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DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS

U. S. LAKE SURVEY
Research Report No. 1-1

CURRENTS AT LITTLE LAKE HARBOR
LAKE SUPERIOR

by

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FOREWORD

A comprehensive survey of Little Lake Harbor, Michigan, on the southern shore of Lake Superior, was initiated during the summer of 1964. The research conducted in the Little Lake Harbor area is concerned with both water motion and shore processes features. This report presents those findings concerned only with currents in the harbor and its vicinity.

The study was accomplished under the general supervision of Dr. L. Bajorunas, Chief of the Research Division, and under the direct supervision of Mr. J. G. Housley, Chief of the Water Dynamics Branch. The investigation was conducted by Mr. J. H. Saylor, project scientist, assisted by Mr. T. E. Ottenbaker in the field measurements. This report was prepared by Mr. Saylor.

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SUMMARY

Currents along the shore of Lake Superior in the vicinity of Little Lake Harbor, and currents in the dredged, breakwater-protected harbor entrance, were measured during the period from 1 to 17 September 1964 by Lagrangian and Eularian techniques. The current survey zone extended from about one kilometer east to about one kilometer west of the harbor. Measurements of currents were made during south-southeast (offshore), and west and northwest (prevailing onshore) winds. Significant wave heights varied from 0 to 2.0 meters.

Strong coastal currents to the east were measured during west and northwest storms. The storm-generated coastal currents reached steady-state conditions within two hours after the start of the blow, and decayed slowly, so that current velocities twenty-four hours after cessation of strong winds were still of the same order of magnitude as the steady-state, wind-driven currents. Eastward coastal currents generated a clockwise eddy in the lee of the west breakwater, the influence of which was observed 300 meters east of the harbor.

Reversing currents through the entrance channel, which result from water level oscillations, were compressed along the west breakwater in a deep, narrow channel and reached high velocities during storm periods. Construction of typical circulation models for the area was accomplished by integration of the detailed current patterns measured under conditions of varying effective forces. These circulation models show the current patterns observed during westerly storms. They are composites of reversing currents driven by water level oscillations in Lake Superior and clockwise eddy currents driven by eastward currents along the shore of the lake.

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CURRENTS AT LITTLE LAKE HARBOR

LAKE SUPERIOR

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INTRODUCTION

This report describes and presents the results of a survey of Little Lake Harbor in Lake Superior, Figures 1 and 2, to determine the origin and patterns of currents in the vicinity of the harbor entrance, and to establish the magnitudes and patterns of, at times, strong reversing currents flowing alternately into and out of the harbor. The survey was conducted during the period 1 to 17 September 1964.

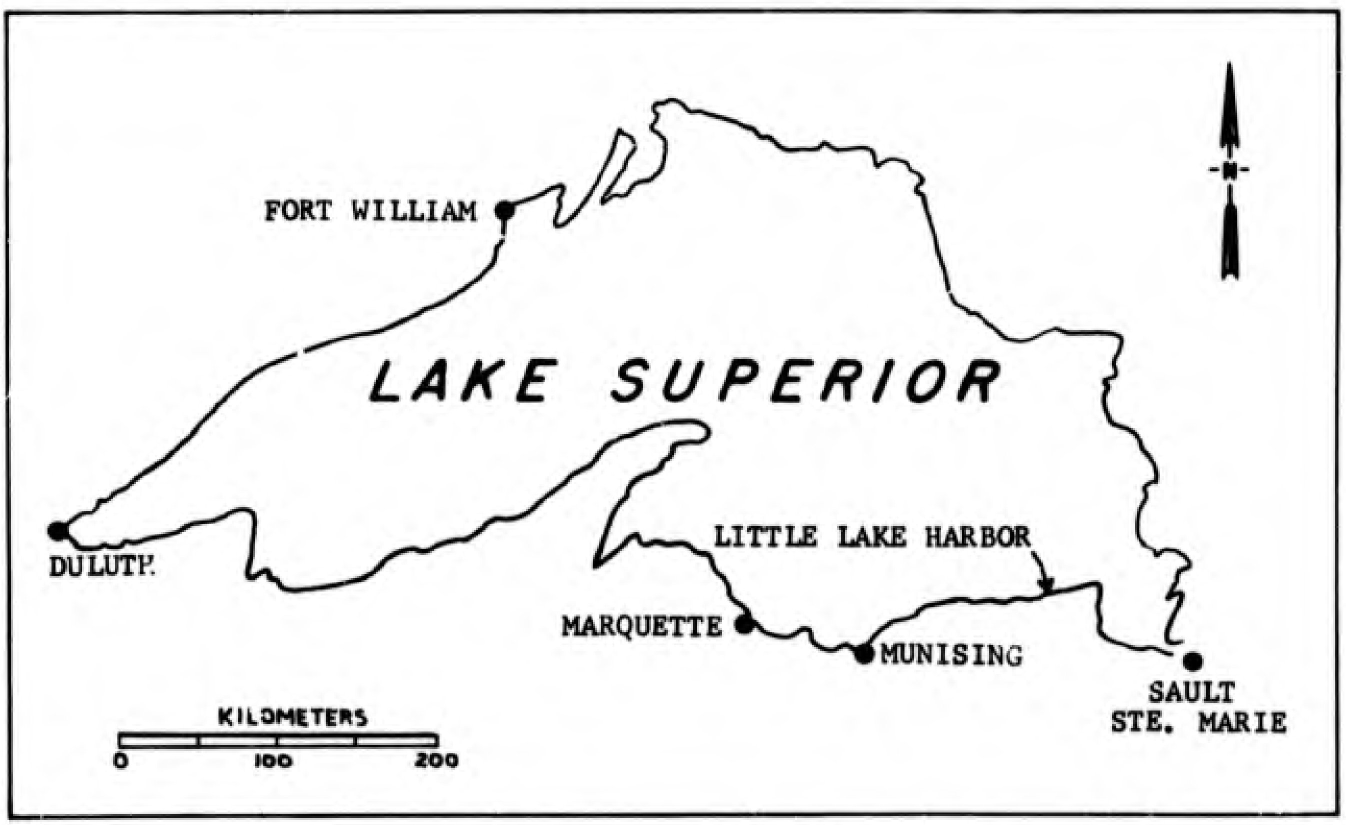

Fig. 1 - Location Map

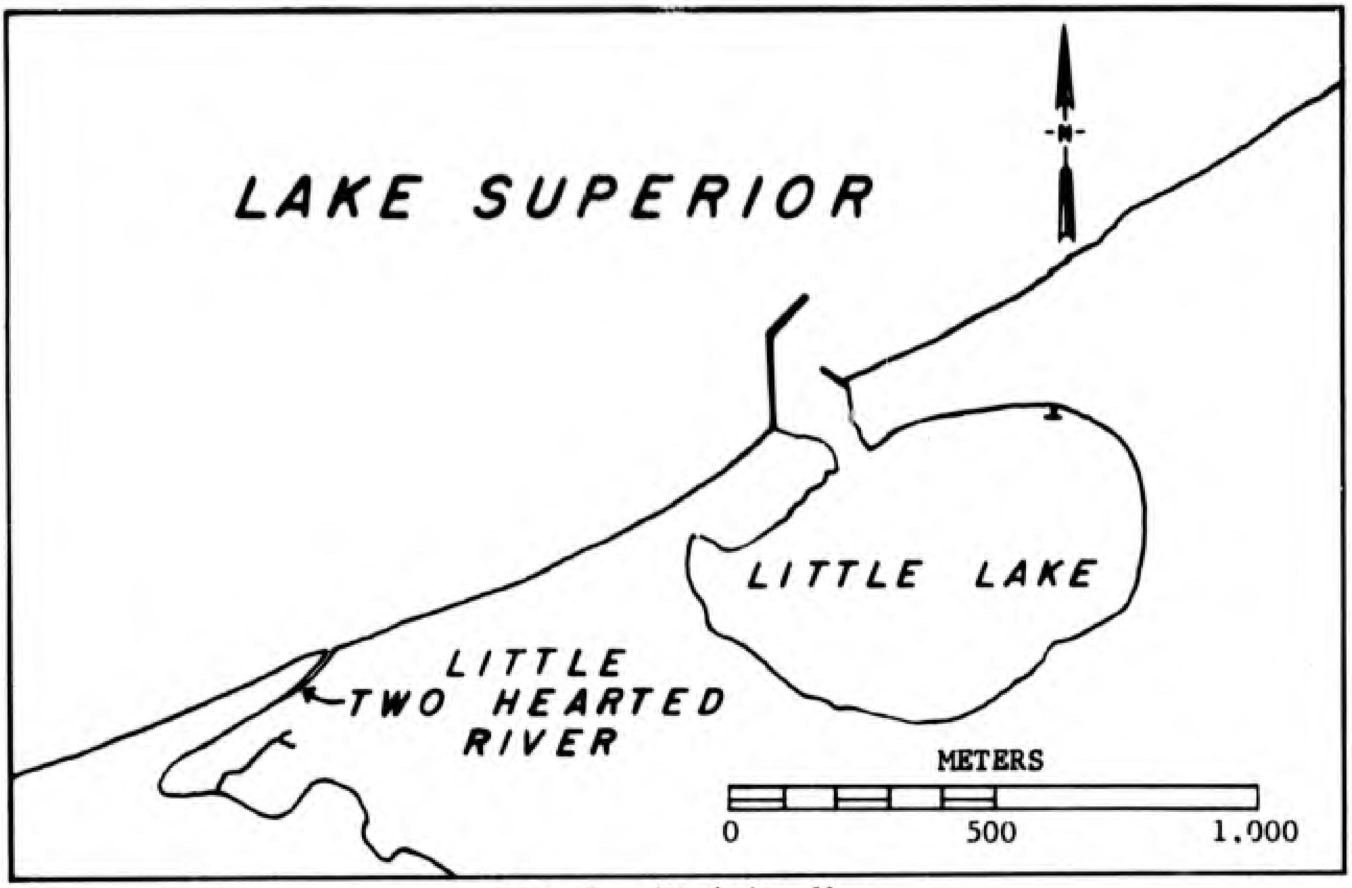

Fig. 2 - Vicinity Map

The Little Lake Harbor was constructed in 1962 as one of a chain of 21 small-craft harbors of refuge on the coasts of the Great Lakes authorized by the River and Harbor Act approved in March 1945 (Public Law 14, 79th Congress, 1st session). The harbor consists of a small lake (surface area of 35×10^4 square meters) connected with Lake Superior by a channel dredged through a narrow sand bar. Figure 3 shows the plan of the harbor as constructed. Protection at the harbor entrance and in the entrance channel from prevailing west and northwest wave action is provided by the west breakwater. The entrance faces easterly, the direction of the least critical waves at the site.

Investigations prior to design and construction of Little Lake Harbor indicated strongly predominant winds from the west and northwest. The annual average along-shore wave energy (the component of the incident wave energy parallel to shore) in the easterly direction exceeded that in the westerly direction by a ratio of about nine to one. Investigations also indicated possibility of heavy movement of littoral material past the harbor site.

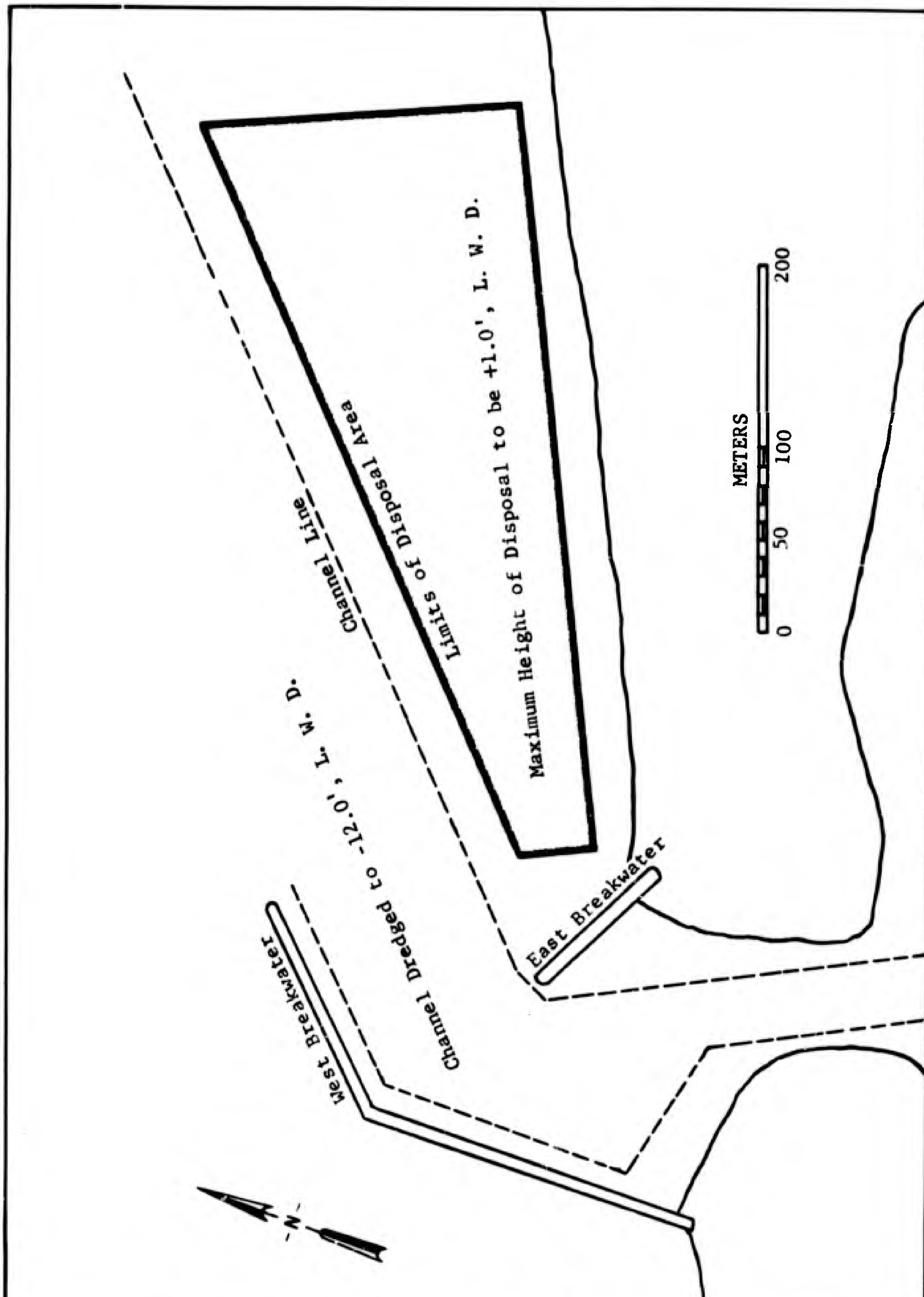

Fig. 3 - Design of Little Lake Small-Craft Harbor

SURVEY METHODS

Currents

Currents were measured with drogues, Price current meters, and dye. The drogues, Figure 4, consisted of large sheet-metal vanes suspended at varying depths below small surface floats afixed with identifying flags. The vanes were hinged and collapsible for convenient storage in the five-meter long boat used to place and retrieve the drogues. Trajectories of drogue drift were followed with two transits. Cut-off angles were read at equal intervals of time, graphical plotting established current velocities and patterns. Price current meters were used at selected points across the harbor entrance to establish histories of the reversing current velocity. These measurements were made at one-half the water depth at each point. Current direction at the metering points was determined with a captive drogue. Rhodamine B dye was released on several occasions in the surf zone east of the harbor. The drift of the dye was followed visually. Photographs showing the prevailing patterns of dye drift were taken.

Fig. 4 Current Drogue

Fig. 5 Little Lake Tower

Wind

Wind speed and direction were recorded at an instrument tower erected in six meter-water depth, 300 meters north of the harbor, Figure 5. Wind speed, at the 10 meter level, was recorded as a continuous analog trace. Wind direction, at the 10.5 meters level, was recorded as an event once each minute in one of eight compass points.

Waves

A step-type, relay, wave staff mounted on the tower, Figure 6, was inoperable during the period of investigation. Visual observations of wave heights and periods were made while currents along the shore of Lake Superior in the harbor vicinity were measured. The procedure was to observe and record the height of each wave passing the tower installation during a four-minute interval. One leg of the instrumented triangular tower was marked at one-foot intervals with reflective tape for this purpose. The average height of the one-third highest waves was recorded as the significant wave height. An average wave period was determined by dividing the length of the recording interval by the number of waves observed during the interval.

Water levels

Water level was recorded digitally at five-minute intervals on punched-paper tape. The float-type gage was located on the tower, and a cylindrical stilling well, Figure 6, was mounted in the center of the triangular tower structure. An electric-tape gage (a steel tape in which an electrical circuit is closed when the tape is in contact with the water surface, which is used to measure the height of a reference level above the water surface) was mounted on the tower to assess the vertical stability of the structure, While current measurements across the harbor entrance were made with Price meters, additional water-level measurements were obtained in the breakwater-protected area with an electric-tape gage.

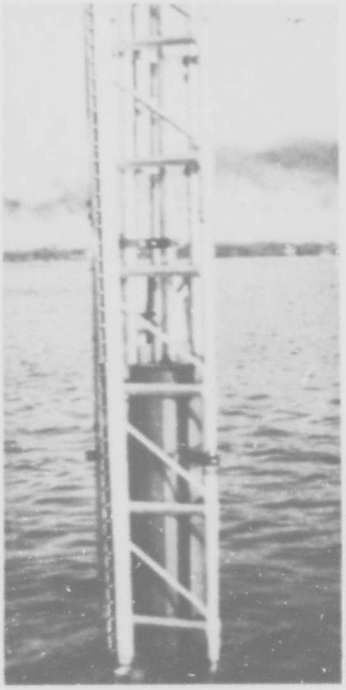

Fig. 6 Wave Staff and Stilling Well

Data

Current measurements by drogues were graphically plotted, and all of such observations at Little Lake are included as Plates 2-8 in this report. It is difficult to assess the accuracy of these measurements. Surface floats were small in comparison with the current-sensing vane, but the effects still remained of the wind-stress upon part of the float and its identifying marking, the stress of the surface current, the stress of currents which result from surface waves, and the resistance of the float to vane travel. Simultaneous observations of drogue and dye drift in the vicinity of the harbor entrance during strong winds indicated that these errors were not large. In this area, the drogues and dye repeatedly traveled in opposition to wind and waves at approximately the same velocities.

Reversing current velocities, measured across the harbor entrance with Price meters, are shown in Figure 7. These meters were carefully calibrated befo. ‿ and after use. Current velocities recorded are accurate within a few percent.

Wind speed and direction were recorded continuously from 23 July to 24 September 1964. Hourly average wind speed and direction were read from the charts and tabulated. The wind track, plotted from six-hour wind vectors, for the duration of this investigation, is shown in Plate 9. Values of hourly wind speed and direction for the recording period are stored in the Great Lakes Regional Data Center of the U. S. Lake Survey.

Water level was recorded at five-minute intervals from 23 July to 24 September 1964. The data for the period of the current survey are shown on Plate 10. The complete current, wind, and water level records are stored in the Great Lakes Regional Data Center.

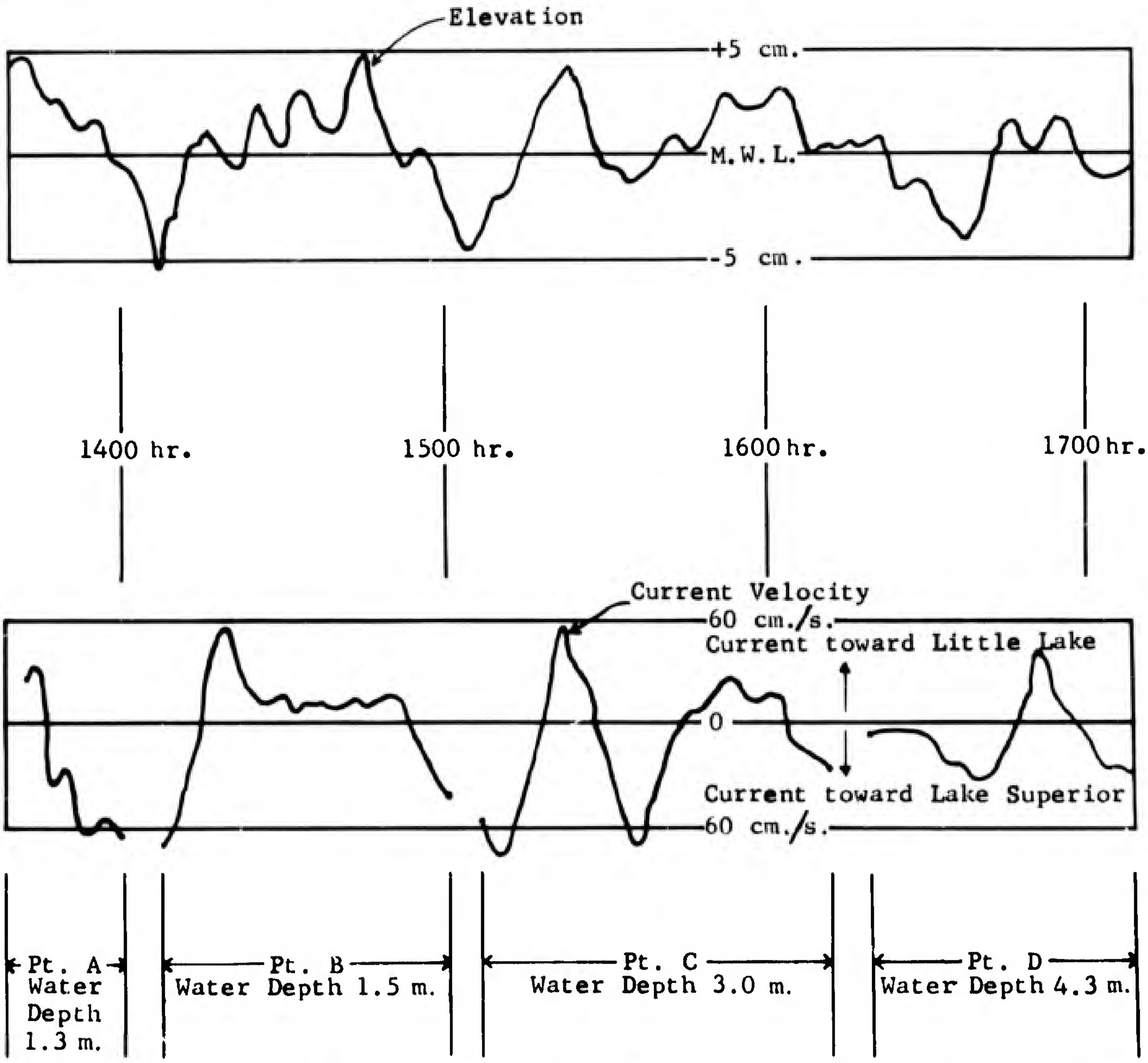

Fig. 7 – Oscillation of Water Level of Lake Superior and Current Velocities Induced Across the Entrance to Little Lake Harbor - 8 September 1964

WIND-DRIVEN CURRENTS

Nearshore currents in Lake Superior at the harbor site were measured during west, northwest, and south-southeast winds. For comparison of these wind directions with directions of prevailing winds, a tabulation of wind speed and direction for the ice-free months compiled from ten years of record at Saulte Ste. Marie is given in Table I. Waves at the harbor site result from winds west-southwest clockwise through east-northeast. The bathymetry of the region in which currents were measured is shown in Plate I.

Currents during south-southeast winds

Currents measured during south-southeasterly winds are shown in Plate 2. Also shown is the wind track (six-hour wind vectors were used to plot the wind track) for the day the current measurements were made, and for three days preceding the measurements. No wave data is given since winds were offshore. The important feature of the current pattern observed is the eastward set of the coastal current, probably a residual of wind-driven currents generated two days earlier by strong north-westerly winds. Near shore, the currents are essentially parallel with the shoreline. Lakeward, currents near the surface have an offshore component due to the offshore wind-stress on the water surface, and currents in the deeper layers are oriented more nearly parallel to the shoreline. Continuity requires that currents at some depth in the water column have an onshore component.

TABLE I

Average Hours Duration of Wind at Sault Ste. Marie - Compiled from 1948 Through 1957 Record for Ice-Free Months

DIRECTION	0-5.5m/s	5.5-11.0 m/s	Greater than 11.0 m/s
N	222	46	0.4
NNE	130	14	0.0
NE	308	28	0.3
ENE	270	27	0.2
E	605	98	1.5
ESE	317	116	1.9
SE	393	105	1.8
SSE	90	21	0.2
S	224	27	0.8
SSW	111	41	1.0
SW	440	121	9.5
WSW	148	38	2.8
W	446	79	5.2
WNW	484	319	10.2
NW	531	342	15.5
NNW	135	32	0.7
CALM	198		

Currents during west winds

Currents measured during westerly winds are shown in Plate 3. The wind track for the day the measurements were made and for the three previous days is also shown. The significant wave heights and average wave periods observed at the tower during the current measurements are included on the plate. Strong coastal currents to the east are generated by the westerly winds. Of interest is the short interval of time required for the coastal currents to approach a steady state. Westerly winds with mean wind speeds of about eight meters per second started in the Little Lake area at 0900 hours. By 1100 hours, the coastal currents for this wind speed and direction were fully developed, as evidenced by the uniformity of current magnitudes measured during the morning and afternoon surveys. Also, of interest are the distribution of current magnitudes and the current trajectories. Currents at the same depth increase in velocity going toward deeper water. The current trajectories, essentially parallel to the shore west of the harbor breakwater, show a bending of the streamlines in the harbor vicinity due to the hydraulic effects of the breakwater.

Currents during northwest winds

Currents measured along the shore of Lake Superior at Little Lake during northwest winds are shown in Plate 4. Also shown on the plate are the wind track and the visually observed wave statistics. Currents along the coast are eastward, but of lower speed than the currents associated with the lower speed west wind of Plate 3. The hydraulic influence of the breakwater on coastal-current streamlines is well illustrated by the trajectories of drogue drift. Currents measured the day following the northwest storm of Plate 4 are shown in Plate 5. Trajectories of drogue drift are almost identical with those observed the previous day. Current velocities are of the same order of magnitude as those measured at the peak of the storm.

CURRENTS DUE TO WATER LEVEL OSCILLATIONS

Currents in the vicinity of the entrance to Little Lake Harbor can result from interaction of the wind-driven waves and currents along the coast of Lake Superior with the region sheltered by the breakwater, and from fluctuations of water level in Lake Superior which cause inflow or outflow through the channel to Little Lake. Reversing currents due to water level fluctuations can be described in detail during periods of calm and gentle lake currents. It is not possible to isolate currents in the area generated purely by wind waves and currents in Lake Superior, since water levels are continuously varying.

Reversing current velocities at four points, equally spaced on a line between the end cells of the east and west breakwaters (Figures 8 and 9) were measured with Price meters on 8 September when winds were light and offshore. Light, offshore winds also prevailed for three days preceding these measurements. Water levels were recorded at two-minute intervals with an electric tape gage mounted on the west breakwater. These measurements were in addition to the digital recording of water levels at five-minute intervals at the tower. Comparison of the two water level records showed little difference.

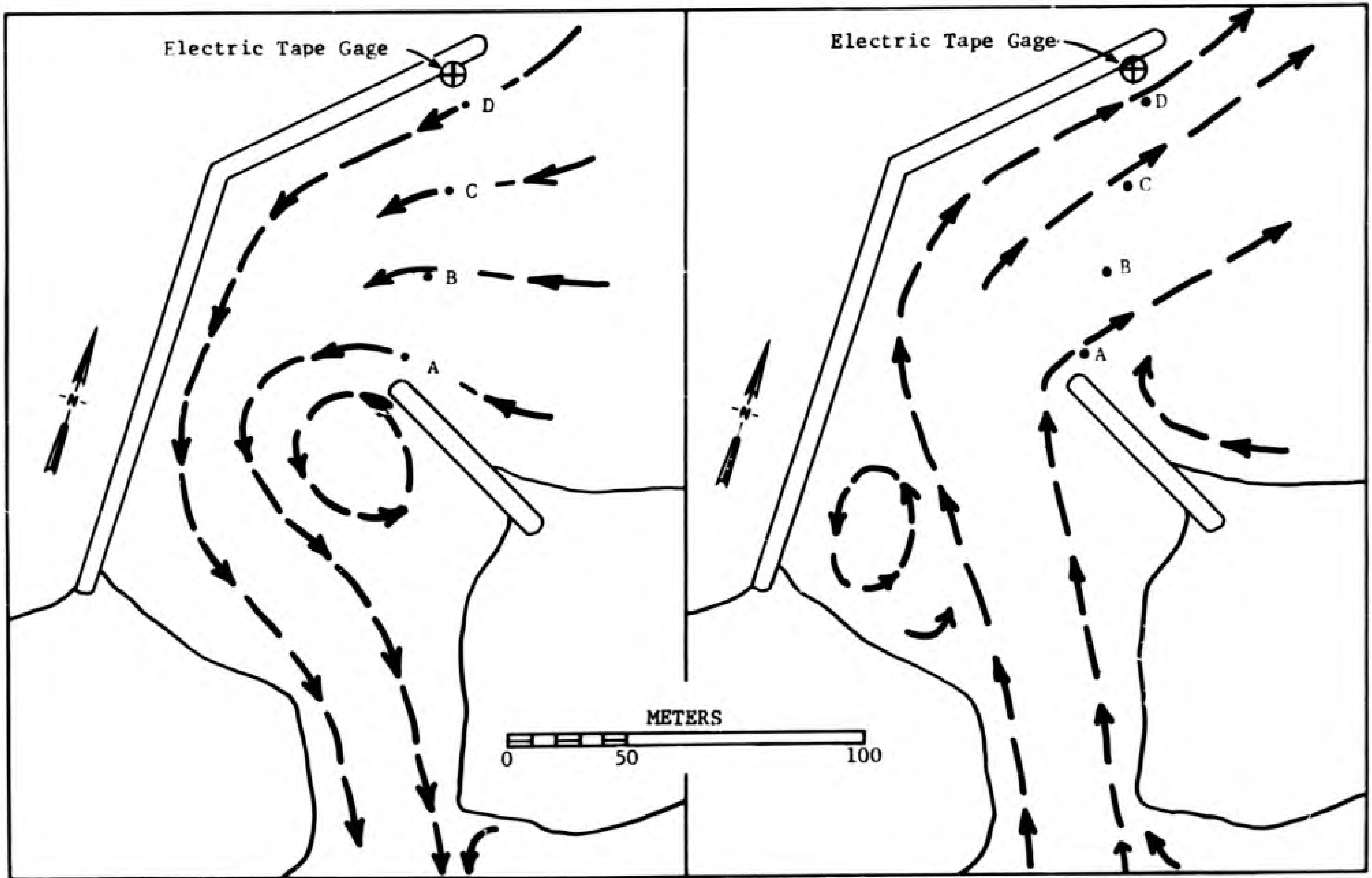

Fig. 8 – Trajectories of Inflow Currents With Negligible Current in Lake Superior

Fig. 9 – Trajectories of Outflow Currents With Negligible Current in Lake Superior

The marigram, and current velocities observed across the harbor entrance, are shown in Figure 7. The currents were measured at half depth. The correlation of reversing current velocities with inflow to, or outflow from, Little Lake because of fluctuation of water level in Lake Superior at the harbor site is obvious. Also evident from Figure 7 is that during this period, the current lags the fluctuations of water level by some six to eight minutes. There is considerable damping in the current record of the shorter period oscillations in the marigram.

Trajectories of the reversing currents were measured with drogues. The observations are too repetitious to present in detail. Essential features of the current patterns are shown in Figures 8 and 9.

Since water level fluctuations and the magnitudes and directions of currents across the entrance channel are so closely related, it is essential to examine the statistics of these fluctuations. In this connection it is convenient to classify the fluctuations as forced or free. Forced, short-term oscillations of temporal mean water level which would cause measurable currents in the channel between Little Lake and Lake Superior include astronomical tides, wind tides, and surges (waves generated by atmospheric pressure anomalies moving across the lake). Free oscillations of the lake surface (seiches) are standing waves, the periods of which are determined by the geometry of basin, the water depth, and the mode of the standing wave. Seiches may result from the decay of wind tides, the reflection of surges, or other forces. The amplitude (or energy) of a seiche generated by an individual impulse dissipates monotonically with time due to bottom friction and entrapment of portions of the energy in bays, harbors, etc.

The important features of the water level record from Lake Superior at the Little Lake Harbor site may be interpreted in terms of the "almost" periodic free oscillations of the lake. Readily identifiable from the records are the first five longitudinal modes of oscillation with periods of 7.8, 4.0, 3.3, 2.7, and 2.2 hours, respectively. These observed periods correspond closely to the periods of the longitudinal modes computed by a finite-difference approximation of the channel equations (Defant, 1961) and in an, as yet, unpublished study by the writer. Many oscillations of shorter period are also found in the water level records from Little Lake Harbor. Figure 10 shows the periods, and frequency of occurrence, of oscillations visually determined from the water level records collected during the current survey program. An explanation of the shorter-period oscillations is not attempted. They may be higher order modes of longitudinal oscillation, transverse oscillations of the eastern part of Lake Superior, or local oscillations of the coastal shelf (Reid, 1958).

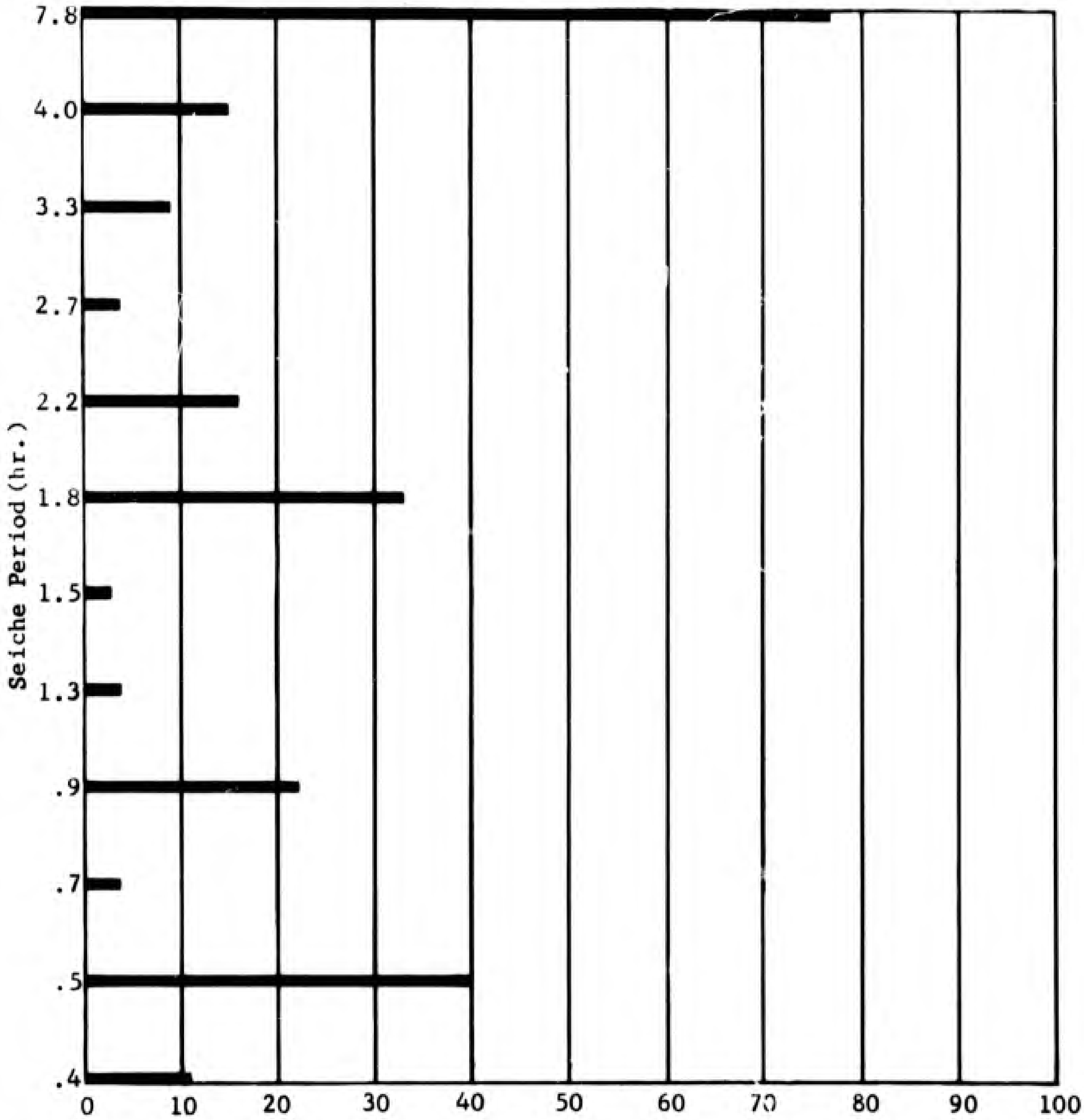

Fig. 10 - Frequency of Occurrence of Seiche Periods Observed in the Water Level Record at Little Lake

Although the long-period oscillations are of much interest, it is the shorter-period oscillations which must control the high velocity reversing currents frequently observed across the harbor entrance. The amplitude distribution of all oscillations with periods between 2.0 and 0.4 hours observed during the current survey is shown in Figure 11. Large amplitude oscillations with periods in this range invariably occur in groups or packets, and are often uncorrelated with local weather conditions. The persistence of a particular period of oscillation, once it is excited, leaves no doubt that these short period waves are normal modes of the lake surface. Reversing current velocities of more than 2 meters per second with an occurrence of once per week, may be postulated by linear extrapolation of the data shown on Figure 11.

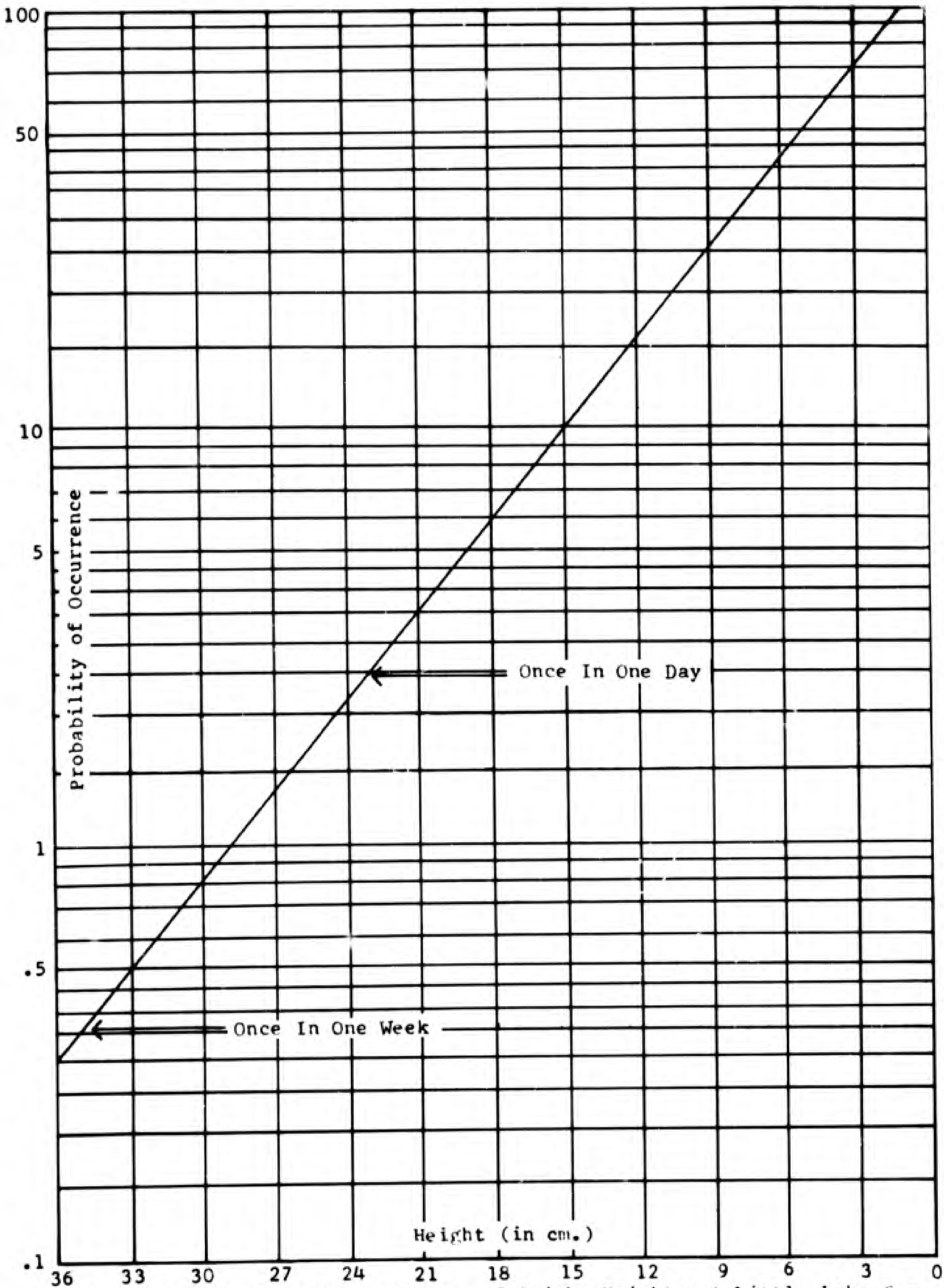

Fig. 11 – Probability of Occurrence of Seiche Heights at Little Lake for Seiches With Periods Between 0.4 and 2.0 hr.

COMPOSITE CURRENTS

Currents measured by drogues in the vicinity of the breakwater-protected entry to Little Lake during a northwest storm (sustained wind speed of 10 meters per second) are shown in Plates 6 and 7. Also shown are the wind track for the day current was measured and for the three previous days, and wave statistics observed at the tower location. Current patterns are considerably more complex than the fundamental inflow-outflow patterns shown in Figures 8 and 9. The dominant feature of the current pattern is the intense clockwise circulation in the breakwater-protected area. Outflow from Little Lake due to water level oscillation is compressed to a narrow stream following the west breakwater. Inflow to Little Lake is no longer distributed uniformly across the harbor entrance as in Figures 8 and 9, it is confined to a westward-flowing stream in the southern portions of the breakwater-protected harbor entrance.

Current trajectories observed about one day following a northwest storm are shown in Plate 8. Also shown are the wind track and wave statistics. The trajectories are very similar to those observed during the storm shown on Plates 6 and 7, indicating a strong influence of the coastal currents in Lake Superior on the circulation of the harbor entrance area.

With reference to Plates 6, 7, and 8, it is possible to construct typical current patterns observed in the harbor entrance area during west or northwest storms. Figure 12 shows a model of the circulation observed with inflow to Little Lake, and Figure 13 shows a model of the circulation with outflow from Little Lake. It is evident that the essential modification of the inflow-outflow patterns of Figures 8 and 9 is the superposition of an intense clockwise eddy generated in the breakwater-protected harbor entry.

Though not traced in detail with drogues, the circulation in this area was observed to be similar during strong west winds. A bright red dye (Rhodamine B) was periodically released near shore about 150 meters east of the east breakwater during sustained 12-meters-per-second west winds. In all cases the dye traveled rapidly westward to the vicinity of the outer cell of the east breakwater. It then moved either westward about halfway across the entrance channel and turned south to Little Lake at the time of inflow currents (Figure 14), or northeastward entrapped in an eddy as delineated in the model representing a composite of eddy currents and outflow currents from Little Lake (Figure 15), similar to the pattern shown in Figure 13.

It is possible that the clockwise circulation in the lee of the west breakwater is reinforced by wave refraction, or by diffraction of waves around the west breakwater, however, such refraction was not observed during the field surveys.

During the field investigation, it was observed that suspended sediment in the surf zone east of the harbor moves westward with the clockwise eddy current. Material thus moved into the sheltered harbor entrance from up to 300m east of the entrance.

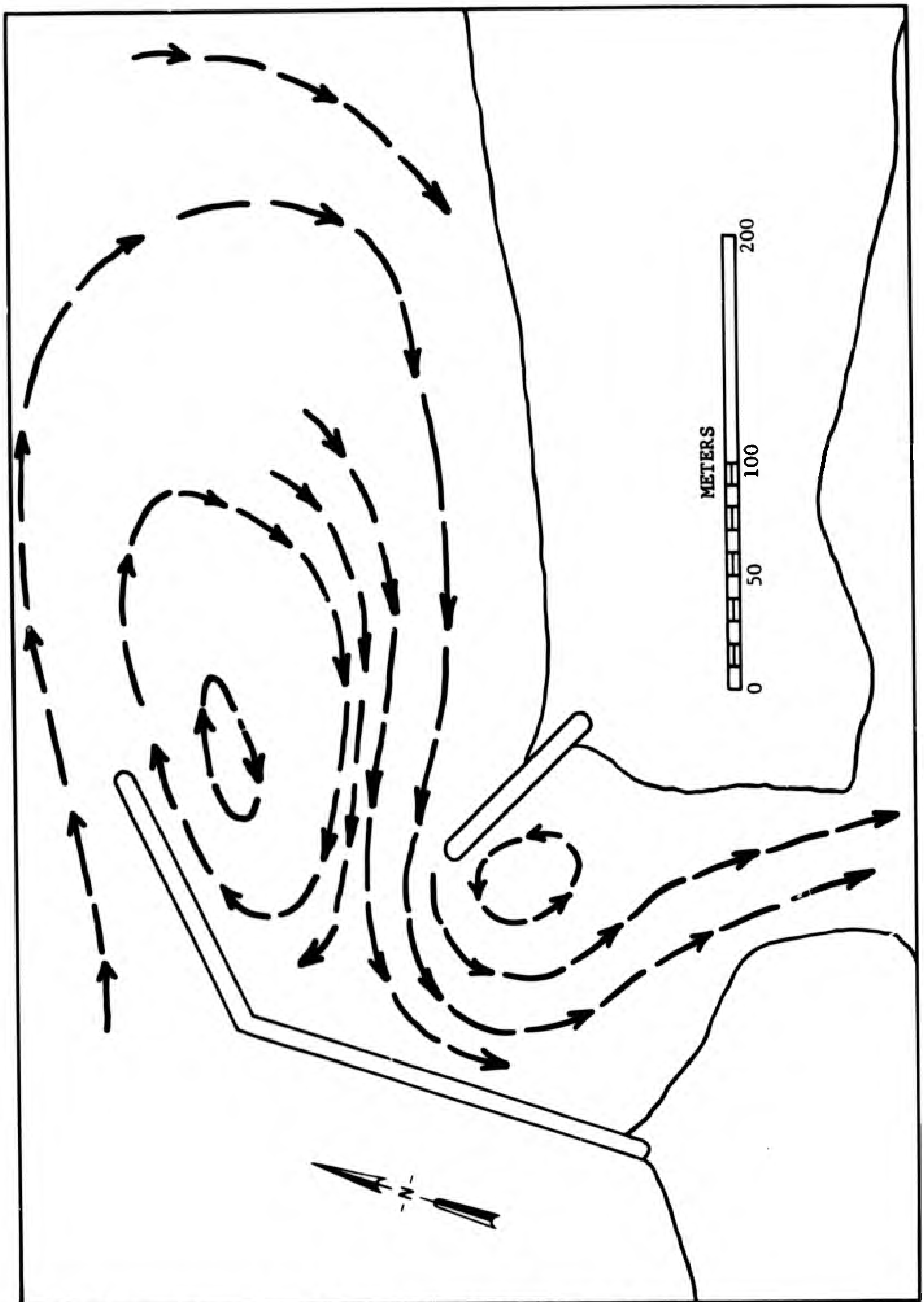

Fig. 12 Circulation Model During Westerly Storm and Inflow

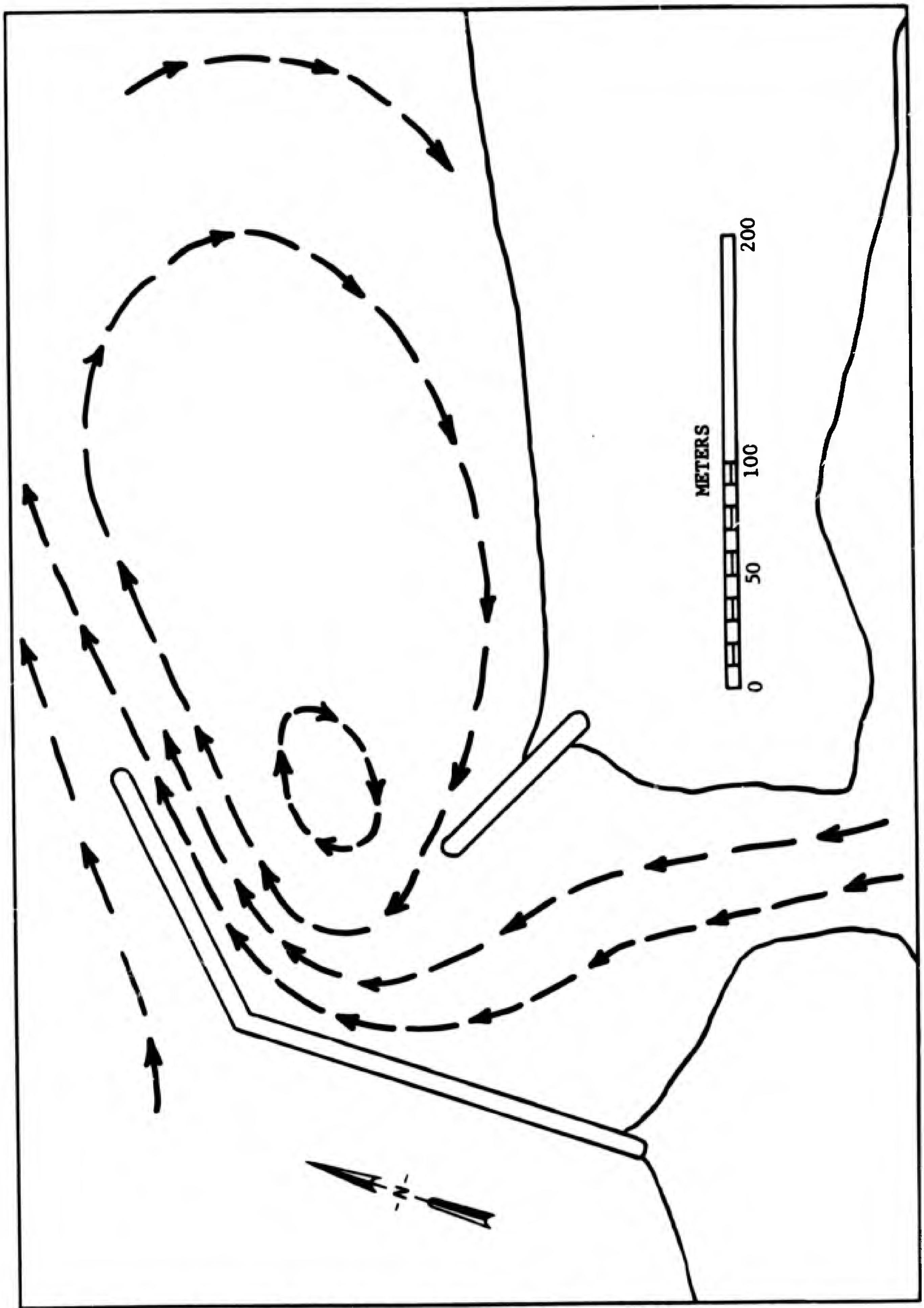

Fig. 13 Circulation Model During Westerly Storm and Outflow

Fig. 14a At Time of Dye Release

Fig. 14b One Minute After Dye Release

Fig. 14c Two Minutes After Dye Release

FIGS. 14a-c CURRENT PATTERN DURING STRONG WEST WIND AND INFLOW

FIGS. 15a-d CURRENT PATTERN DURING STRONG WEST WIND AND OUTFLOW

Fig. 15a At Time of Dye Release

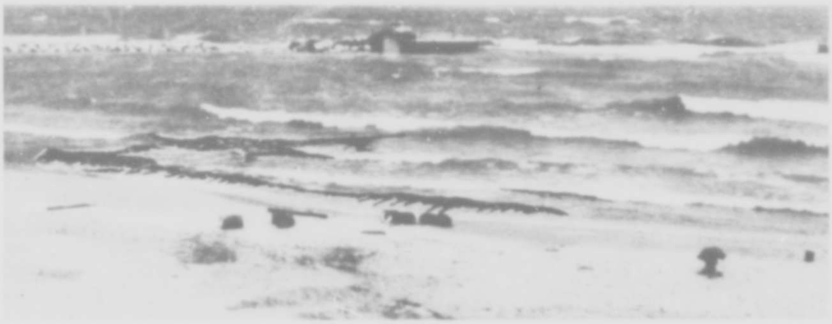

Fig. 15b One Minute After Dye Release

Fig. 15c Two Minutes After Dye Release

Fig. 15d Three Minutes After Dye Release

CONCLUSIONS

Strong coastal currents directed toward the east are generated by the prevailing west and northwest winds at Little Lake. The measurements show that the coastal currents generated by storms from these directions approach steady-state conditions within two or three hours, and that it takes a minimum of three or four days for these storm-generated currents to decay. The currents are of higher speed for west winds than for northwest winds of the same speed.

Reversing currents through the channel connecting Little Lake with Lake Superior are driven by fluctuations of water level in Lake Superior. The direction and higher velocity components of the currents are controlled mainly by oscillations with periods of less than two hours.

Eastward flowing coastal currents in Lake Superior drive a clockwise eddy in the lee of the west breakwater of Little Lake Harbor. This clockwise circulation is intense during west and northwest storms. In the region of clockwise circulation east of the harbor, material suspended in the water near the beach by wave action moves toward the harbor entrance. This westward drift was observed 300 meters east of the harbor.

Clockwise eddy circulation compresses the reversing currents against the harbor side of the west breakwater. The high speeds of the inflow-outflow currents maintain a narrow, deep channel along the breakwater.

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2. Anonymous, 1959b, "Harbor of Refuge at Little Lake, Michigan. General Design Memorandum". Detroit District, Army Corps of Engineers, Detroit, Michigan. (unpublished).

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5. Reid, R. O., 1958. "Effect of Coriolis Force on Edge Waves (I) Investigation of the Normal Modes. Jour. Mar. Res. 16, 109-144.

LIST OF PLATES

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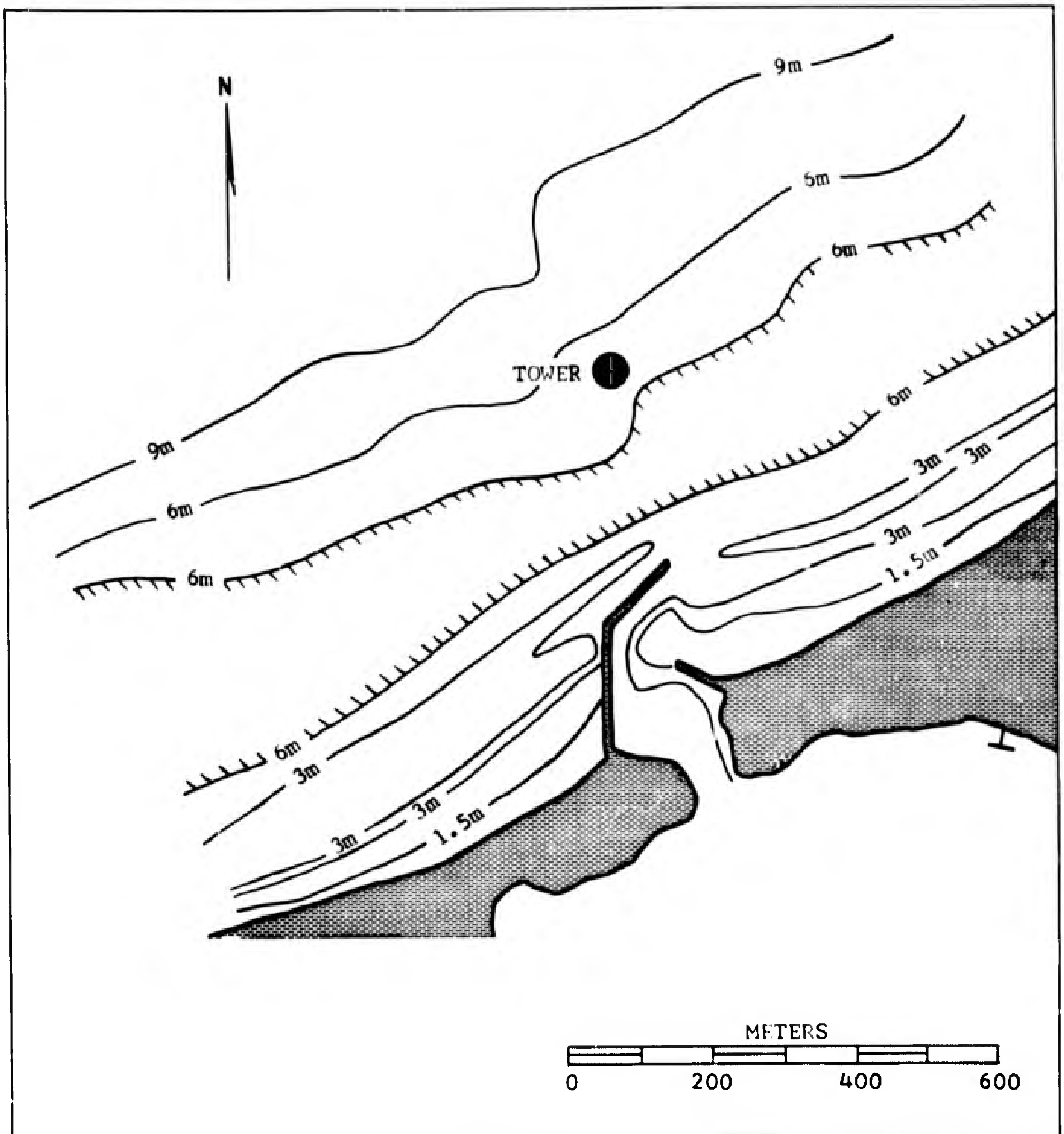


BATHYMETRY
OF THE LITTLE LAKE AREA
AT TIME OF CURRENT SURVEY

PLATE 1

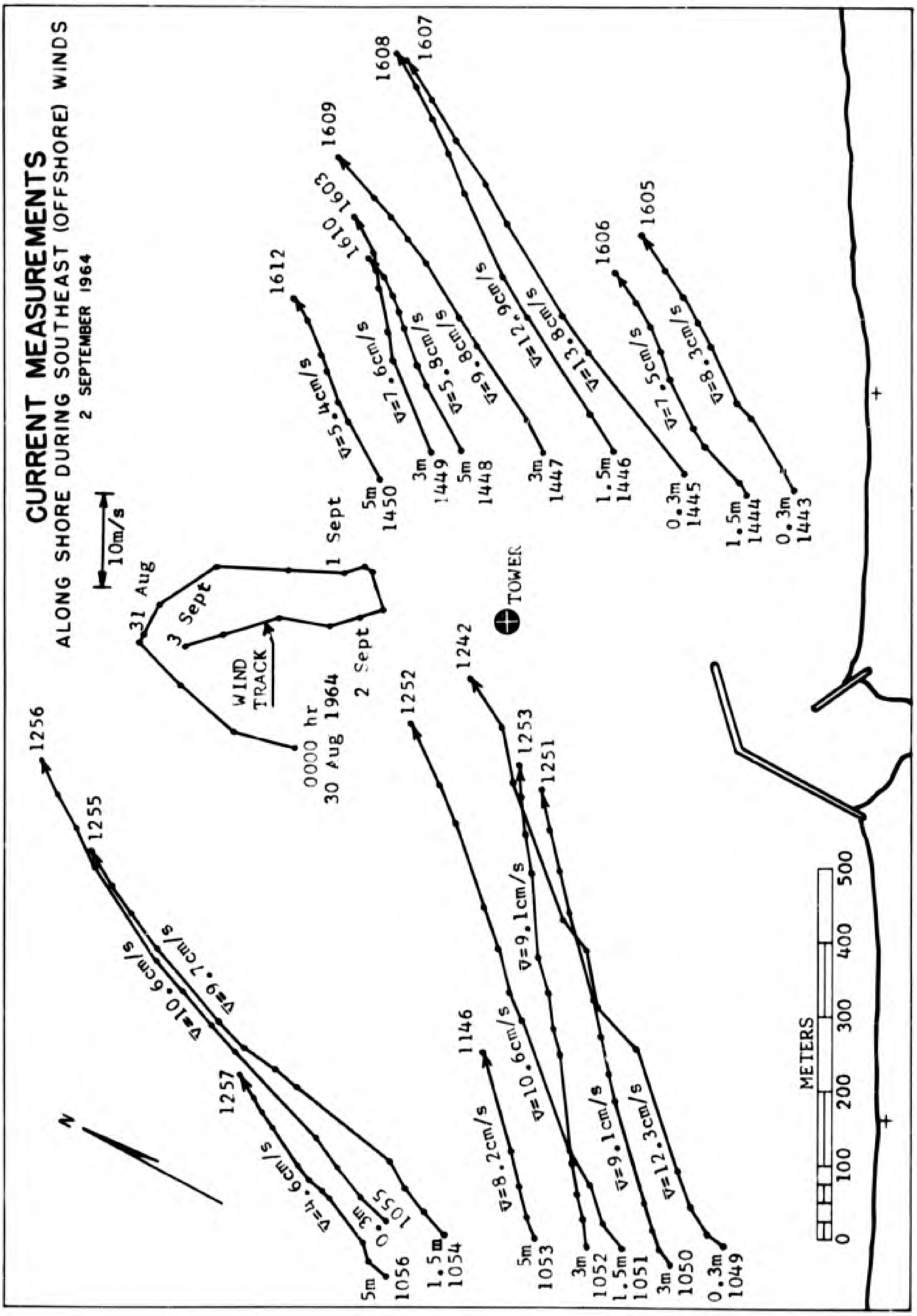
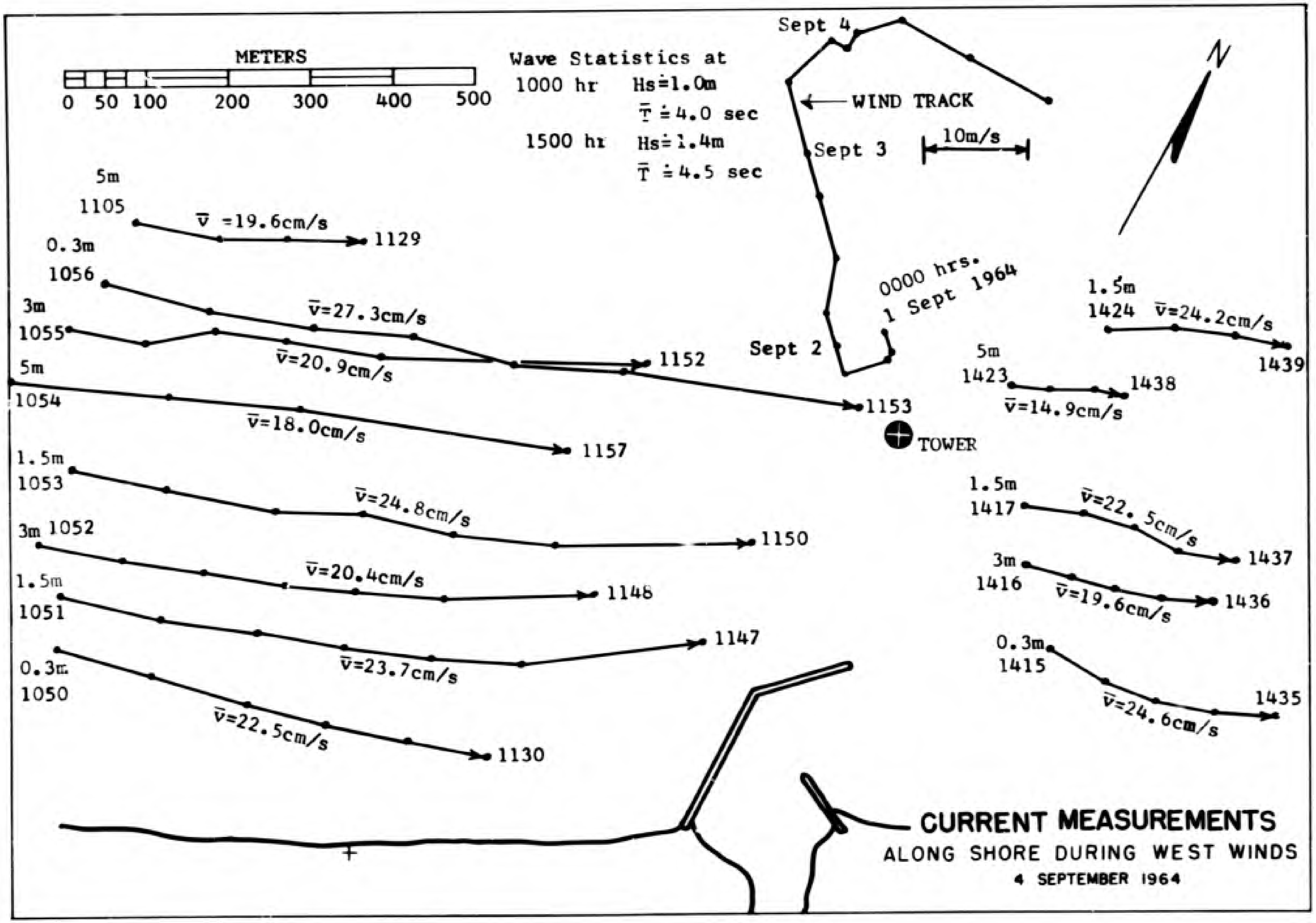
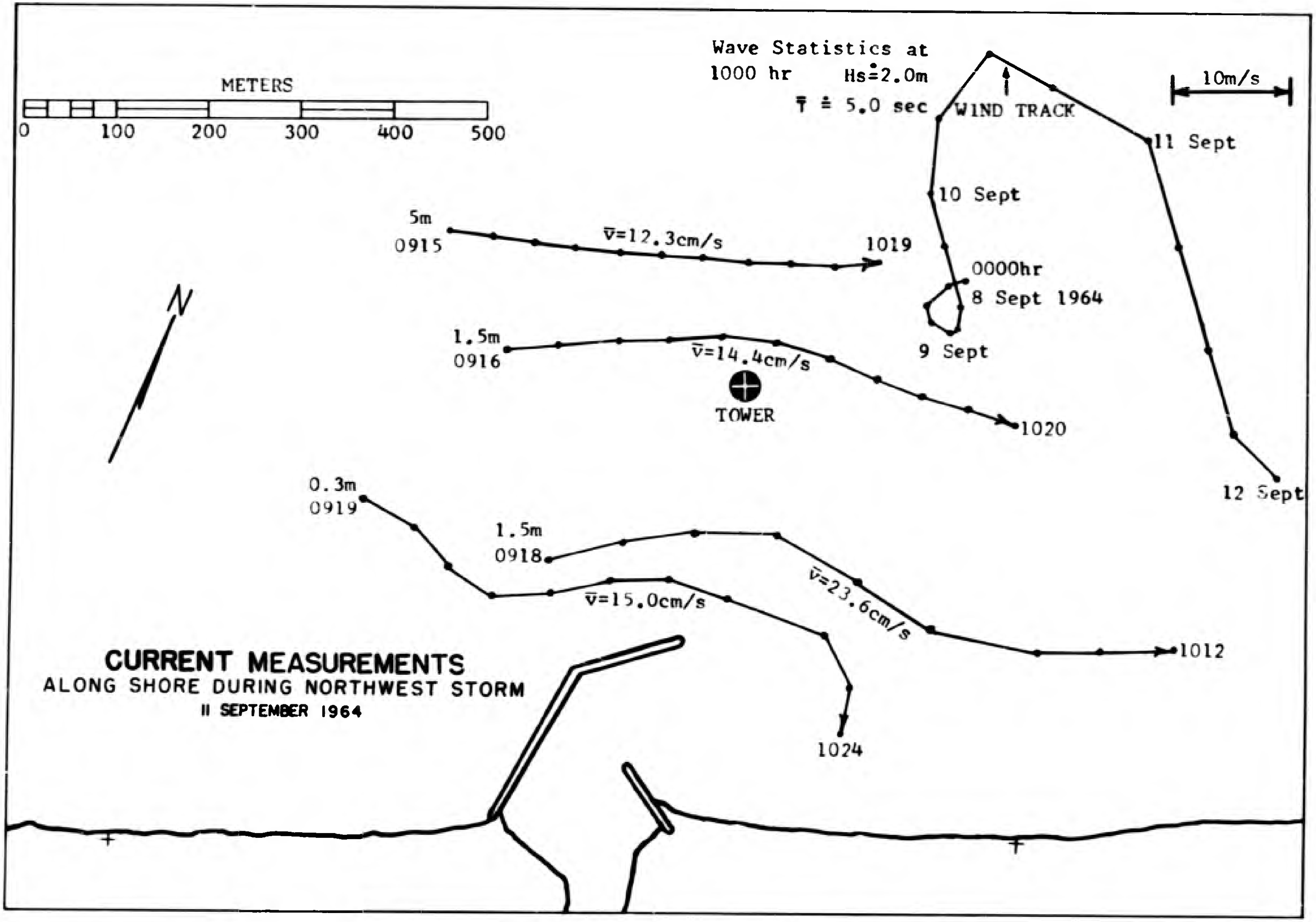

CURRENT MEASUREMENTS
ALONG SHORE DURING SOUTHEAST (OFFSHORE) WINDS
2 SEPTEMBER 1964
10m/s
WIND TRACK
0000 hr
30 Aug 1964
31 Aug
1 Sept
2 Sept
3 Sept
TOWER
METERS
0
100
200
300
400
500
N

PLATE 2



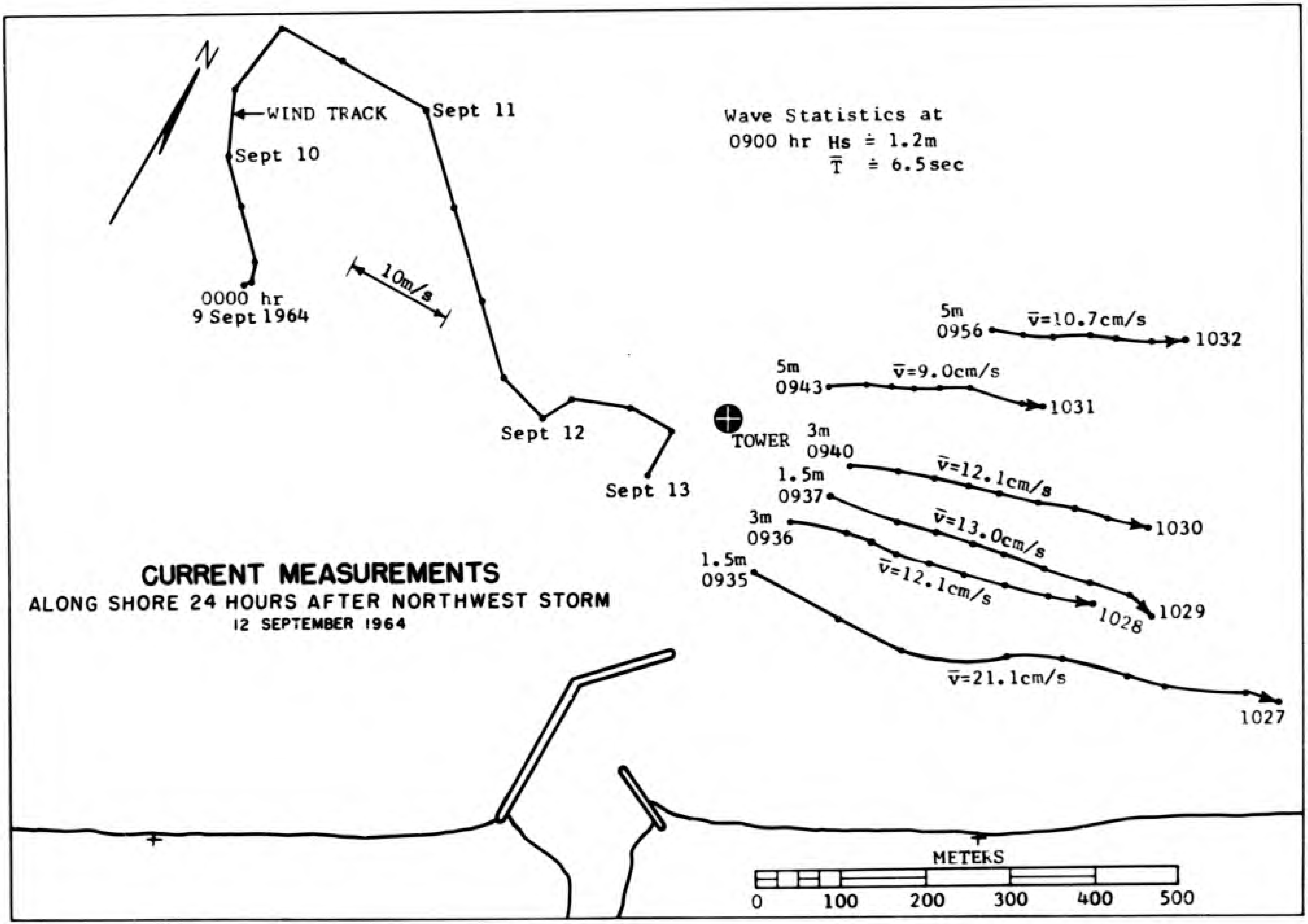
CURRENT MEASUREMENTS
ALONG SHORE DURING WEST WINDS
4 SEPTEMBER 1964

PLATE 3



CURRENT MEASUREMENTS
ALONG SHORE DURING NORTHWEST STORM
11 SEPTEMBER 1964

PLATE 4


CURRENT MEASUREMENTS
ALONG SHORE 24 HOURS AFTER NORTHWEST STORM
12 SEPTEMBER 1964
N
WIND TRACK
Sept 10
Sept 11
Sept 12
Sept 13
0000 hr
9 Sept 1964
10m/s
Wave Statistics at
0900 hr Hs ≐ 1.2m
T̄ ≐ 6.5sec
TOWER
5m
0956
v̄=10.7cm/s
1032
5m
0943
v̄=9.0cm/s
1031
3m
0940
v̄=12.1cm/s
1030
1.5m
0937
v̄=13.0cm/s
1029
3m
0936
v̄=12.1cm/s
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METERS
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100
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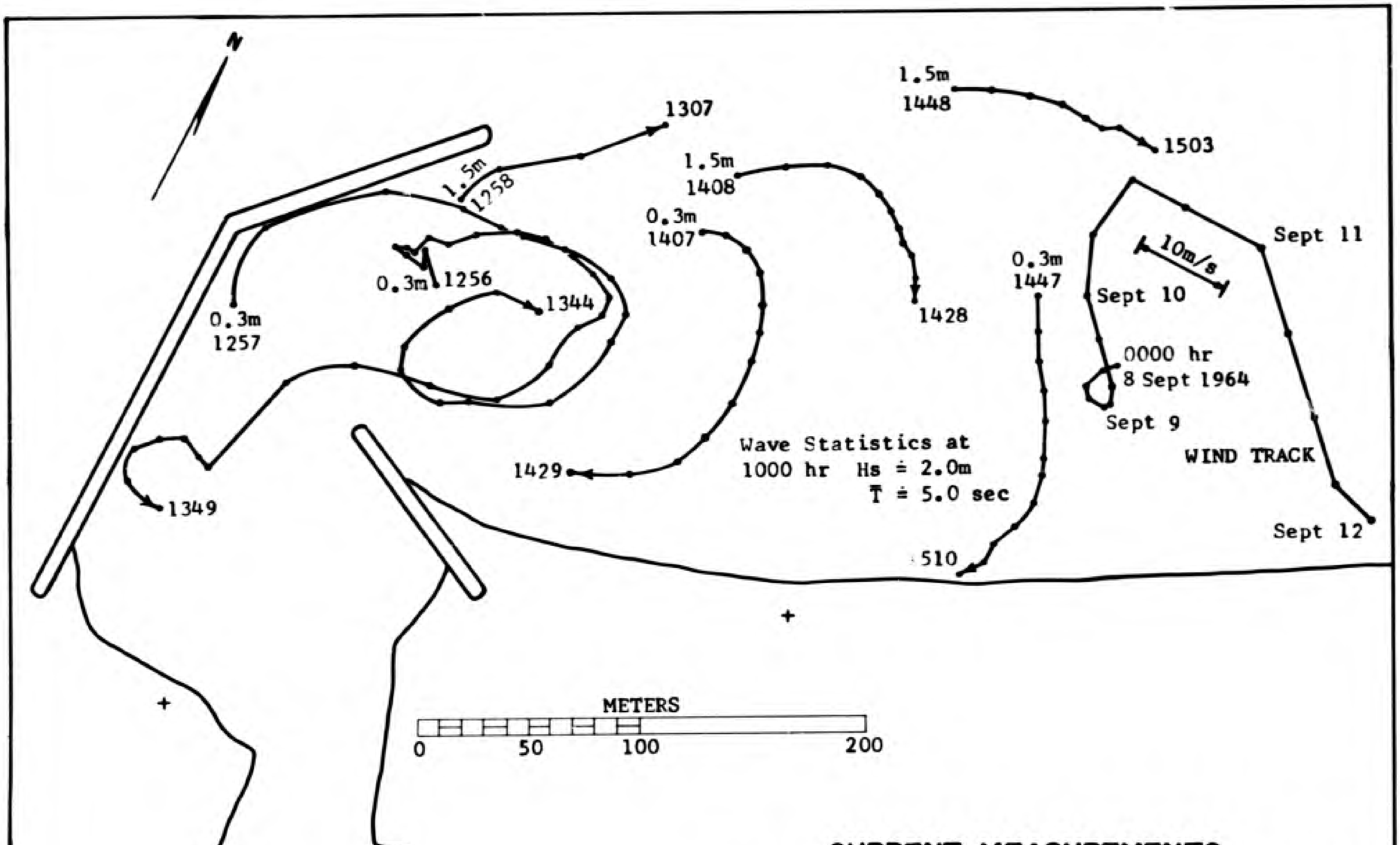
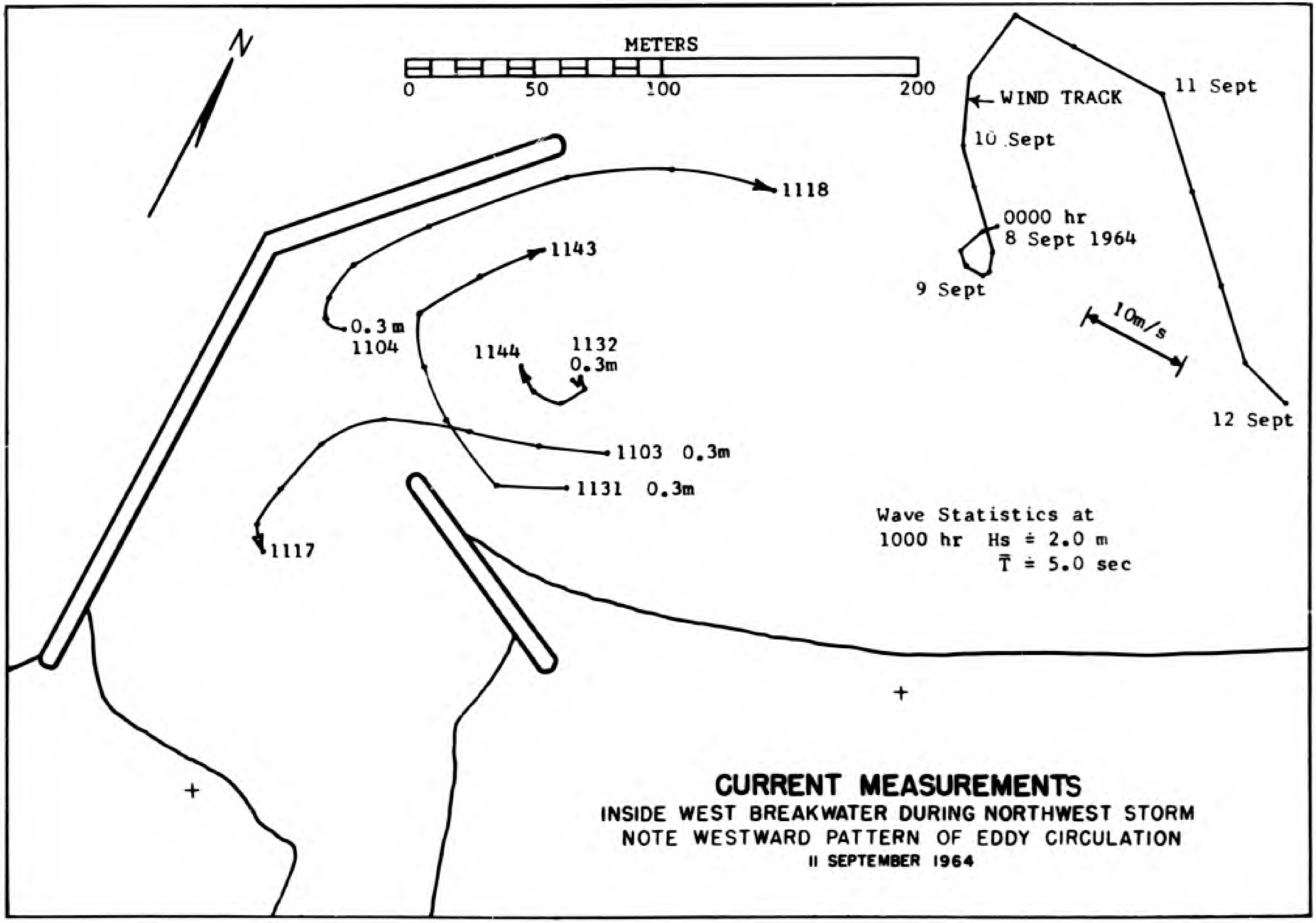
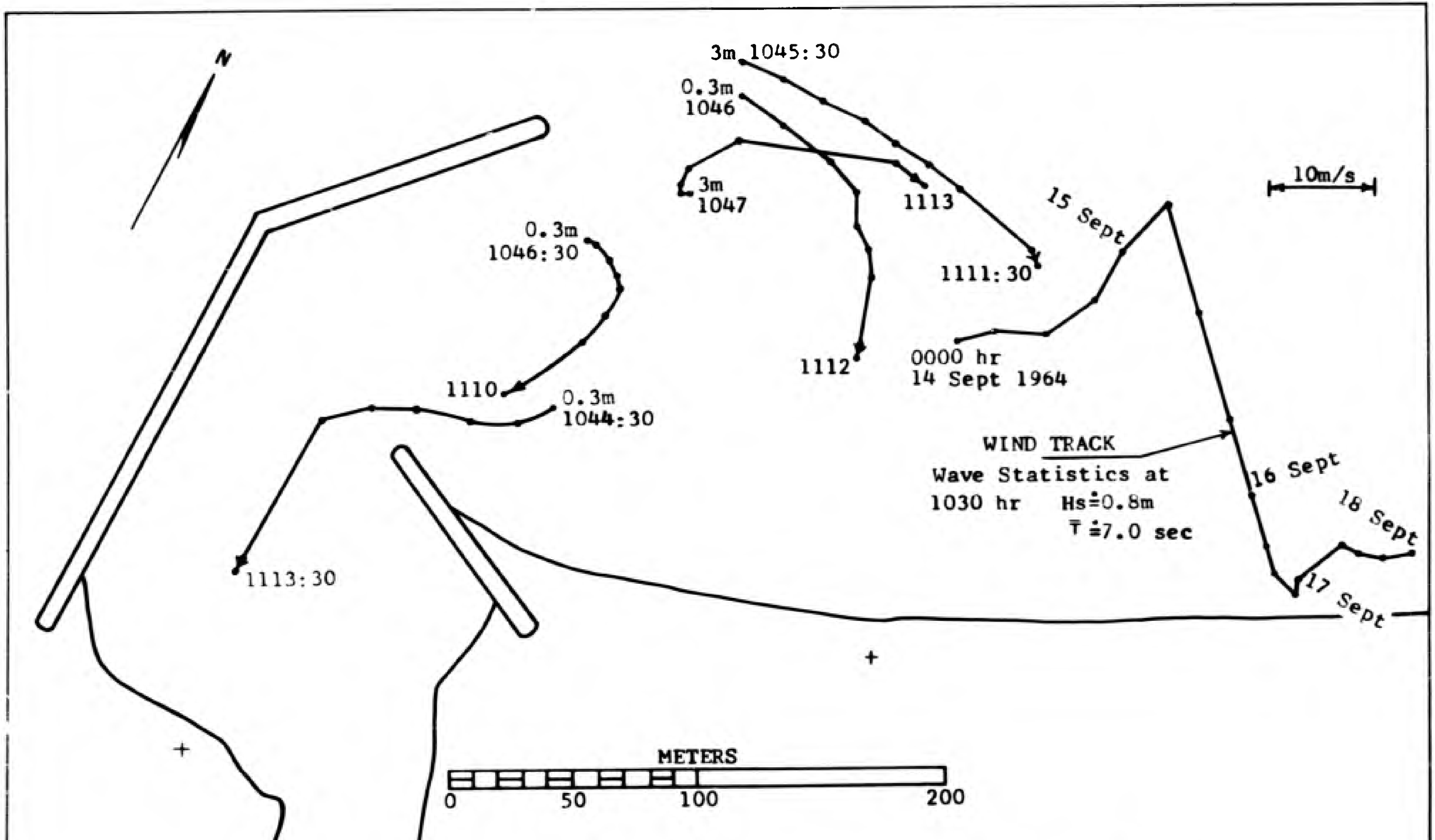


CURRENT MEASUREMENTS
INSIDE WEST BREAKWATER DURING NORTHWEST STORM
11 SEPTEMBER 1964

PLATE 6

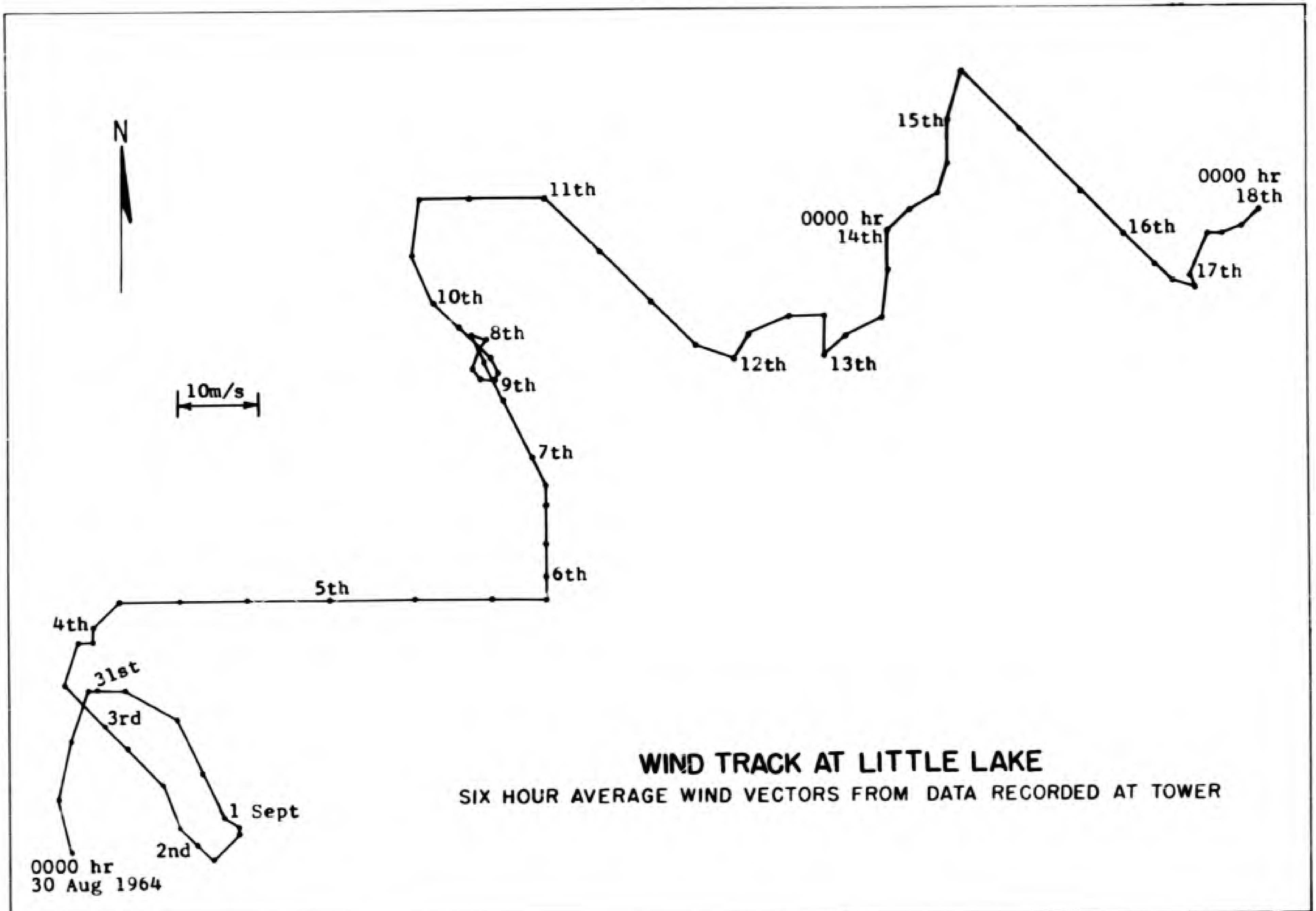

N
METERS
0
50
100
200
WIND TRACK
10 Sept
11 Sept
0000 hr
8 Sept 1964
9 Sept
10m/s
12 Sept
1118
1143
0.3 m
1104
1144
1132
0.3m
1103 0.3m
1131 0.3m
1117
Wave Statistics at
1000 hr Hs ≐ 2.0 m
T̄ ≐ 5.0 sec
CURRENT MEASUREMENTS
INSIDE WEST BREAKWATER DURING NORTHWEST STORM
NOTE WESTWARD PATTERN OF EDDY CIRCULATION
11 SEPTEMBER 1964



CURRENT MEASUREMENTS

INSIDE WEST BREAKWATER 24 HOURS AFTER NORTHWEST STORM

17 SEPTEMBER 1964



WIND TRACK AT LITTLE LAKE

SIX HOUR AVERAGE WIND VECTORS FROM DATA RECORDED AT TOWER

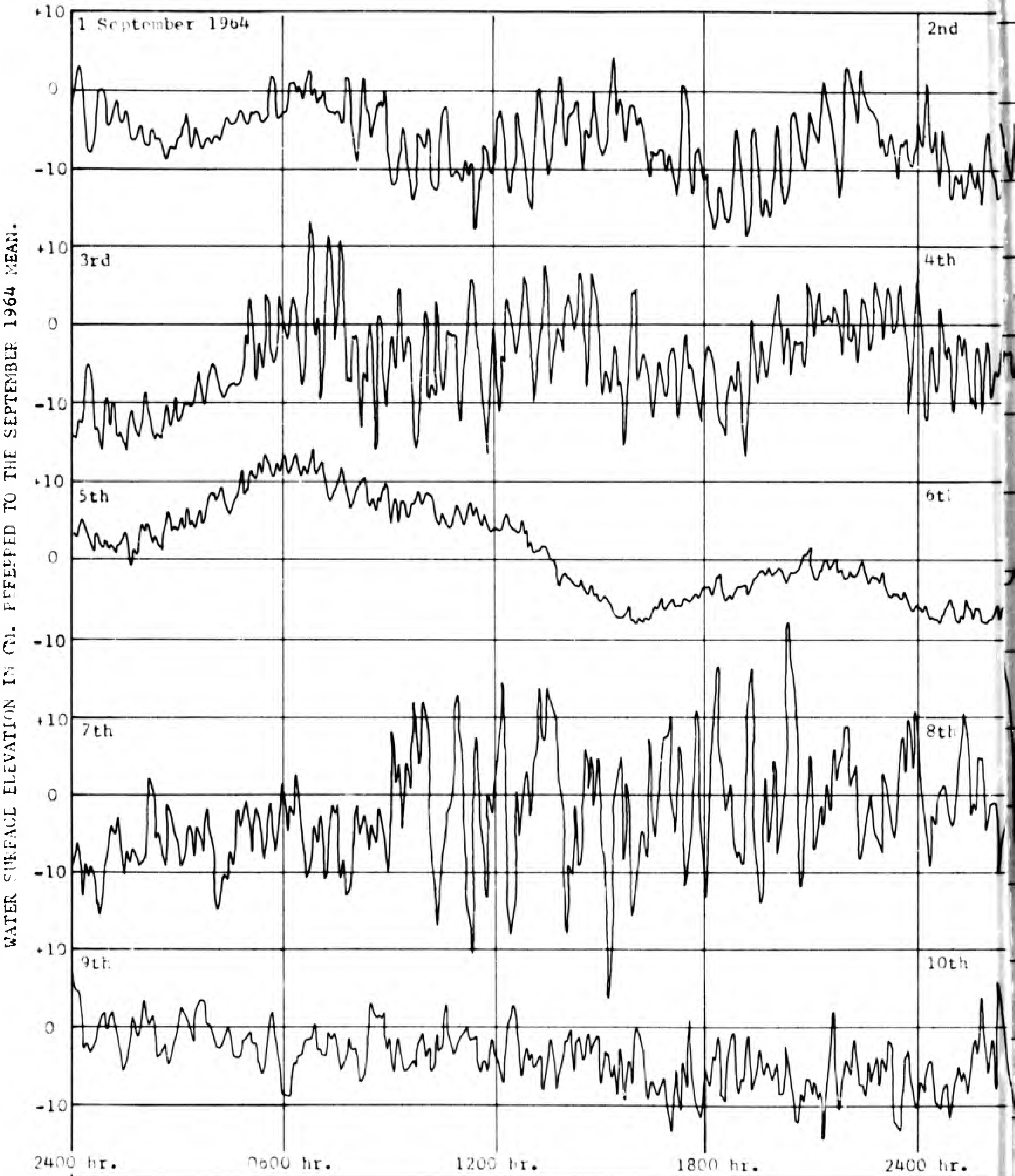
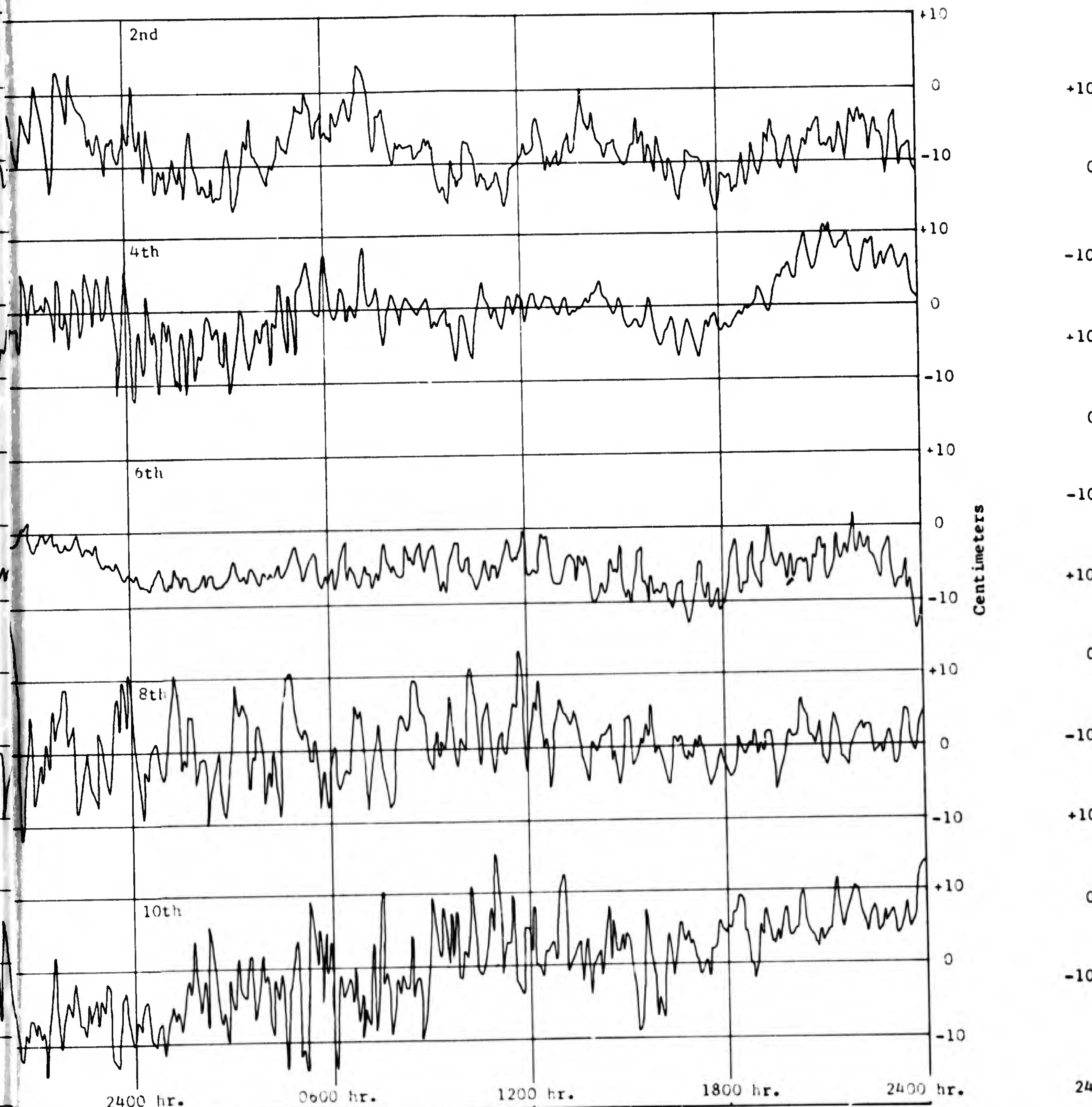


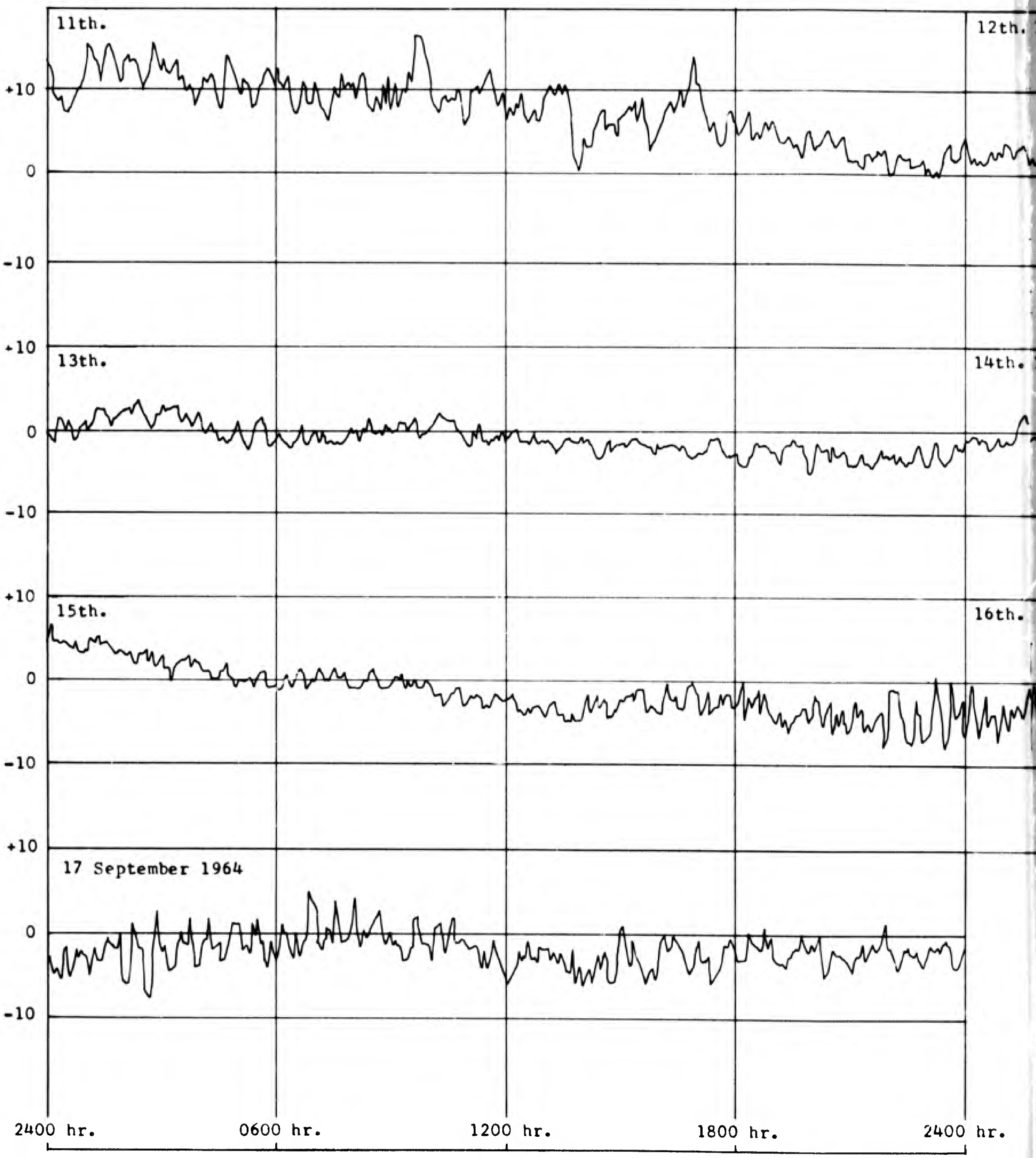
PLATE 10

SHEET 1 of 2

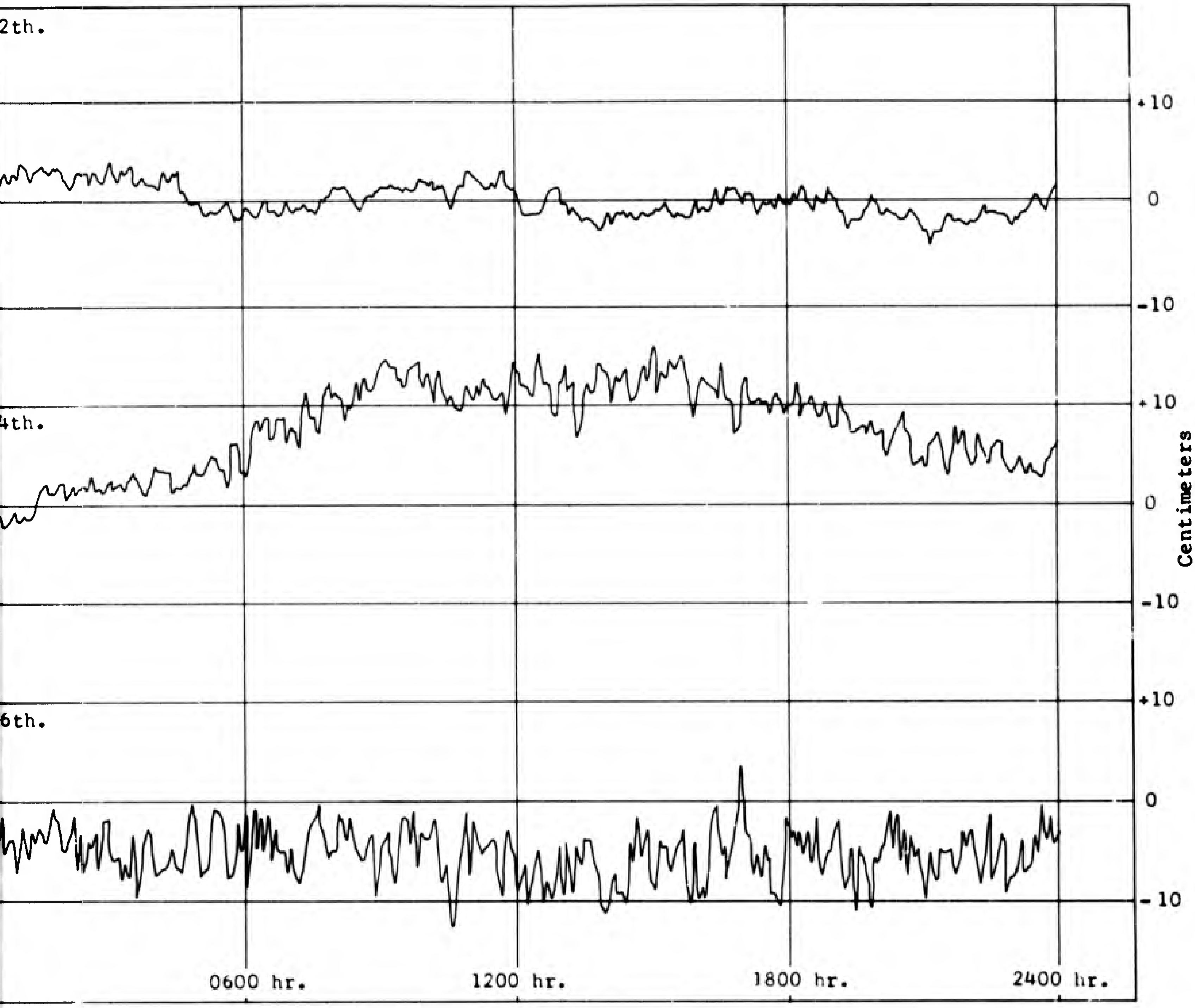
A


2nd
4th
6th
8th
10th
+10
0
-10
Centimeters
2400 hr.
0600 hr.
1200 hr.
1800 hr.
2400 hr.

B


11th.
12th.
13th.
14th.
15th.
16th.
17 September 1964
+10
0
-10
2400 hr.
0600 hr.
1200 hr.
1800 hr.
2400 hr.

A



hr.

WATER SURFACE ELEVATION
RECORDED AT THE LITTLE LAKE TOWER

REFERRED TO THE SEPTEMBER 1964 MEAN LEVEL