ANL-AMD-TM--198

DE93 006400

INITIAL OBJECTIVES OF ON-SITE EMPIRICAL MODELLING OF THERMAL PLUMES: A PRELIMINARY EVALUATION OF A RIVER-SITE AND A LAKE-SITE THERMAL PLUME

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Operated by
The University of Chicago under
Contract W-31-109-Eng-38
for the U. S. Atomic Energy Commission

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Applied Mathematics Division

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May 1970

Technical Memorandum No. 198

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*Work performed under the auspices of the U.S. Atomic Energy Commission. This report intended for internal distribution only.

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ABSTRACT

This report recommends developing a statistical model to characterize the three-dimensional pattern of thermal plumes. It indicates the danger of drawing detailed conclusions on the basis of a small number of observations, and emphasizes the need for proper interpretation of empirical measurements. Two reports, on the discharges (1) from the Dresden Power Station into the Illinois River and (2) from Waukegan Station into Lake Michigan are analyzed. In conclusion, a plan for interpretation of temperature measurements is recommended.

1. Introduction

An interdisciplinary group at Argonne is currently involved in evaluating the various physical, biological, chemical and meteorological effects of thermal discharges in the Great Lakes, and in particular in Lake Michigan. Lake Michigan[1,4] is the sixth largest fresh water lake in the world with a surface area of 22,400 square miles, an average depth of 276 feet and a volume of 1116 cubic miles. The lake has two basins, a southern and a northern basin. Figure 1 indicates that the coastline in the southern basin is very shallow but in the northern basin, it is not quite as regular. Much of the coastline is known to be sandy and forms weak underwater surfaces not quite suitable for attachment and growth of aquatic organisms.

Among the sites Argonne has considered modeling is the outfall of Commonwealth Edison's Waukegan generating station. This is a fossil fuel burning plant with a discharge canal at the shoreline rather than some distance out into the lake. In the vicinity of the discharge the lake is very shallow with a depth between 3 ft and 6 ft. In fact, a depth of 10 ft exists at a distance not less than 800-1100 ft from the shore line. Hence, we would expect that in this shallow region, the plume will be greatly influenced by local bottom topography, by shore currents (which are not necessarily subject to the main movements of the water in the lake), by wind direction and speed, etc. We also expect, because of the limit on the amount of water that could be entrained, that the heated discharge will be carried a maximal distance off shore. This is true unless the plume is deflected towards shore, in which case it will cover a relatively greater distance. Our first main concern is to study the characteristics of the thermal plume. L. P. Beer and W. O. Pipes have done an initial study of the thermal plume at Waukegan.[3,4] We shall comment on their study in Section 4 below. In order to understand the techniques of these authors we have found it desirable to comment on their relevant experimental and analytical work on thermal plumes in rivers. Section 3 is devoted to their study of the effects of discharge of condenser water into the Illinois River.[2]

2. Plume Characteristics

A main objective of on-site empirical modelling is to study in detail a typical thermal plume, its general pattern and the probable changes of this pattern due to various changes in environmental conditions. Analysis of "Heat Dissipation Characteristics" of a representative site would involve:

1. Temperature distribution study (both spatial and temporal)
2. Exchange coefficient evaluation and correlation with wind speed, direction, topography and other flow characteristics,
3. Temperature statistical analysys,
4. Meteorological and limnological statistical analysis.

Success in developing a reliable statistical model of the spatial and temporal patterns of the plume at different parts of the year for differing meteorological and limnological conditions are very essential for a reliable study of the physical, biological, chemical and meteorological effects of the plume. Our initial concern therefore is to develop a three-dimensional picture of the plume, and to study its variation with time.

Several analytical and numerical models of plumes already exist, but their universal applicability has not been validated. For example, the excellent study done at Cayuga Lake[5] suggests that when a jet of hot water is dishcarged on the surface of relatively deep water, a discrete surface plume develops and can be characterized by three distinct regions. The first region is the region where the initial momentum of the discharged water dominates. In this region, turbulent mixing dilutes the warm water of the plume by the horizontal and vertical entrainment of ambient colder water into it. The rate of vertical entrainment is proportional to the local value of the bulk Richardson number B, defined as[5]

$$B = \frac{gh}{V2} \frac{\rho_a - \rho}{\rho_a}$$

Here ρ, h and V are suitable average values of the density, thickness and velocity of the plume relative to the ambient water and ρ_a is the density of the ambient water. The Richardson number B initially increases as the velocity decreases. The vertical entrainment ceases and the first region ends when B reaches a critical value $B_c = 0.8$. The second region is a diffusion convection region. In this region, because of buoyancy gradients, there is no vertical entrainment; but horizontal entrainment from the edges continues. In this region the velocity of the plume tends to a constant value appropriate to that of the ambient current. Since the density difference $\rho_a - \rho$ continues to decrease, the value of B will begin (and then continue) to decrease. Vertical entrainment sets in again when B falls below $B_c = 0.8$ and this characterizes the beginning of the third region.

What we would expect on the basis of our limited knowledge is that the vertical cross sections away from the point of the discharge will look as shown in Fig. 2. Once we know the boundaries of the plume, then we can analyze to advantage the various cooling mechanisms including entrainment, heat exchange with the atmosphere etc. Except possibly in the third region, the boundaries of the plume would typically be characterized by one or all of the following factors: large temperature difference, large density difference, possibly large current difference (local motion of water in the plume in opposite direction to that of the ambient water) and turbulence at the edges where entrainment takes place. It is valuable to check whether or not the edges of the plume can be localized experimentally. Of course isotherms should give us a good idea of the shape of the plume.

3. Evaluation of a River-Site Study[2]

In the Fall of 1968, L. P. Beer, W. O. Pipes and a group of supporting engineers and scientists carried out what seemed to be an initial in-depth investigation of the effects of heated water discharges of the Dresden Station power plant on the Illinois River.[2] We shall not be concerned here with their evaluation of the effects on the aquatic environment of the Illinois, but rather with their conclusions regarding the characteristic of the three-dimensional plume they analyzed. It should be emphasized that taking into account the short time limitation of their study and the small number of measurements they were able to make, their results are indicative of the characteristics of the plume (the same conclusion applies to their evaluation of the "Waukegan Station" discharges quoted below). However, their conclusions regarding the actual shape of the plume are erroneous, and as such, cannot be justified on the basis of their data.

As is shown in Figure 3, the DesPlaines River and the Kankakee River join to form the Illinois River. The DesPlaines River has a rate of flow normally 3 to 9 times greater than that of the Kankakee. In October 1968, its waters were also 5 - 8°F warmer.[2] The analysis of Dresden Station plume is complicated because of its location in the vicinity of the confluence of these two rivers, in fact, we expect classical methods of analysis to break down in such a situation. The study of Beer and Pipes in the Dresden pool in October 1968 indicates the existence of a vertical thermocline together with horizontal and vertical stratification.

Beer, et al., measured, among other things, water temperatures at various positions at various depths in the DesPlaines, Kankakee and Illinois rivers. Of interest to us are the positions in the neighborhood of the power plant discharge, shown in Fig. 7. Beer, et al., conclude that the resulting temperature isotherms at 1 ft, 4 ft, and 8 ft below the river surface are as shown in Figs. 4, 5, and 6. Note that these figures indicate that the hot water jet is restricted to a depth less than 4 ft up to a distance of about 300-400 ft, and then dips to a depth of 8 ft. Our initial reaction was to justify such a phenomenon. If we assume that the thermal jet influences and is influenced by the existence of a vertical thermocline, then it is not unreasonable to observe a dip of the thermal jet. Figures 4-6 also indicate that the hot water spreads towards the north shore and, possibly because of water currents and horizontal stratification, it is reflected to the deeper layers. As a result, warmer water at 74°F exists below cooler 72°F water.

The relevant measurements taken by Beer, et al., are reproduced in Table I. As can be easily checked, none of their measurements justifies the actual details given in Figs 4-6 or the interpretation given above. With the exception of the measurement of position 21, Table I indicates that the temperature is uniform in depth only at a few isolated locations and in almost all the locations, the temperature decreased with increasing depth. The rest of the data taken by Beer, et al., which have not been quoted here also imply that the temperature decreases with depth. This implication regarding temperature gradient variation in depth, can conceivably be violated at the surface due to various wind, surface currents, and heat exchange phenomena, but, under normal conditions we do not expect a violation of this observation at greater depth.

Since the measurements of Beer et al., are by necessity not simultaneous, the fluctuation at any one point gives an indication of the error involved in correlating the various measurements. For example, the measurement at position 24 indicates that the temperature of 74°F is uniform with depth 0-17 ft. Yet another measurement 23 min later at almost the same position (No. 33) indicates temperature stratification with depth with Δt = 2.5°F, from top to bottom.

In conclusion, Beer, *et al.*, have selected a difficult site to model. Because of the time limitation of their study, they were unable to carry out all the desirable measurements; furthermore, they did not properly interpret their temperature data. Again, we have no comments on the major part of their report[2] dealing with the biological and chemical effects of the condenser water discharge.

4. Evaluation of a Lake-Site Study[3]

This section is restricted to the parts of the study by Beer, *et al.*,[4] dealing with the three-dimensional characteristics of the Commonwealth Edison Waukegan generating station plume. The study of Beer, *et al.*, performed in April 1968 gives a reasonable estimate of the dimensions of the plume for a particular time of the year and a particular meteorological condition. Their report includes a representative sample of numerical and graphical results including Figs. 8 and 9 reproduced in this report. Fig. 8 and the rest of the figures given by Beer, *et al.*, seem to indicate that 54°F cold water is trapped and is floating on top of warmer water. While it is possible to have cold water on top of hot water for extended periods of time, due to combination of wind and current effects, such instabilities as indicated by Fig. 8 can hardly be expected to last during the two-or-more-hour period of the measurement. Figure 9 indicates the positions of temperature measurements, the numerical order in which these measurements were taken, and explains one of the sources of difficulty. The relevant measurements at positions 1, 2, 3 were carried out at 8:30-8:40 a.m. (April 30, 1968) when the water circulation was 699,000 gpm; at positions 14, 15 at 9:25-9:30 a.m.; and at positions 35, 36 at time 10:25-10:30 a.m. when the water circulation was increased to 763,000 to maintain a Δt of 12°F. Changes in wind velocities of about 5 mph are reported but *no measurements of water currents seem to have been taken.* In summary, instead of concentrating on the near-shore region and performing as many measurements as possible to get a meaningful idea of its characteristics and then moving to other regions, Beer, *et al.*, elected to traverse the whole plume from near region to far region and repeat the traverses at time intervals where the plume can very well change, particularly in the region close to the outfall. Rapid changes could not be ruled out if we note that the vicinity of the outfall seems to have an irregular bottom topography and that the water up to 600 ft from shore is very shallow, with depth ranging from 3 to 6 ft. Local currents and waves are usually highly variable over this range. We have plotted Fig. 10 on the bases of the data given by Beer, *et al.*, to estimate the bottom contours for the Waukegan plume.

Other temperature measurements were made by the FWPCA[6] but are admittedly insufficient for an accurate characterization of the plume.

5. Conclusion and Recommendations

We conclude from the above that for on-site modelling of a particular plume, it is essential to take into consideration the various factors affecting the heat exchange mechanism and the spatial and temporal structure of the plume, including *bottom topography, local currents and wind direction, temperature, velocity, etc.* It is also essential, to be able to model each zone separately, to repeat some measurements to estimate errors and fluctuations, and to interpret empirical measurements (or their averages) properly.

For modelling of hot water discharge patterns, such as the Waukegan plume with a discharge canal at the shallow shoreline of the southern basin of Lake Michigan for example, we recommend the development of detailed contours of bottom topography. For example, the 3 ft and 4 ft depth contours in Fig. 10 explain the bending of the plume in Fig. 8 in a direction opposite to that of the wind at the time of the measurement. Such contours and bottom irregularities may prove advantageous for determining reference positions for measurements.

At the present, as far as we know, the three-dimensional pattern of the Waukegan plume reported by Beer, *et al.*, does not resemble any existing theoretical model. In fact, for plumes such as the Waukegan we recomment the semi-empirical modelling of two distinct zones rather than the three regions discussed in Section 2 above: Zone I, a shallow water zone in which the major part of the plume is in contact with the bottom sediments; Zone II, a deep water zone in which the plume is over ambient water. For the Waukegan plant, the Beer, et al., report suggest to us that in Zone II the temperature difference is relatively small, the relative velocity is very small (probably negligible at a depth of 14 or more feet below the surface) and that the effect of gravitation is dominant. We also expect that the wind and current conditions may sometimes be such as to drive the plume to the shore in Zone I (the north shore for the Waukegan plant) and thus to extend Zone I for a rather long distance at the shore. If such a situation is undesirable, then a different design of the outfall or two breakwaters on both sides of the outfall will help to push the plume to Zone II.

Finally, to aid the semi-empirical treatment, we plan to develop a computer program which would require as input the time and position of each measurement, the errors in the position and in the measurement, and other variables such as currents, wind velocities, etc. The program would then correlate the various measurements, use physically meaningful constraints such as admissible temperature gradients in depth, and yield two-dimensional isotherms, the areas between isotherms, and possibly the volume of water within ΔT of a specified temperature T. The experience of D. L. Phillips and the author in smoothing techniques (regularization techniques) may prove useful in this connection.

ACKNOWLEDGMENTS

The author is grateful for the helpful comments he received from J. Asbury, J. Carson, P. Gustafson, B. Hoglund, T. Hughes, H. Moses, D. Phillips, M. Prastein, G. Romberg, A. Szewczyk, J. Tokar and R. Wessel.

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2. L. P. Beer and W. O. Pipes, "The Effects of Discharge of Condenser Water into the Illinois River," Industrial BIO-TEST Lab. Inc. Report No: IBT-W7178, June 1969.

3. L. P. Beer and W. O. Pipes, "A Practical Approach: Environmental Effects of Condenser Water Discharge in Southwest Lake Michigan," Industrial BIO-TEST Lab. Inc., no date given.

4. F. W. Kittrell, "Pollution of Lake Michigan and Its Tributary Basin," Proceedings, Vol. 2, U.S. Department of the Interior, Federal Water Pollution Control Administration (Feb. 25, 1969).

5. T. R. Sundaram, C. C. Easterbrook, K. R. Piech, and G. Rudinger, "An Investigation of the Physical Effects of Thermal Discharges into Cayuga Lake (Analytical Study)," CAL Report No. VT-2616-0-2, November 1969.

6. U.S. Department of the Interior, "Preliminary Sampling Survey, Waukegan and Zion Power Plant Sites," FWQA, Lake Michigan Basin Office, Chicago, April 1970.

Table I. ILLINOIS RIVER STUDY - OCTOBER 2, 1968

LOCATIONS, WEATHER, TEMPERATURE DATA

(Water Circ. 166,000 gpm, Water Temperature at Inlet 70°F and at Outlet 82°F, ΔT = 12°F).

Position No.	PM Time	Straight Line Distance From Discharge Outfall *	Depth (Ft.)	Water Temp. °F at Ft. -Depth		Wind		Air Temp. (°F)
						Vel. (mph)	Direct. (Deg.)	
18	3:30	85	9	76 74	0-7 7-9	26	180	
19	3:32	171	9	76 75 73	0-4 4-6 6-9	14	240	
20	3:35	215	9	73	0-9	20	225	
21	3:37	310	8	78 70 [illegible]	0-2 2-4 4-8	20	210	
22	3:39	529	10	76 75 73 72 71 70 69	0-2 2-3 3-4 4-6 6-7 7-9 9-10	17	220	
23	3:42	585	13	74 73 72	0-3 3-9 9-13	25	215	
24	3:46	720	17	74	0-17	22	240	
25	3:48	630	13	73 70 69 68	0-9 9-11 11-12 12-13	23	225	
26	3:50	505	8	68	0-8	28	230	77
27	3:50	310	8	68	0-8	28	230	
28	3:54	315	9	77.5 77 75 67	0-3 3-5 5-7 7-9	25	232	

* Note that the straight line distance from outfall is not meaningful in the absence of an angle of reference (the x and y coordinates are not given in either Ref. 2, or Ref. 3 !).

Table I (Cont. 1)

Position No.	PM Time	Straight Line Distance From Discharge Outfall	Depth (Ft.)	Water Temp. °F at Ft.-Depth		Wind		Air Temp. (°F)
						Vel. (mph)	Direct. (Deg.)	
30	4:00	395	9	77.5	0-1	15	240	73
				77	1-9			
31	4:03	555	7	74	0-2	8	210	
				73.5	2-3			
				73	3-4			
				71.5	4-5			
				71	5-7			
33	4:09	720	17	75	0-7	9	232	
				74	7-9			
				73.5	9-13			
				72.5	13-17			
34	4:11	897	17	74	0-8	10	210	74
				72	8-9			
				71	9-16			
				70	16-17			
35	4:15	944	18	74	0-6	21	180	
				73	6-7			
				72	7-8			
				70.5	8-10			
				70	10-17			
				69.5	17-18			
36	4:16	1075	17	74.5	0-5	16	229	
				73.5	5-6			
				73	6-7			
				71.5	7-8			
				71	8-11			
				69.5	11-17			
37	4:19	990	16	74	0-6	23	233	
				73	6-8			
				72	8-9			
				71	9-10			
				69.5	10-16			
38	4:22	1070	17	74	0-12	24	240	75
				71.5	12-13			
				71	13-14			
				70.5	14-17			
41	4:33	849	18	73.5	0-11	15	197	
				73	11-15			
				71	15-16			
				69.5	16-18			

Table 1 (Cont. 2)

Position No.	PM Time	Straight Line Distance From Discharge Outfall	Depth (Ft.)	Water Temp. °F at Ft.-Depth		Wind		Air Temp. (°F)
						Vel. (mph)	Direct. (Deg.)	
42	4:37	761	17	73.5	0-10	17	220	
				73	10-11			
				72	11-13			
				71	13-17			
43	4:40	851	19	74	0-11	15	253	
				73	11-13			
				72.5	13-19			
44	4:45	973	18	74	0-9	18	220	
				73	9-10			
				72	10-11			
				71.5	11-15			
				70.5	15-16			
				69.5	16-18			
45	4:52	1085	18	73	0-5	18	210	
				72	5-6			
				71	6-8			
				70.5	8-11			
				70	11-18			
48	5:01	546	6	72	0-6	15	242	
49	5:04	556	10	73	0-4	20	249	
				72.5	4-5			
				72	5-6			
				71.5	6-8			
				71	8-10			
50	5:07	686	15	75	0-1	12	195	
				74.5	1-4			
				74	4-7			
				73.5	7-11			
				73	11-12			
				72	12-15			
51	5:10	840	18	73.5	0-10	17	213	
				73	10-18			
52	5:12	592	13	74.5	0-7	14	249	
				73.5	7-10			
				73	10-11			
				72.5	11-13			
53	5:15	481	10	74	0-7	14	210	
				73	7-8			
				72	8-10			
54	5:17	150	8	73	0-1	16	223	
				72.5	1-3			
				72	3-8			

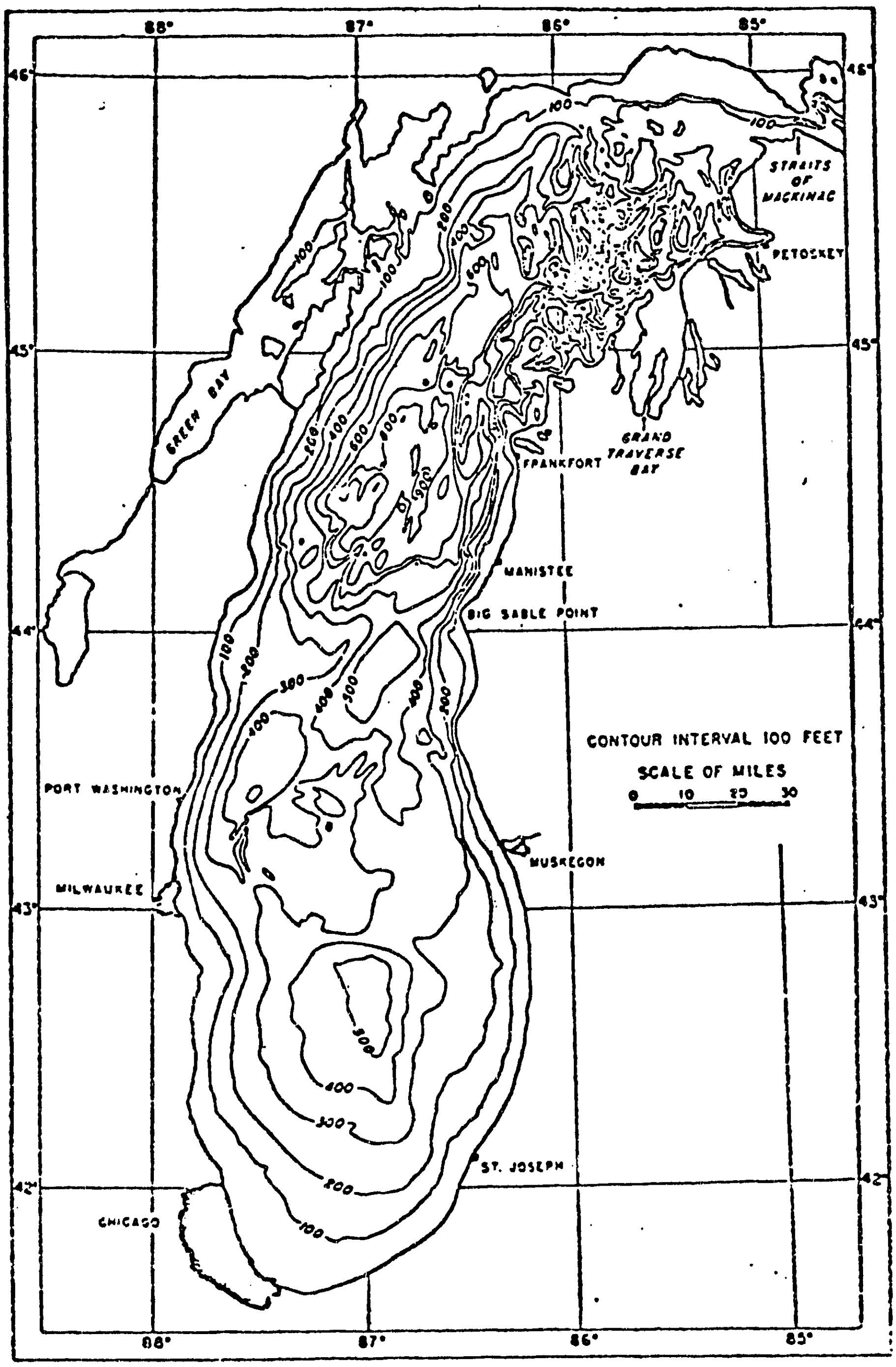
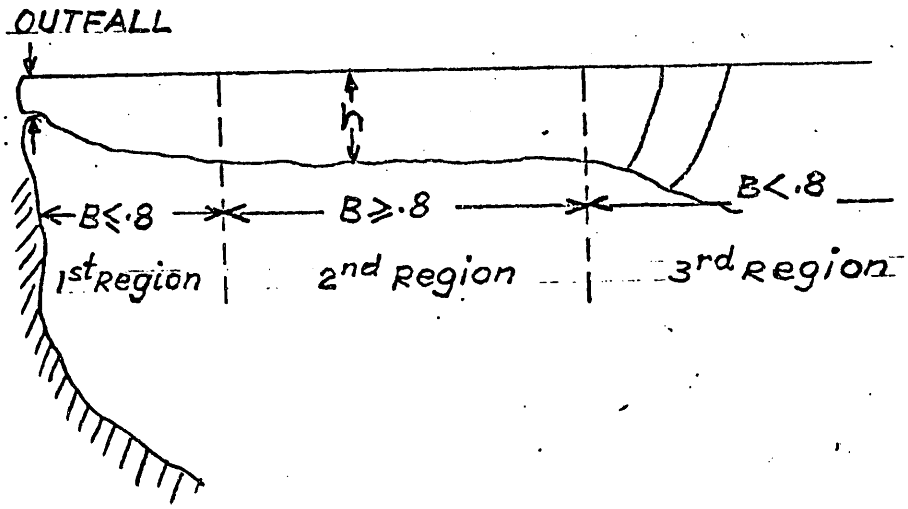
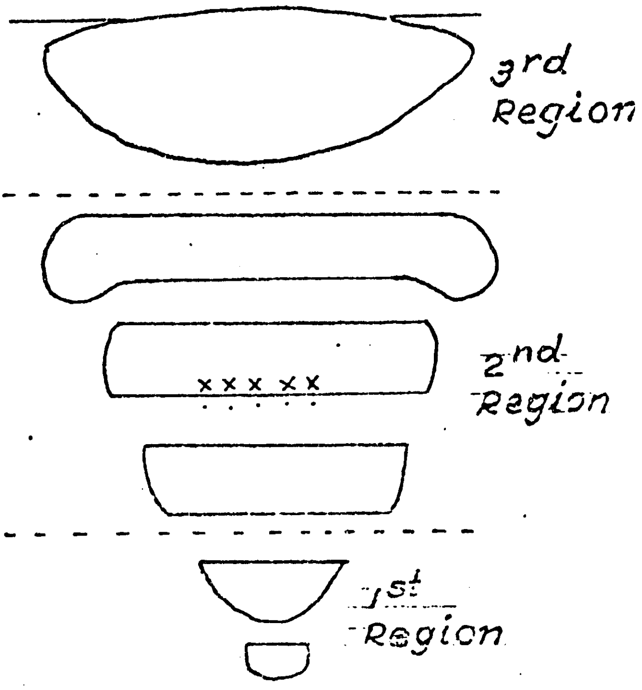


Fig 1. BOTTOM TOPOGRAPHY LAKE MICHIGAN

SOURCE: Reprinted from *Geology of the Great Lakes*, by Jack L. Hough.



a) x-z Cross section



b) y-z Cross section

FIG. 2 Anticipated vertical cross-sections of the Plume over deep waters

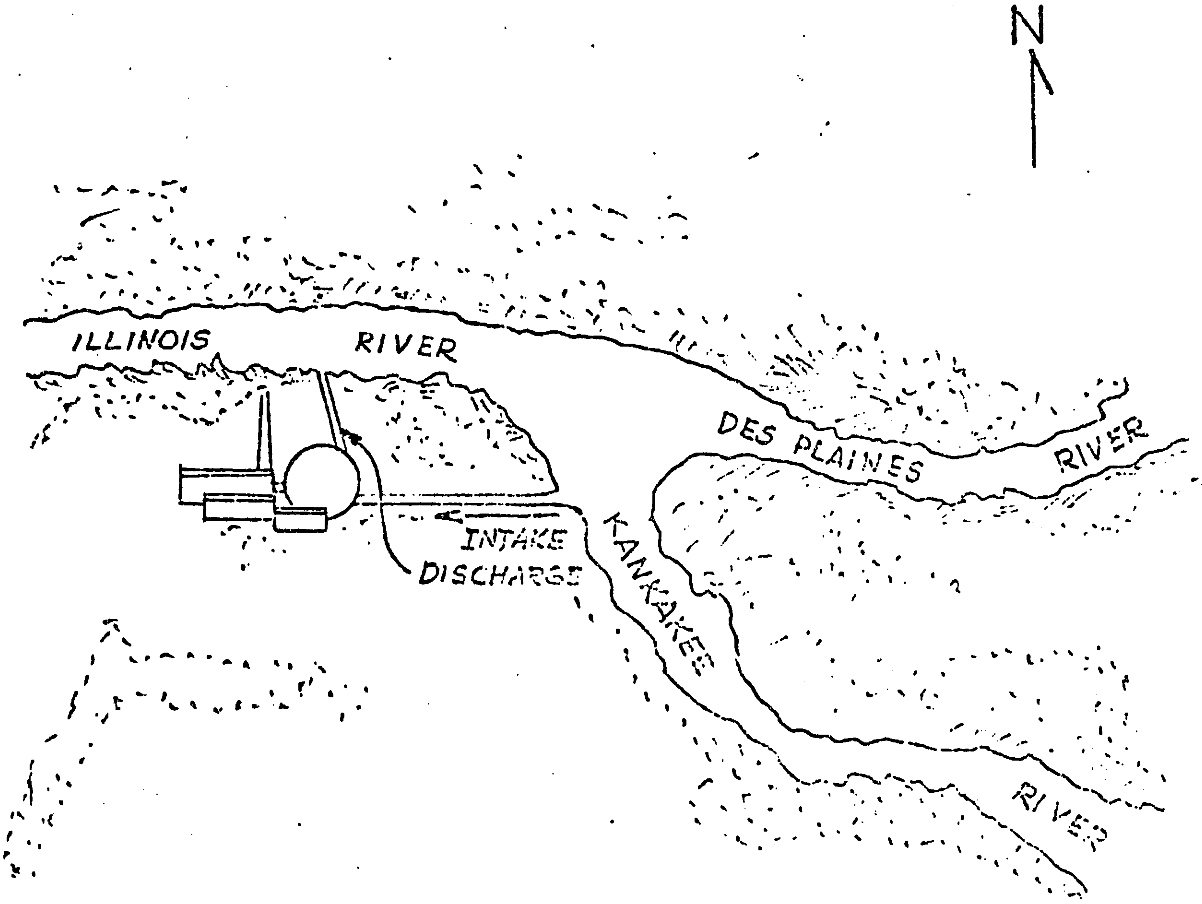


FIG.3 DRESDEN STATION

SOURCE: REF. [2]

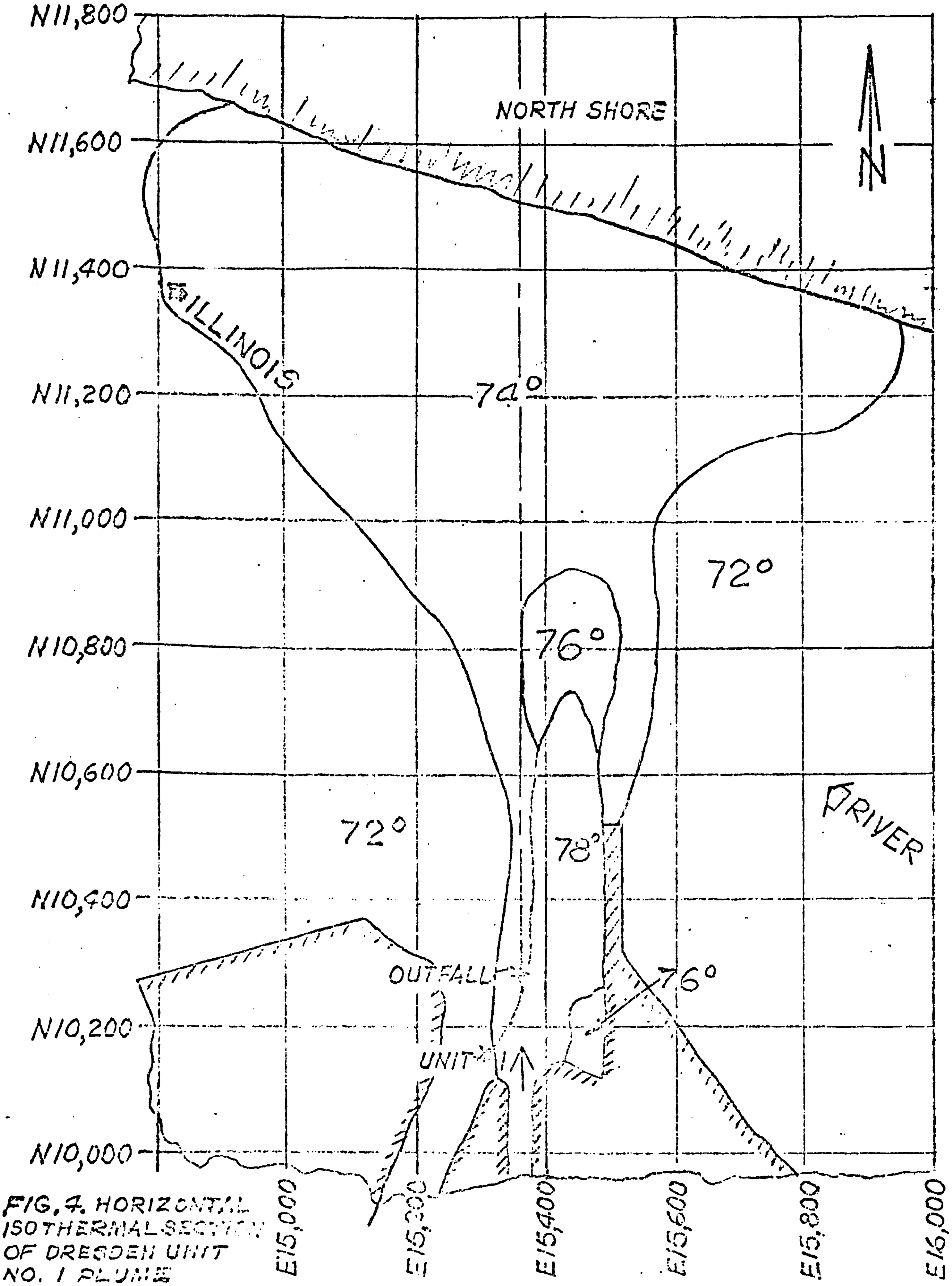


FIG. 4. HORIZONTAL ISOTHERMAL SECTION OF DRESDEN UNIT NO. 1 PLUME

SOURCE, REF. [2]

1 FT. BELOW SURFACE

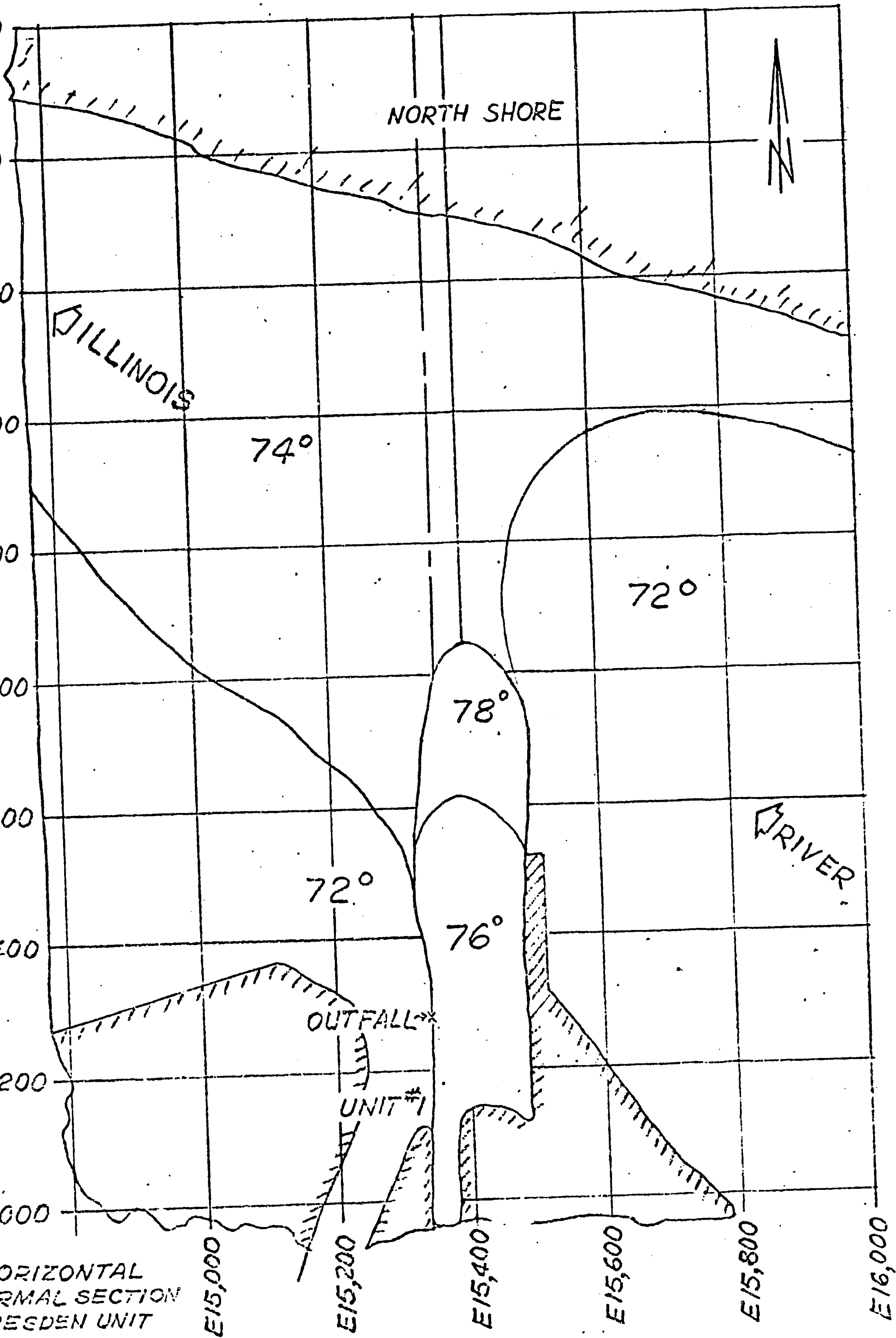


FIG. 5. HORIZONTAL ISOTHERMAL SECTION OF DRESDEN UNIT NO. 1 PLUME

SOURCE: REF. [2]

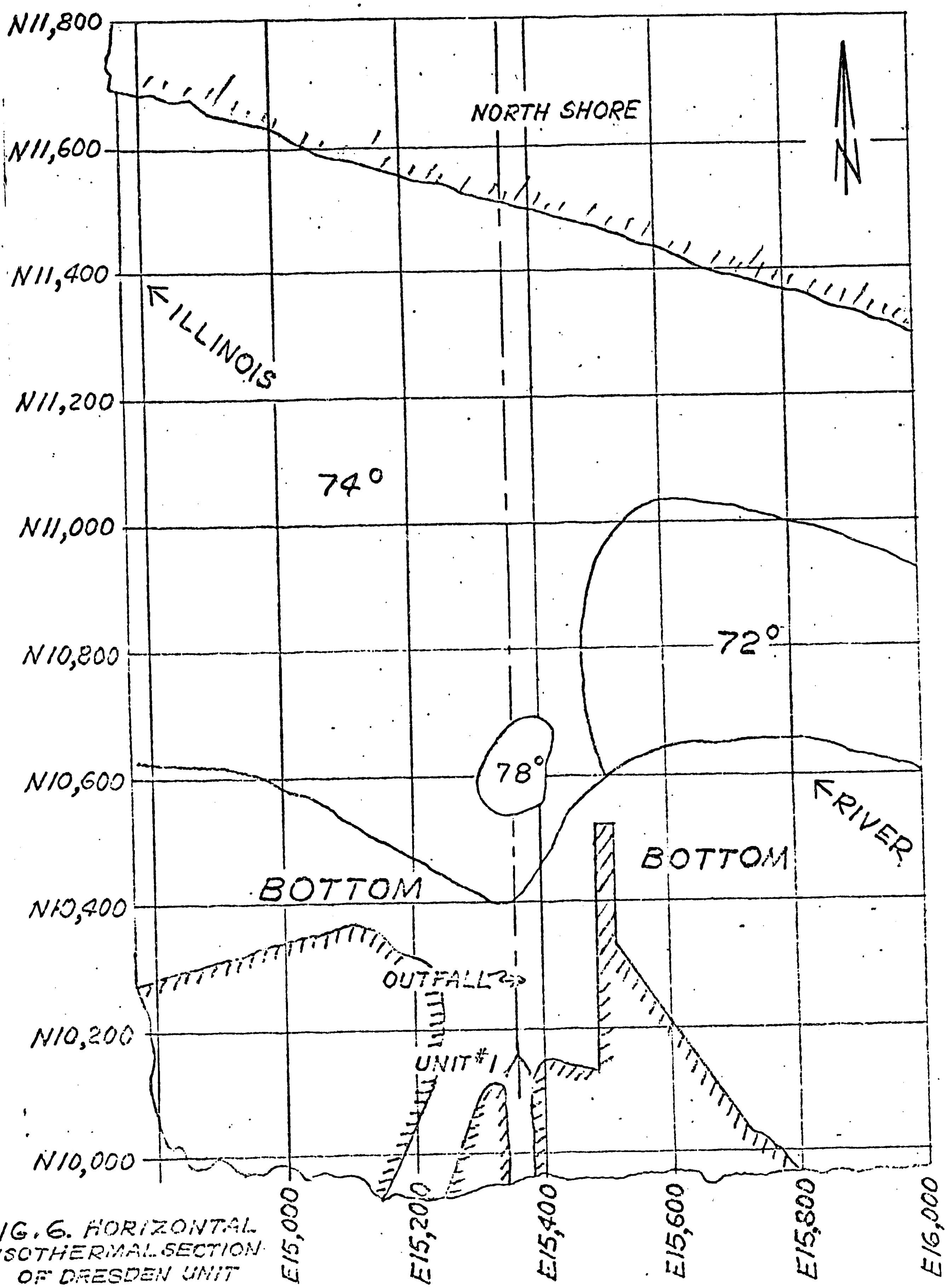


FIG. 6. HORIZONTAL ISOTHERMAL SECTION OF DRESDEN UNIT NO. 1 PLUME

SOURCE: REF. [2]

8 FT. BELOW SURFACE

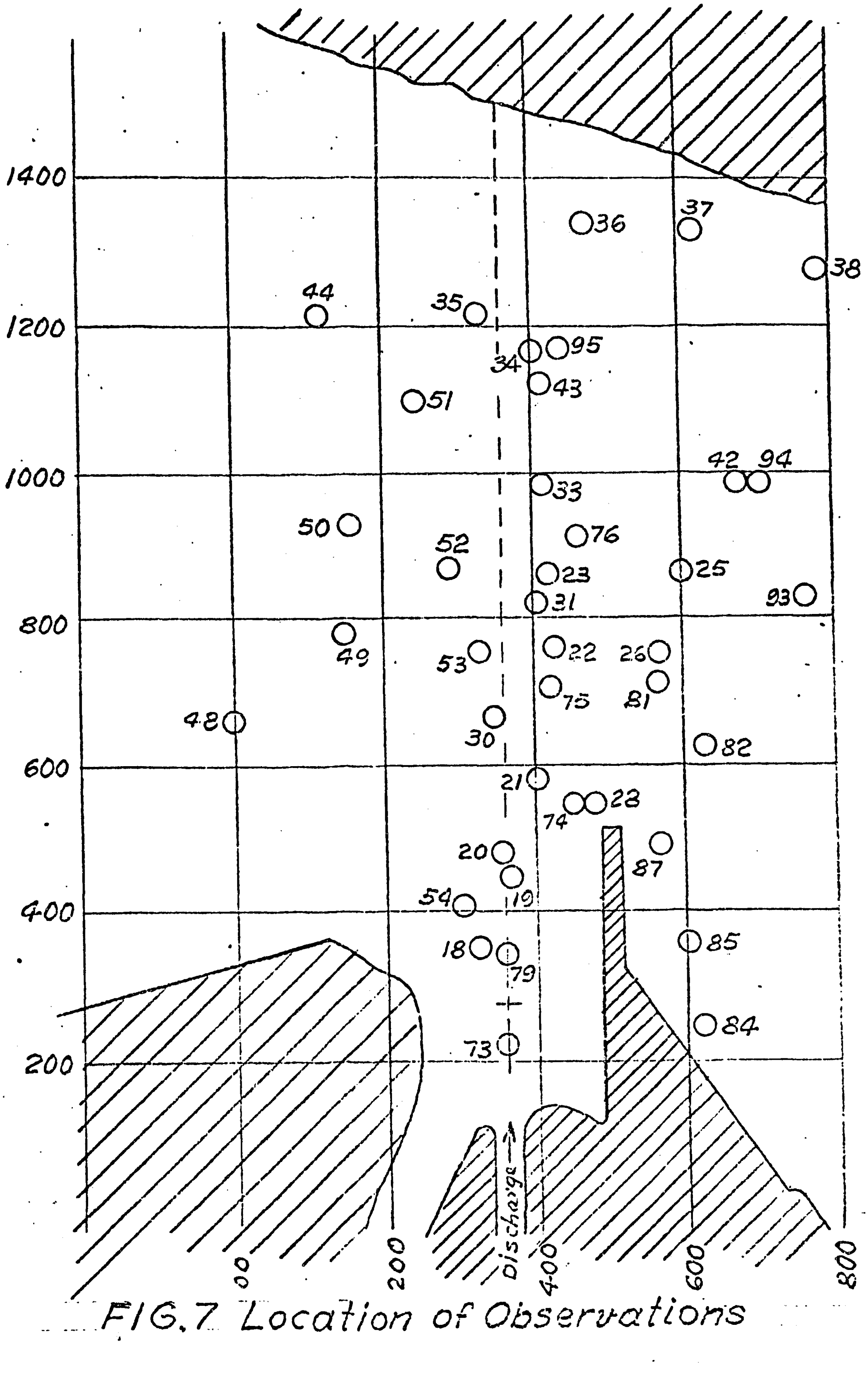


FIG. 7 Location of Observations

TEMPERATURE STUDY -- WAUKEGAN STATION - APRIL 1968

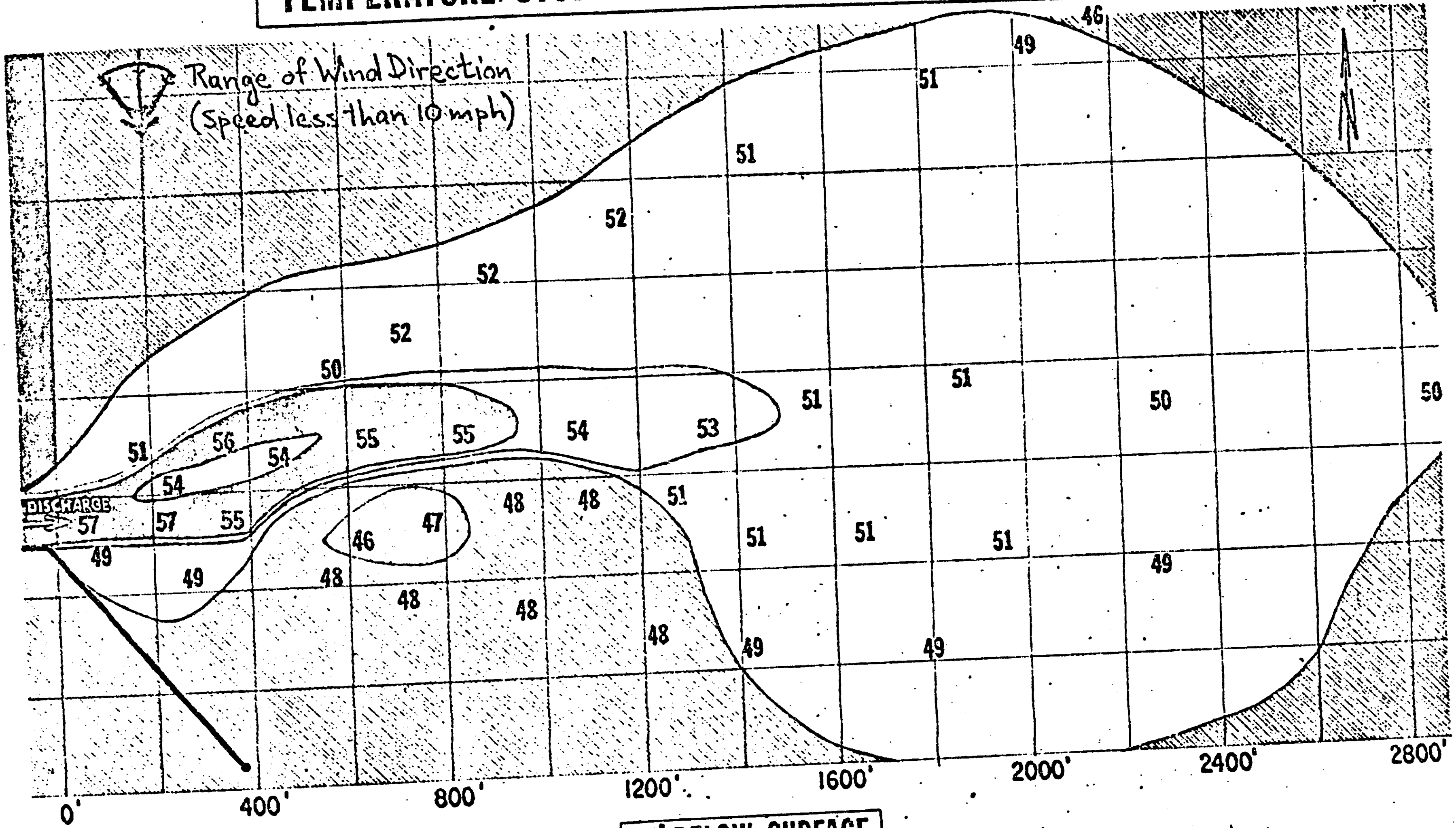


FIG. 8. 1' BELOW SURFACE

SOURCE: Ref. [3]

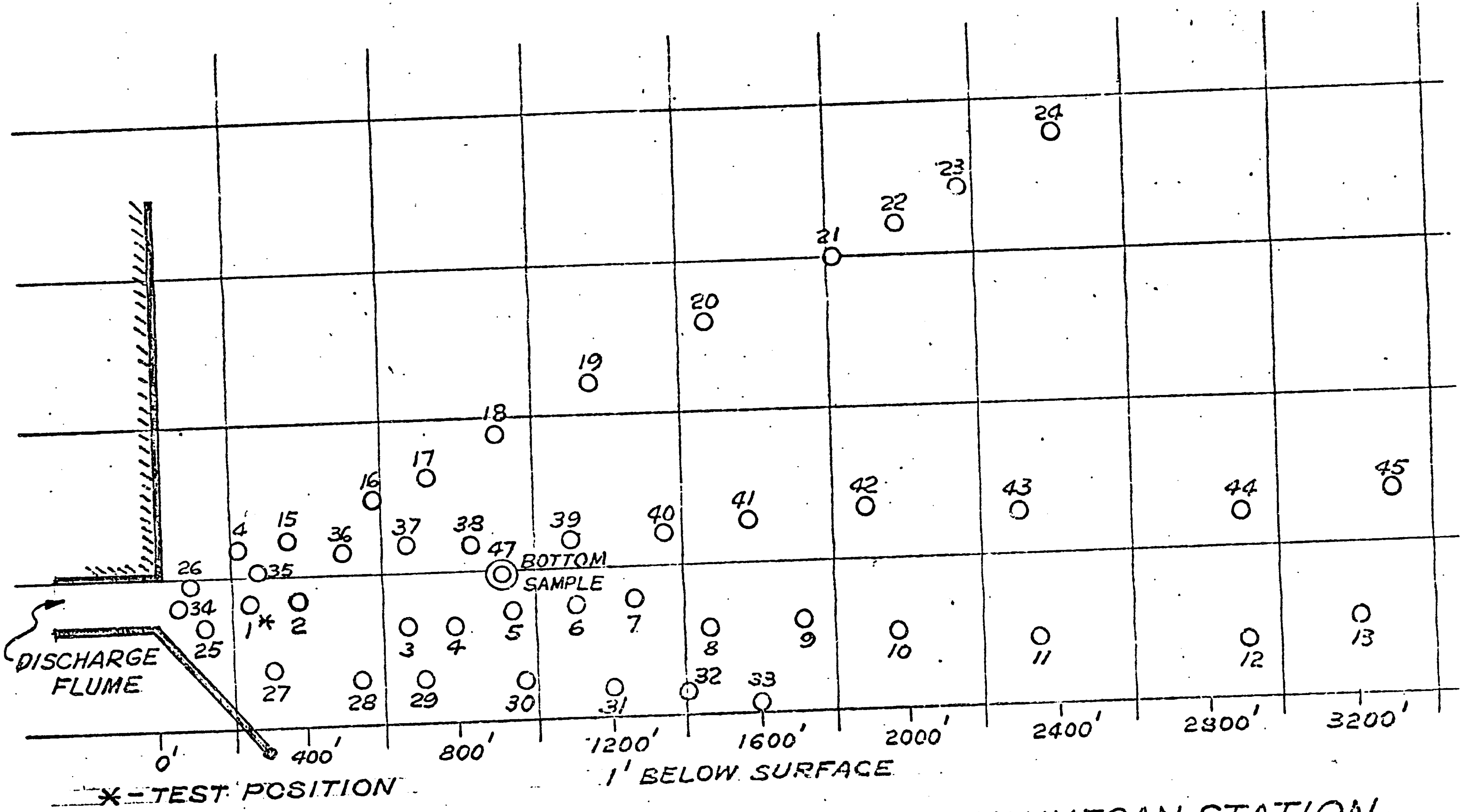


FIG. 9 POSITION MEASUREMENTS–WAUKEGAN STATION
APRIL 30, 1968 DATA

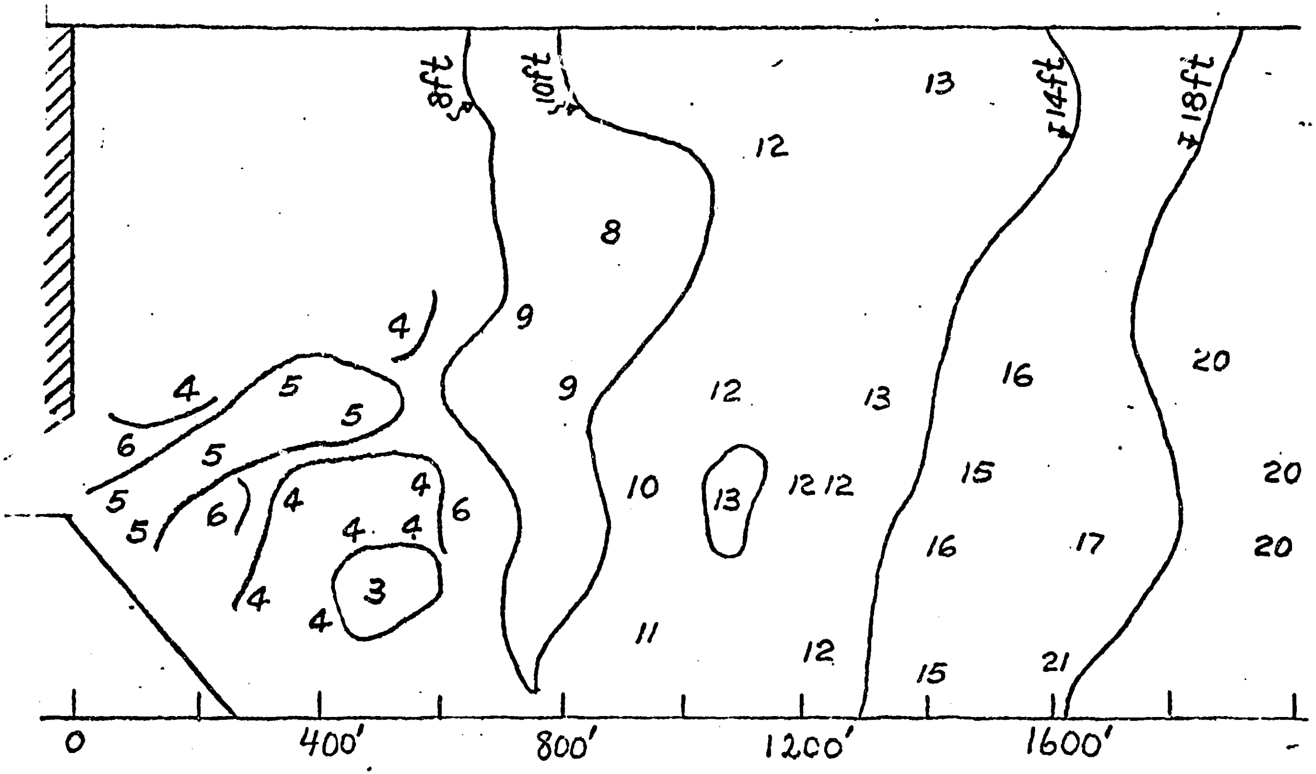


FIG.10 Bottom contours at the Waukegan Pool
Numbers indicate depth in feet.

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