs in the deep holes and the shallowest on the steep slopes, ridges, and shoulders, while flat places other than those in the zone of active wave action near shores and at the bottom of deep holes have an intermediate amount. For example, in section A-A the deep hole between borings 7 and 9 has 43 feet of sediment at hole 8, while on the steep slope at the west end of the section, between borings 3 and 5, where the slope is short and steep (about 3.4°), there is very little sediment,—none at boring 4. On the more gradual (about 2.5°) and longer slope at the east side of the section, between borings 9 and 11, there is an intermediate amount of sediment,—22 feet at boring 10. The same point is further illustrated along the other sections; for example, along section B-B the depths of sediment in the depressions, at borings 28 and 35, are 43.5 feet and 51.2 feet, respectively; on the ridge at boring 30 the depth is 9.8 feet; while along the gentle and longer slope between borings 32 and 34, the depth of sediment is again intermediate in amount,—21.6 feet at boring 33.

Volumes of Sediment.—The volumes of sediment in the different frustra of the lake and the total volume of sediment are shown in Table I. The total volume is seen to be 14,819,625 cubic meters. The volume of the original basin, not shown in the table, is 33,934,857 cubic meters; that of the present basin is 19,115,232 cubic meters. The volume of sediment is 43.6% of the original basin.

Distribution of Sediment.—The distribution of sediment in relationship to the original basin can be ascertained from Table I by comparison

TABLE I.—Volumes in cubic meters of the sediment in the frustra of Winona Lake when the lake is regarded as a cone divided into frustra by the contours of the original and present basins. For explanation see text.

Depth of Frustra	Volume of Sediment	Total to Level	Percentage of Total Volume of Sediment
1. 0-2 M.	1,560,776	1,560,776	10.53
2. 2-4 M.	1,178,160	2,738,936	18.48
3. 4-6 M.	1,568,240	4,307,176	29.06
4. 6-8 M.	1,499,200	5,806,376	39.17
5. 8-10 M.	1,426,848	7,233,224	48.80
6. 10-12 M.	1,278,808	8,512,032	57.43
7. 12-14 M.	1,142,872	9,654,904	65.17
8. 14-16 M.	952,020	10,606,924	71.57
9. 16-18 M.	756,852	11,363,776	76.68
10. 18-20 M.	611,088	11,974,864	80.80
11. 20-22 M.	557,760	12,532,624	84.56
12. 22-24 M.	593,000	13,125,624	88.56
13. 24-26 M.	525,112	13,650,736	92.11
14. 26-28 M.	377,680	14,028,416	94.66
15. 28-30 M.	307,968	14,336,384	96.73
16. 30-32 M.	228,736	14,565,120	98.28
17. 32-34 M.	146,880	14,712,000	99.37
18. 34-36 M.	78,880	14,790,800	99.85
19. 36-38 M.	27,168	14,817,968	99.98
20. 38-38.8 M.	1,657	14,819,625	100.00

of the totals of sediment down to any level with the total volume of sediment. This is shown in the column labeled "total to level". The column marked "percentage of total volume of sediment" indicates the relationship which the volume to that level bears to the total volume. For example, the total to the six meter level (bottom of frustrum 3) is 4,307,176 cubic meters, which is 29.0% of the total volume of sediment.

Perhaps the most valuable way to examine the distribution of sediment is to determine the contour inside and outside of which 50% of the sediment occurs and compare the area of the original lake surface outside this contour and below which 50% of the volume of sediment occurs with the area inside the contour and below which the other half of the sediment occurs. This can be referred to as the 50 percentile line or contour.

One-half the total volume of sediment in the lake amounts to 7,409-812 cubic meters. This is approximately the volume indicated in Table I from the surface down to the bottom of frustrum number 5, that is, to the 10-meter level. Since this 10-meter plane runs through the basin horizontally, it is impossible to tell from the data exactly where a projection of the vertical 50 percentile contour is, but it has to pass through the basins between the 10-meter contours of the two basins. An examination of the map showing both sets of contours (Fig. 4) shows that the 8-meter contour of the present basin lies between the two. Therefore, it can be used as a basis of calculation of surface areas of the original lake basin within and without the 50 percentile line.

Calculation of the surface area of the lake within the 8-meter contour gives 917,376 square meters. This figure subtracted from the surface area of the original lake basin (3,255,872 square meters) gives 2,338,496 square meters as the area of the original basin lying outside the 50 percentile (8-meter) contour. The last figure is 2.5 times as great as that for the area inside the 50 percentile (8-meter) contour. This means that the rate of settling inside the 50 percentile contour has been 2.5 times as fast, on the average, as the rate outside.

Marl Islands.—The profiles and contour maps (Figs. 3 and 4) show the marl islands to be accumulations of sediment on the tops of knobs or swells of the original bottom. The larger island, in fact, is an elevation at the end of a ridge of the original bottom extending on a southeasterly direction from Yarnell's point. This can be ascertained by an examination of the contour map of the original bottom (Fig. 4). The smaller marl island is built on a somewhat more isolated knob of the original bottom. The original peaks of the larger and smaller knobs were 8 and 10 meters, respectively, from the present water level. They rise 4 to 10 meters higher than the bottom immediately surrounding them. The depth of sediment on the islands is as great as or greater than that in the depressions immediately surrounding them, which is just the opposite of the condition ordinarily obtaining on ridges and in their adjoining depressions.

Uniformtiy of Depth of Sediment in the Originally Deep Holes.—There are five deep holes in the original bottom (Fig. 4, A, B, C, D, and E), some located near the original shores of the lake and some nearer the middle. The depth of sediment in the different holes is strikingly uniform. The absolute depth of the original hole apparently affects the depth of deposition very little as long as the depth is great enough to protect the sediment from the action of waves or shore currents. For example, in hole A (Fig. 4) the original depth was 26.6 meters, and the sediment 13.1 meters; in hole B the original depth was 38.8 meters, and the sediment 14.8 meters; in hole C the original depth was 21.5 meters, and the sediment 15.5 meters; in hole D the original depth was 20.3 meters, the sediment 9.8 meters; and in hole E the original depth was 16.6 meters, and the sediment 13.6 meters. These data indicate strongly that the factors which are responsible for the distribution of sediment have affected its distribution uniformly over the entire lake except in the littoral region.

Proportion of the Basin Obliterated.—As stated in the section on Volume of Sediment (p. 300), 43.6% of the volume of the original basin is now occupied by sediment. The original area of the lake, 3,255,872 square meters, minus 2,037,128 square meters, the present area of the lake, equals 1,218,744 square meters. The portion of the original lake area that is now emergent (1,218,744 sq. m.) is 37.4% of the original area. There is probably no significance to the fact that the two percentages are nearly equal.

Discussion

The foregoing facts lend themselves to the following interpretation of the origin and subsequent history of this lake:

The original basin is marked by knobs, swales, and ridges very much like those of the surrounding morainic topography. Some assortment of the bottom materials due to lake currents took place before the more typical lake sediments of carbonates and organic matter became dominant and covered the original bottom of gravel. In other words, the lake must have had a considerable history before organisms became well established. The assortment of the original bottom materials is made evident by the fact that the original ridges are covered with coarse gravel and sometimes unsorted materials and the depressions with fine sand.

When the characteristic lake sediment became sufficient to dominate the bottom accretions, it probably accumulated much more rapidly in the deep holes than on the ridges and knobs. Because of the effects of lake currents, deposition occurred only in the holes until they were filled to the level of the adjoining ridges. After the holes were filled to the level of the adjacent ridges the bottom contours were smooth and regular, and filling was probably more uniform over the whole bottom of the lake, or at least those portions where the above conditions obtained, because the currents were more uniform. This sequence of events is what one would expect from the influence of the bottom contours on the deposition of sediment, or upon its fate after it had settled, and it accounts for the fact that the accumulated sediment is now much shallower on the ridges, shoulders, and knobs than in the holes and on the relatively flat parts of the bottom. The above argument is supported by the work of Trask[3] on marine deposits; he found that currents are very effective in assorting the sediment when the depth is below the zone of active wave action.

The fact that all the five deep holes of the original bottom have almost equal depths of sediment, indicating that the rate of deposition in all the basins is fairly uniform regardless of depth, can be accounted for on the assumption that the sediment involved is so fine that it stays in suspension long enough to become very evenly distributed over the lake and settles out at a fairly uniform rate, that portion settling on the ridges being removed by currents and carried to the depressions where it settles out and remains undisturbed. It is hard to see how settling could occur at different rates over different parts of the bottom and always be greater over the holes than over the ridges. It seems to make little difference whether the hole is near the shore or distant from it, since in actual fact some of the original holes were close to shore (C and E, Fig. 4), some an intermediate distance (A and D, Fig. 4) and one (B, Fig. 4) near the middle of the lake.

To account for the fact that most of the sediment of the lake lies

[3]Trask, Parker D., 1931. Sedimentation in the Channel Islands Region, California. Economic Geology. **26**:24-43.

on the deep-water side of the shore zone, it is necessary to assume that most of the accretions of sediment along shore are abraded and ground to such fineness that they go into suspension and are distributed generally over the lake to settle out in the deep water. The unabraded sediment settles out along shore. This interpretation is made likely by the fact that the sediment in the middle of the lake averages almost 50% silicon dioxide, as contrasted with only about 10% near shore, all but 5% of the remainder of the sediment in both places being carbonates.

The occurrence of the marl islands, with their thick deposits of sediment, 90% carbonates, on top of knobs on the original bottom, which ordinarily would be expected to have very little sediment, can be accounted for by assuming that their original peaks were near enough to the surface (8 and 10 meters), at least in the earlier and less turbid stages of the lake, to permit the lodgement and growth of vegetation, which not only contributed sediment to them at a rapid rate but furnished protection from the currents that ordinarily would tend to dislodge the accumulations. Of course, such isolated accumulations would not be submitted to the actions of the undertow and shore currents to such an extent as would similar accumulations along shore. Probably the reason that the islands are not now emergent (they are about 1½ meters below the water surface) is that, where the accumulation gets close enough to the surface to be materially affected by waves, the accumulations erode as rapidly as they form and are carried away to be deposited in deeper water.

Conclusions

A new approach to the study of the problem of sedimentation is presented by securing data making it possible to construct a contour map and cross section diagrams of the original lake basin, from which the volume of sediment can be determined. A new method of drilling and sampling is described.

The unevenness of the floor of the original basin, as compared with the present bottom, is noted, together with the apparent fact that there was considerable assortment of the original bottom material before the characteristic lake sediment began to accumulate.

The original bottom is shown to be gravel and sand.

It is apparent that although the finely abraded sediment is probably fairly evenly distributed over the lake by currents, either the rate of settling is not uniform or its final place of lodgement is dependent to a large extent on the configuration of the bottom, most of it finding permanent lodgement in the depressions, at least until the depressions are filled to the level of the surrounding ridges.

The total volume of sediment is shown to be 43.6% of the volume of the original basin; it has settled mainly in the deep water, away from the shore zone, showing that the lake is filling more rapidly in the middle than along the shore, contrary to what has often been assumed.

The "marl islands" in the lake are shown to be relatively thick deposits of sediment resting on mounds of the original bottom which rise considerably above the level of the bottom immediately surrounding them. A theory is proposed to account for the unusually heavy sedimentary deposits covering them.

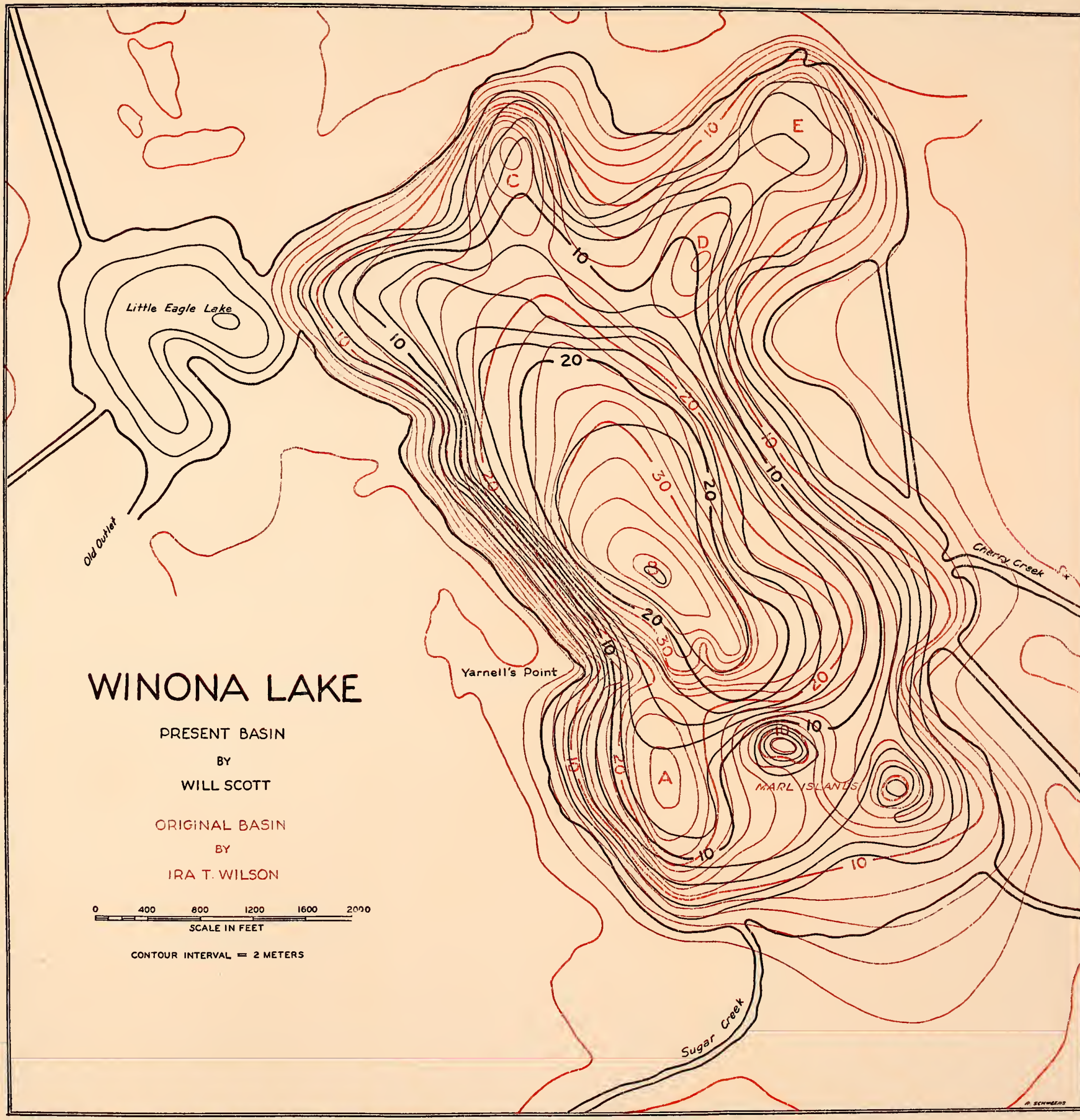

FIG. 4. A contour map of the original basin (red lines) superimposed upon the contour map of the present basin (black lines). The 5 holes of the original basin are labeled A, B, C, D, and E. The contour interval is two meters.