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by
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FOREWORD

This paper is a reprint of a paper submitted to the 1966 Army Science Conference, held at West Point on 14-17 June 1966, and sponsored by the Office of Chief Research and Development, Department of the Army.

The paper is based on research accomplished by Mr. J. H. Saylor, Senior Project Scientist in charge of the harbor current subprojects, under the general direction of Mr. J. G. Housley, Chief of the Water Motion Project, and Dr. L. Bajorunas, Director, Great Lakes Research Center, U. S. Lake Survey. Permission to publish this paper was granted by the Office Chief of Engineers.

MODIFICATION OF NEARSHORE CURRENTS BY COASTAL STRUCTURES

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INTRODUCTION

Patterns of water circulation along the shores and in the harbors of the Great Lakes have been studied little. The water currents are of direct importance to navigation, water intake placement, and waste disposal, and are contributors to patterns of sediment transport, deposition, and erosion. There is a definite need to be able to predict water currents and their effects before construction of new or modification of existing coastal structures to insure enlightened planning in the rapidly increasing utilization of Great Lakes waters and shorelines.

This paper describes and presents the results of water current studies conducted along the shores of Lakes Superior, Michigan, and Erie. The studies have been made at various harbor locations, indicated on figure 1, with the purpose of establishing current magnitudes and patterns within the harbors and in the adjacent coastal areas, and relating the measured currents with the causative forces.

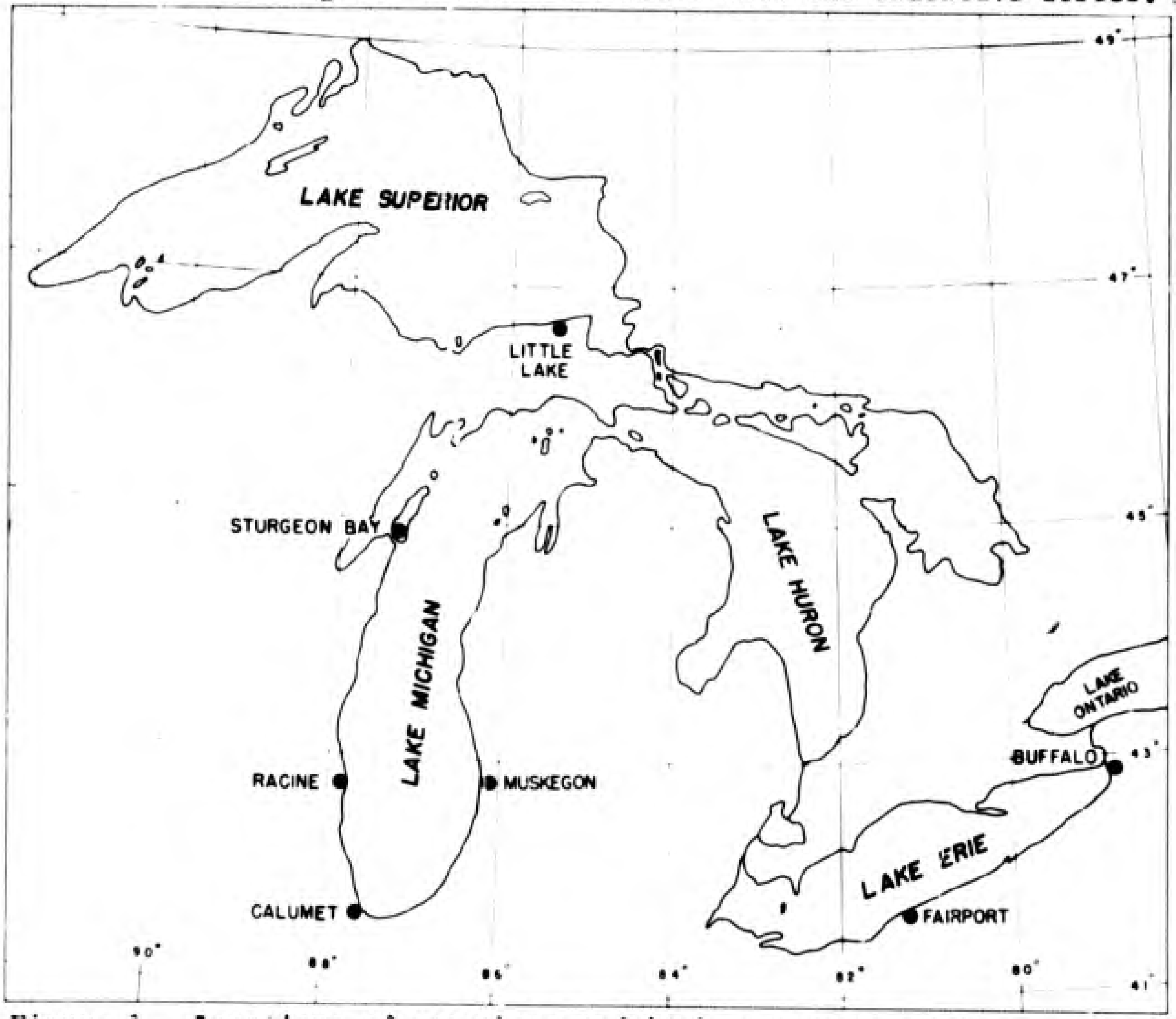

Figure 1. Locations of nearshore and harbor current studies

SURVEY METHODS

The primary forces driving nearshore and harbor currents on the lakes are wind and fluctuations of water level. Wind stress, in addition to directly driving currents, produces a secondary drift due to a small net transport of water in the direction of travel of the waves. For measurement of over-water wind speed and direction, water levels representative of the open lake, and waves before extensive modification by shoaling, offshore towers were erected at each site studied to serve as suitable instrument platforms, figure 2. Wind speed at the 10-meter level was recorded continuously as an analog trace. Wind direction was recorded once each minute as an event. Water level was recorded digitally on punched-paper tape at five minute intervals. Waves were recorded in analog form continuously on magnetic tape and strip chart. The wave sensor was a 6.5-meter long step-resistance wave staff mounted on one side of the triangular instrument tower, with resistors spaced at 0.06 meters. The output of the wave staff was transmitted by cable to the recorders placed on shore. Auxilliary measurements made from the towers were air and water temperature.

Currents were measured with drogues, Savonious-rotor type recording current meters, and dye. The drogues consisted of large sheet-metal vanes suspended at varying depths below small surface floats affixed with identifying flags. The drogues were placed in the area of interest and trajectories of drift were followed with two transits. Cut-off angles were read at equal intervals of time and the drogue paths were plotted graphically. The current meters were placed at strategic points in each harbor and on several of the offshore towers to continuously record current speed and direction. The currents recorded at fixed points were compared with the areal distribution of currents determined with drogues. The drift of Rhodamine B dye was traced visually and photographically.

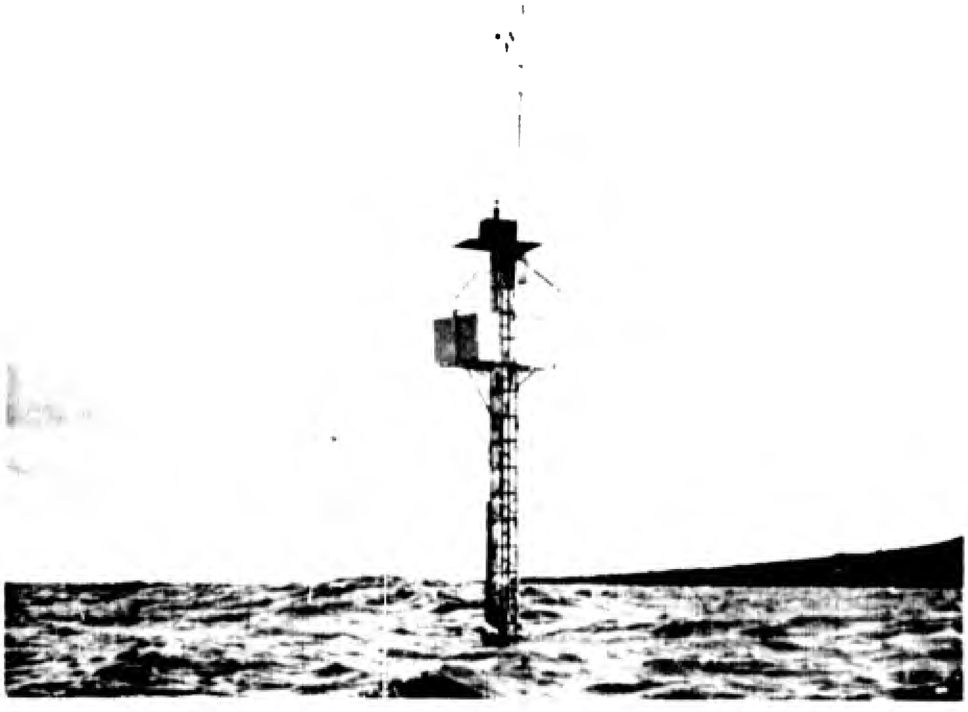

Figure 2. Offshore tower at Little Lake, Lake Superior.

WIND-DRIVEN CURRENTS

The relation between the surface wind (V_a) and surface current (V_s) has been studied by many investigators. The ratio of the two parameters is a function of the Reynolds number based on the shear velocity. For Reynolds numbers $V_a h/\nu > 10^5$, where h is the water depth, ν is the kinematic viscosity of water, Keulegan (1) found in wind-tunnel experiments that for wind speeds up to 10 meters per second,

$$V_s/V_a \sim 0.033$$

Van Dorn (2) extended these experiments up to wind speeds of 15 meters per second (measured at one-meter height). He verified Keulegan's relation, and also found that the surface current was independent of wave action. These results are applicable to the center region of most unstratified lakes. An equation of Witting (3) has been found to present well the relation between the actual wind and current velocity in the oceans,

$$V_s = K \sqrt{V_a}$$

The constant K varies slightly with water depth. As an average, the value 0.026 can be used if the mass transport by waves is considered to be included, and an average current velocity in the upper three meters is desired.

Less information exists concerning the direction of the currents. In deep, homogeneous water, Ekman (4) found that the surface currents were directed 45 degrees to the right of the stress vector, that the angle of current deflection increases regularly in a clock-wise manner with increasing depth of measurement beneath the water surface, and that current speed decreases monotonically with increasing depth of measurement. Recent investigations indicate that the surface current in offshore areas in the middle latitudes is directed less than 45 degrees to the right of the wind: Lisitzin (5) - 12 degrees, Gaul (6) - 15 degrees, Bowden (7) - 18 degrees, and Stommel (8) - 20 degrees. Moreover, it has been observed that the current deflection depends upon the wind speed. Witting (3), from observations in the Baltic Sea, proposed the relation

$$\beta = 34 - 7.5\sqrt{V_a},$$

where β is the deflection (in degrees) of the current to the right of the wind and V_a is in meters per second. In shallow water, and in water sharply stratified at shallow depth (the Great Lakes develop strong, shallow thermoclines during the summer months), theory and observation show currents directed more nearly parallel to the stress vector.

Nearshore currents have been measured in the vicinity of the harbors at Little Lake on Lake Superior, at Muskegon, Calumet, Racine, and Sturgeon Bay on Lake Michigan, and at Fairport and Buffalo on Lake Erie; see figure 1. Eastward-flowing nearshore currents measured in Lake Superior at Little Lake during westerly wind are shown in figure 3. This figure illustrates several features common to nearly all measurements of nearshore currents which have been made at the various locations. As expected, the currents flow essentially parallel with the shoreline. The currents shown on the figure were measured during west wind of eight meters per second. The average speed of the surface drogues was about 0.25 meters per second, and the ratio of surface current to wind speed is very close to that determined by Keulegan. Ratios near Keulegan's value have been repeatedly observed during conditions of strong wind blowing nearly parallel with the shoreline. During onshore or offshore wind, this ratio was approached as the surface current measurements were extended greater distances from shore.

Another feature illustrated by the nearshore current observations shown on figure 3 is the short interval of time required for steady-state conditions to be established. Westerly wind with mean speed of eight meters per second began abruptly at 0800 hours on the fourth of September, after four days of light, offshore wind. By 1100 hours, the nearshore currents were fully developed, as evidenced by the uniformity of current speeds and directions measured during the morning and afternoon surveys. Thus, steady-state conditions were established within the three-hour interval between the start of the west wind and the earliest current measurements. Observations made at several of the other study sites during periods of abrupt wind changes show that for wind speeds of six meters per second or greater, full response of coastal currents to applied wind stress is generally quicker than three hours, with a steady state being achieved in most observations in periods of one hour or less. The measurements also indicate that coastal current speed and direction are practically independent of surface wave activity.

Observations at all sites have shown that with light onshore or offshore wind stress, currents near the surface tend to flow in the direction of the stress. Currents at mid-depth are then oriented nearly parallel with the shoreline, and continuity is achieved by return flow near the bottom. Higher nearshore current speeds are observed during onshore wind and the highest speeds are observed when the wind is nearly parallel with the shoreline. With onshore wind, a boundary region is established along the shore in which the currents at all depths flow parallel with the shoreline. The width of this boundary region increases with increasing wind and current speeds.

The direction and speed of current flow along the coasts of the Great Lakes were found to be governed almost entirely by the shear stress of the wind over water and the coastal bathymetry. This stress is proportional to the square of the wind speed, and it was found that the large energy inputs during periods of high wind speed effectively control the currents. For the duration (three weeks in September 1964) of the study of nearshore currents in Lake Superior at Little Lake, the flow along the coast was eastward. There were four periods of sustained high wind speeds directed either nearly parallel to the shoreline (two periods of west wind) or onshore (two periods of northwest wind). During each period, the eastward flow quickly reached a steady state and afterward decayed slowly, with current speeds 24 hours after cessation of strong wind only slightly reduced from those observed during the strong wind. These currents persisted, with slowly decaying speeds, until the next period of high energy input. The direction of flow of the nearshore currents along the coast has been discussed by Saylor (9). Analysis of data collected along the shores of Lake

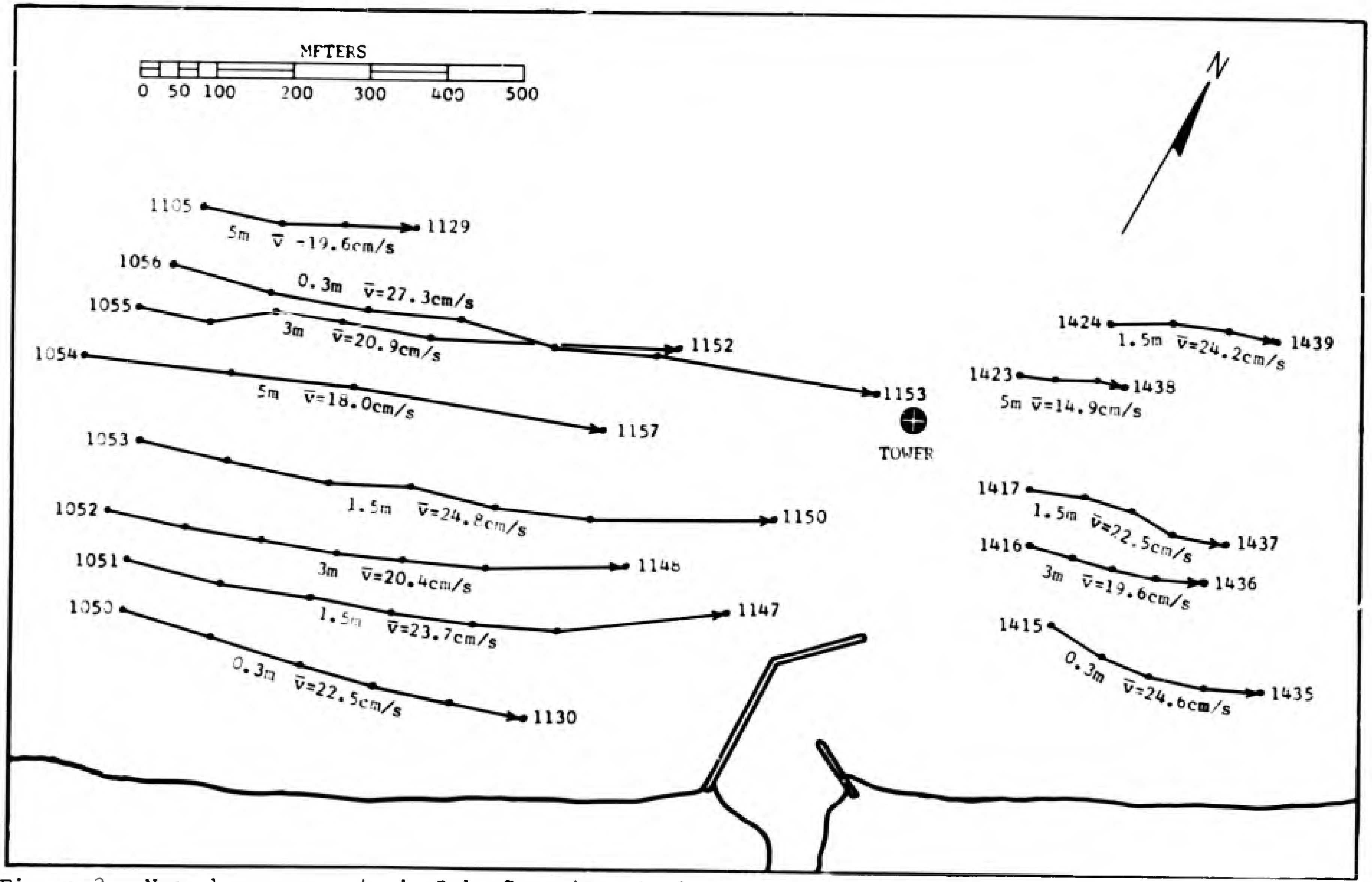

Figure 3. Nearshore currents in Lake Superior at Little Lake measured during sustained 8 m/s west wind on 4 Sept 1964. Each trajectory is labeled with time of first and last location fix, depth of current-sensing vane, and average current speed. Average wave height was 0.7m, at 1000 hr, 1.2m, at 1400 hr.

Michigan showed that the effective wind-driven current was directed about 15 degrees to the right of the surface wind, and that the direction of flow along the coast was determined principally by the conservation of momentum of these currents.

CURRENTS DUE TO WATER LEVEL FLUCTUATIONS

The relatively small size of each of the Great Lakes permits only small response to the astronomical-tide-producing forces. A lack of data on currents in the lakes harbors is attributable in a large part to this fact. Large displacements of temporal mean water level do occur, however, due to wind tides, surges, and seiches. Wind tides result from a piling up of water in the direction of the wind stress. The magnitude of the wind tide (also called "wind set-up") depends upon the water depth, the configuration of the shoreline, and the wind speed and duration. Surges result from the propagation of meteorological anomalies across the lakes. The waves entrained in these disturbances can reach large amplitudes if the anomalies travel at the same speed as the free wave on the water surface. Seiches are the free, natural oscillations of a lake's surface. They are standing waves, with periods determined by the lake's configuration, the speed of wave propagation (a function of water depth), and the mode of the standing wave. They result chiefly from the decay of wind tides.

Currents generated in the harbors by these disturbances can in most instances be described by the methods of classical tidal hydraulics. However, each harbor is subject to a different long-wave climate that prohibits any generalization of principle current-driving forces and effects. For example, the harbor at Calumet at the south end of Lake Michigan is located near an antinode of all longitudinal oscillations of the lake. These oscillations include the semi-diurnal astronomical tide with mean spring range of about seven centimeters, the fundamental mode of longitudinal seiches with a period of nine hours, and many higher order modes. The harbor at Muskegon, near the mid-point of the longitudinal axis of Lake Michigan, experiences tidal and longitudinal amplitudes much reduced from those observed at Calumet, but is located at an antinode of a persistent, large-amplitude transverse seiche across the lake's southern basin with fundamental period of 2.2 hours. Thus, quasi-tidal currents in Great Lakes harbors depend not only on the harbor dimensions and layouts, but to a larger extent on the spectrum of long waves incident at their entrances.

For protection from waves, the harbors in general have narrow, restricted communication with the open lake. Through these restricted openings, the quasi-tidal currents attain their maximum speeds. Little effect of water-level fluctuations on nearshore currents has been observed. In no instance has oscillatory motion toward and away from the shore due to standing wave currents transverse to the shoreline been perceptible.

EFFECTS OF COASTAL STRUCTURES

The current patterns observed in and adjacent to the harbors are usually resultants of complex interactions of wind-driven coastal currents and currents due to water-level fluctuations. The relative importance of each of these two major components in controlling the current patterns depends upon the harbor's location and layout. An example of strong coastal current interaction is afforded by currents measured at Little Lake Harbor, a small-craft harbor constructed in 1962 in southeastern Lake Superior. The harbor is a small lake (surface area of 3.5 x 10^5 square meters) connected with Lake Superior by an entrance channel dredged through a narrow sand bar. The plan of the harbor entrance is shown in figure 4. It is protected from prevailing west and northwest waves by the west breakwater.

As noted earlier, intense, eastward-flowing currents along the shore of the lake at the harbor site are driven by strong west and northwest winds. Records from a nearby weather station show that high-speed, onshore wind in this area occurs predominantly from these directions. Studies prior to construction of the harbor indicated a heavy transport of sand past this location, with eastward transport dominating by a ratio of nine to one. It is well established that sediment is deposited up-drift from such coastal structures and is eroded down-drift.

The small size of the harbor permits a rapid response to fluctuations of water level at its entrance. Measurements of the quasi-tidal reversing current speeds through the harbor entrance, and water-level observations within the harbor, showed a full response for oscillations of 15-minute period or longer. The fundamental mode of longitudinal oscillation of Lake Superior (period about eight hours) and several higher order modes are easily discernible in the water-level record at Little Lake. In addition, there are many persistent oscillations present with periods between 15 minutes and two hours. The shorter-period oscillations are most prominent in the record and are of large amplitude during periods of high wind speed, or storms. Due to the rapid response of the harbor to fluctuations of water level at its entrance, the direction and speed of reversing currents through the entrance channel are mainly controlled by the shorter-period oscillations. Peak reversing current speeds of 0.6 meters per second were associated with an oscillation of one-hour period and 0.1 meter height. These measurements were made following several consecutive days of light, offshore wind and were representative of pure reversing currents, uniformly distributed across the harbor entrance. Reversing current speeds on the order of two meters per second may be postulated by extrapolation of the water-level records which occur during storm periods.

The current pattern observed in the vicinity of the harbor entrance during west or northwest storms with inflow to Little Lake is also shown in figure 4; the current pattern during west or northwest storms with outflow is shown in figure 5. The important feature of the current patterns is the intense clockwise circulation in the lee of the west breakwater. Inflow to the harbor is confined to a narrow stream flowing westward across the southern one-third of the harbor entrance. Outflow from the harbor is compressed to a narrow stream flowing along the inside of the west breakwater. The clockwise eddy circulation was observed more than 300 meters east of the harbor and caused material suspended by wave action in this region to be carried westward toward the harbor entrance. The configuration of a shoal built by the eddy circulation across the harbor entrance bears a close resemblance to the observed current patterns. A narrow, deep channel is observed along the inside of the west breakwater. The eddy is driven by eastward-flowing nearshore currents in Lake Superior. Current patterns in the harbor entrance measured 24 hours after cessation of strong westerly wind showed similar clockwise circulation, though reduced in intensity from that observed at the peak of the storm.

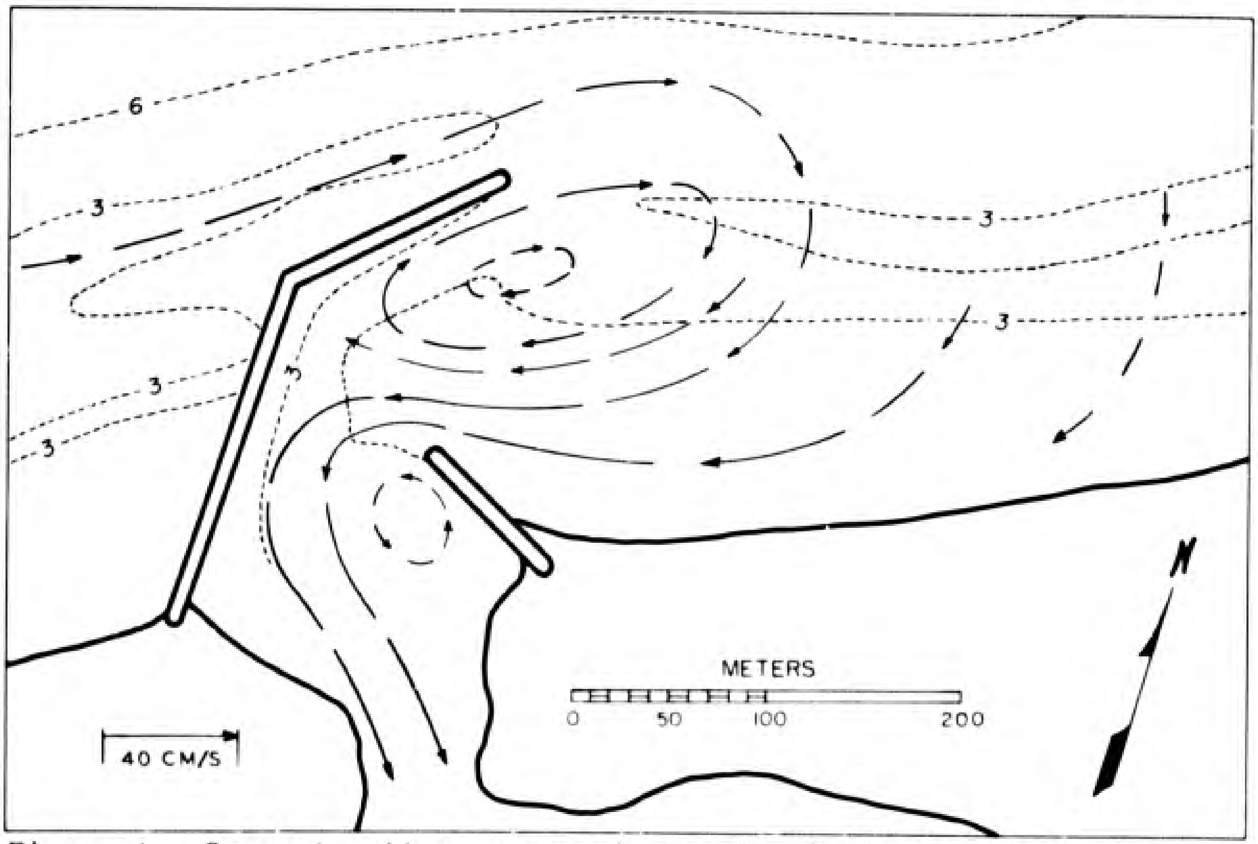

Figure 4. Current pattern near entrance to Little Lake Harbor during strong westerly wind with inflow to harbor. Depth contours in meters.

Fairport Harbor is typical of a series of harbors located on the southern coast of the central basin of Lake Erie. The layout of the harbor is shown in figure 6. It is similar in many respects to the harbor at Little Lake, though much larger in size to accommodate the lake freighters. Terminal facilities are located along the banks of the dredged Grand River. The mouth of the river is protected from prevailing westerly waves by the west breakwater. Protection from infrequent northeast storms is afforded by the long east breakwater, which is aligned parallel with the shoreline. The east end of the outer harbor is widely exposed to waves and currents. Sediment transport in this part of Lake Erie is predominately eastward. Much of this material has been trapped west of the harbor, creating a wide sand beach.

Two distinct patterns of circulation were observed at Fairport during periods of strong, eastward nearshore currents. The current pattern observed during high-speed west or west-southwest

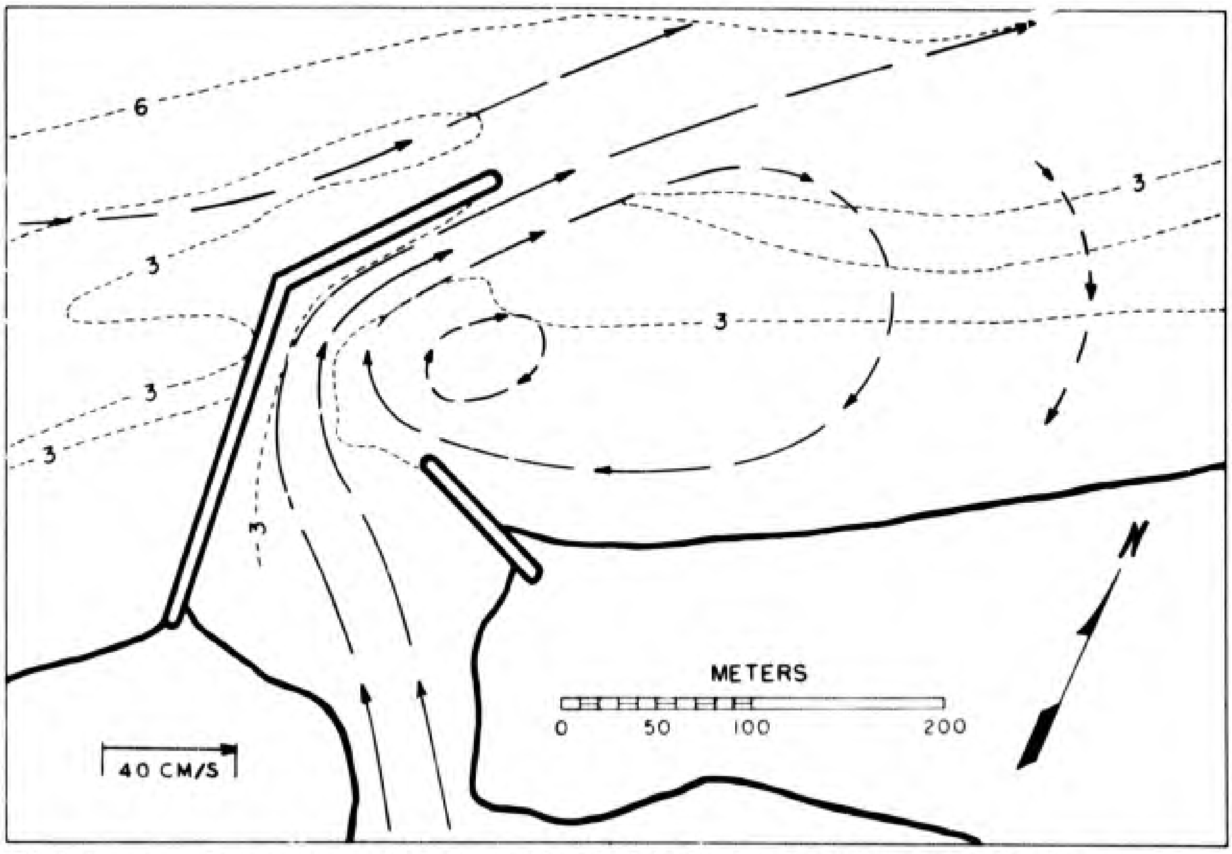

Figure 5. Current pattern near entrance to Little Lake Harbor during strong westerly wind with outflow from harbor.

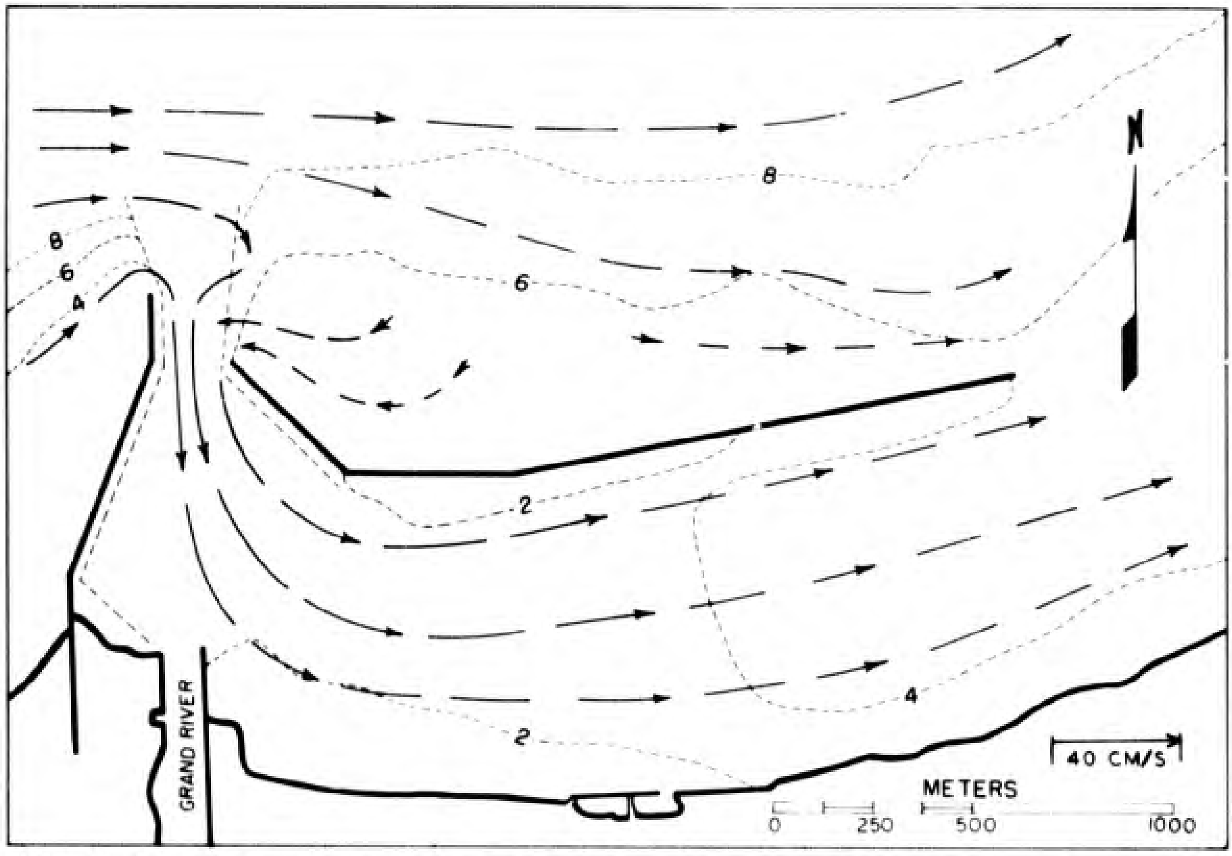

Figure 6. Current pattern at Fairport Harbor during high-speed west or west-southwest wind.

wind is also shown in figure 6. A relatively long wind fetch over the shallow water in the outer harbor east of the navigation channel results in the development of an eastward drift current flowing through the outer harbor. Continuity is achieved by inflow through the navigation entrance. The current pattern observed during conditions of strong, eastward-flowing nearshore currents following cessation of high-speed westerly wind is shown in figure 7. A large, clockwise eddy is observed lakeward of the east breakwater. In the outer harbor the currents are westward with outflow through the navigation entrance. The clockwise circulation is similar to that observed at Little Lake, and is driven by the eastward flow along the shore of Lake Erie. During conditions of north or northeast wind, both westward-flowing nearshore currents and intense, westward flow through the outer harbor were observed at Fairport. Currents in the harbor caused directly by water-level fluctuations of Lake Erie at

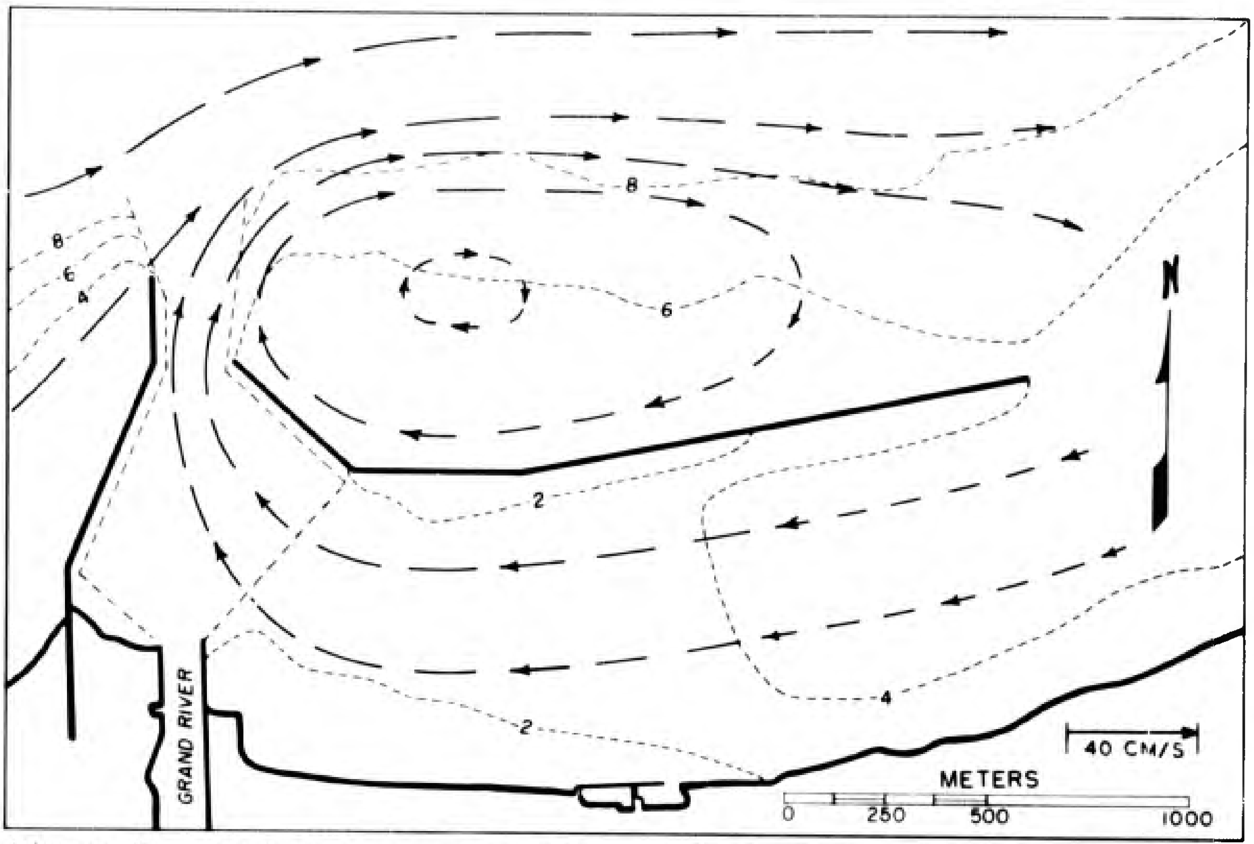

Figure 7. Current pattern at Fairport Harbor with eastward-flowing nearshore currents after cessation of high-speed wind.

Fairport are of small magnitude. This results from the nearly unrestricted communication of the outer harbor with Lake Erie and from the absence of large-amplitude, short-period oscillations of water level like those occurring at Little Lake. The main effect of Lake Erie water-level oscillations in producing currents in Fairport Harbor is associated with longitudinal seiches of the lake, and the standing-wave currents flowing parallel to shore which the seiches generate. It is interesting to note that the wind-driven coastal currents measured in Lake Erie decayed much more rapidly after cessation of high-speed wind than those observed in Lake Superior. At Fairport, these currents decayed to negligible speeds within three days following periods of high-energy input. This is probably due to the shallowness of Lake Erie and the rapid dissipation of the water-current energy by bottom friction. In contrast to the adverse effect of the eddy driven by nearshore currents at Little Lake Harbor, a similar circulation in vicinity of Fairport Harbor produces no undesirable effects but is beneficial in promoting rapid flushing of the outer harbor.

The layout of Calumet Harbor, located in the southern part of Lake Michigan, is shown in figure 8. The breakwaters shelter the mouth of the Calumet River from north and northeast waves, and provide refuge during periods of critical waves. Currents measured at Calumet during conditions of high-speed north or northeast wind are also shown in figure 8. Strong nearshore currents flowing southeastward in Lake Michigan control the circulation in the harbor. An intense current flows through the breakwater gap and across the harbor. Currents measured during west, south, or east wind are shown in figure 9. The circulation in the harbor is controlled by clockwise flow in the southwest part of Lake Michigan. Northwest-flowing nearshore currents penetrate only a short distance into the harbor. All such flow turns northward and joins the main current lakeward of the breakwater. Because of the unrestricted communication of Calumet Harbor with Lake Michigan, currents caused by fluctuations of water level are slight during normal conditions. However, the low-speed reversing currents through the breakwater gap caused by these fluctuations are the principle flushing mechanism for the nearly stagnant water in the north end of the harbor. Water discharged from the Calumet River (principally by reversing flows due to the fluctuations of water level) is therefore confined to the north end of the harbor and slowly exchanged through the breakwater gap. The boundary between this water and that flowing along the shore of Lake Michigan is often defined by a distinct color change.

The currents flowing parallel to the breakwater and through the breakwater gap during north or northeast storms are hazardous to navigation. Adverse currents through this gap also result from occasional, large-amplitude surges along the Chicago waterfront which may occur during conditions of local fair weather. To avoid this hazard, ships enter the harbor through an entrance channel dredged around the south end of the breakwater. Proposals to close this gap have been considered periodically during the past thrity years. However, this closure would significantly reduce the harbor flushing rate.

DISCUSSION

Current patterns measured at three harbors in which the circulation is largely controlled by currents flowing along the shores of the Great Lakes have been presented. The current patterns are determined by the configuration of the breakwaters and the strength and direction of coastal flow. Nearly unrestricted communication of the outer harbors at Fairport and Calumet with the open lake causes currents driven by fluctuations of water level to be of negligible speeds at these sites during normal conditions. The pattern of flow of strong reversing currents through the restricted entrance to Little Lake is shaped by a clockwise eddy in the lee of the west breakwater driven by nearshore currents in Lake Superior. From these studies, it appears certain that with adequate information on the nearshore-current and long-wave climates, the pattern of circulation can be forecast before construction of new or modification of existing coastal structures. This is of special importance on the Great Lakes not only to avoid adverse effects of the currents, but also to provide for adequate harbor flushing. The absence of significant astronomical tides in the lakes and the

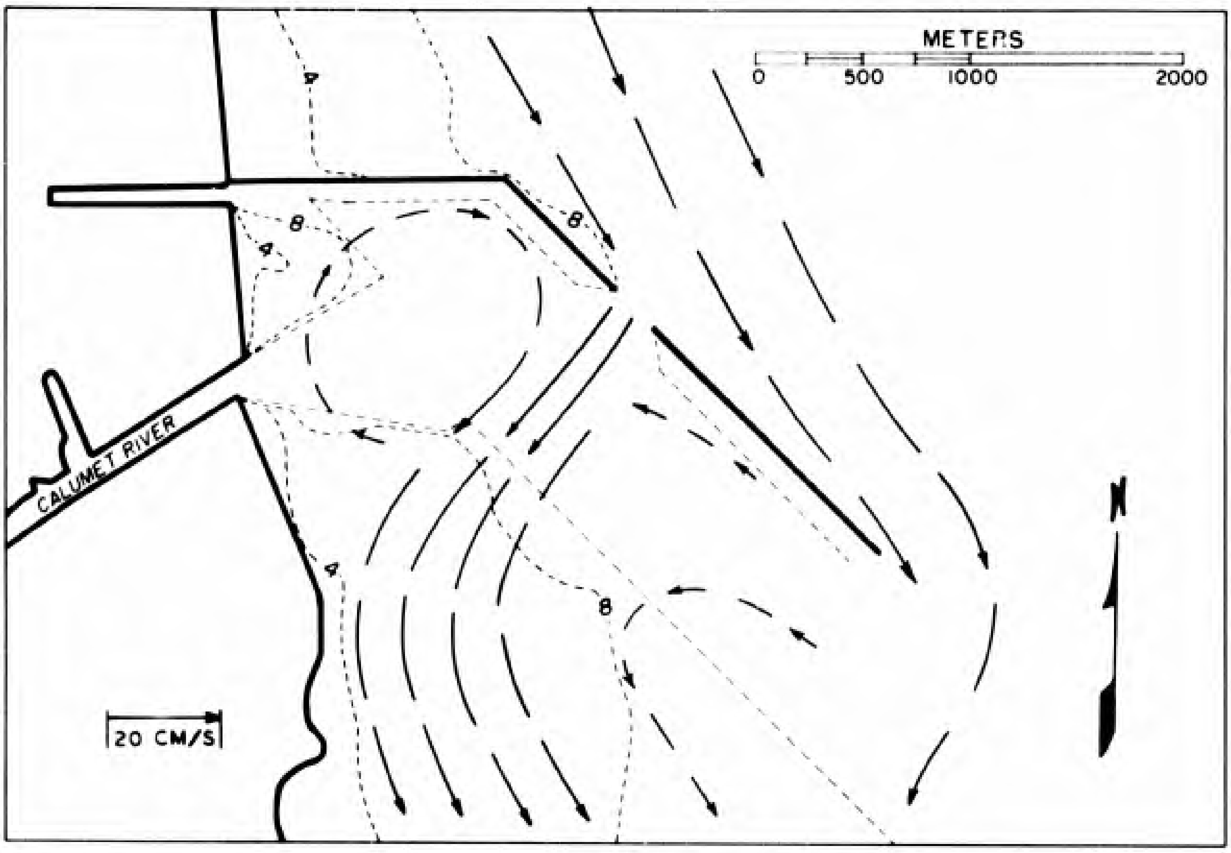

Figure 8. Current pattern at Calumet Harbor during high-speed north or northeast wind.

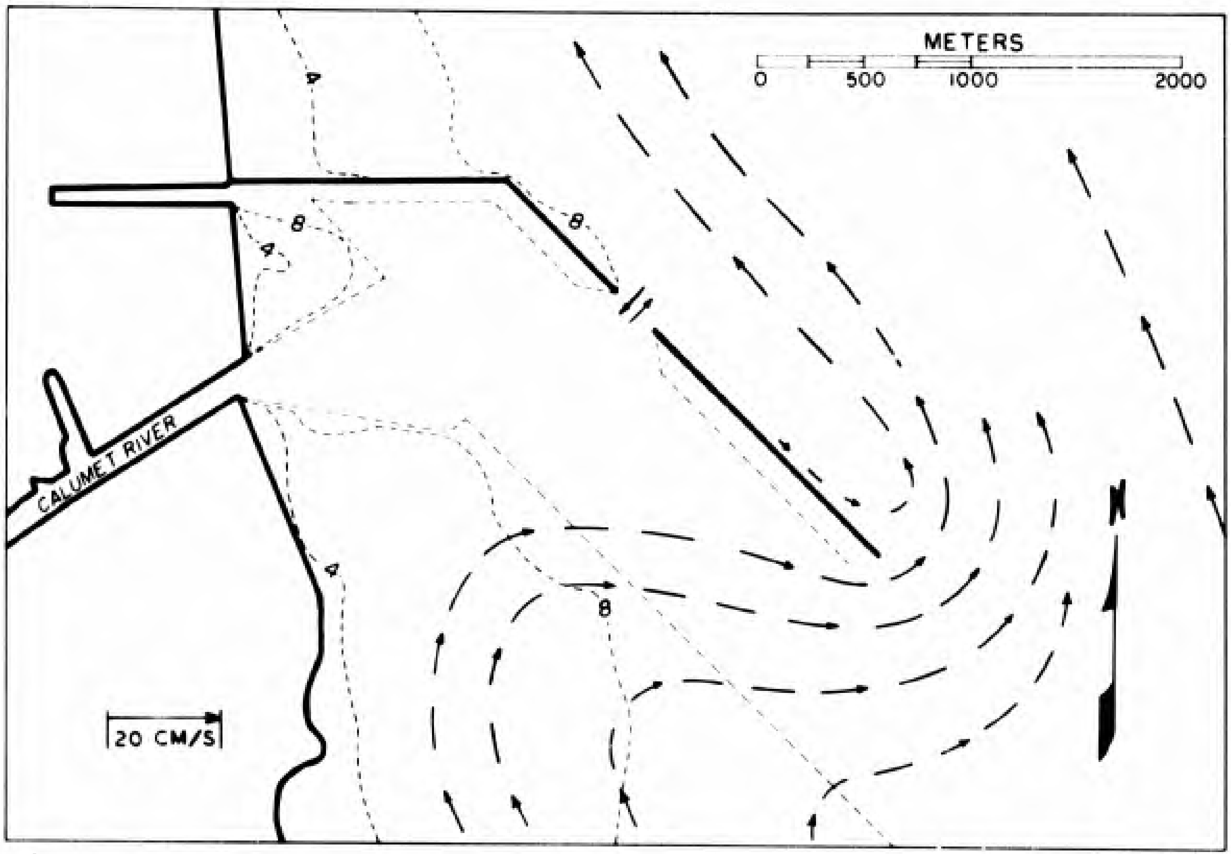

Figure 9. Current pattern at Calumet Harbor during prevailing wind and nearshore current conditions.

absence of other large-amplitude oscillations of water level makes interaction of the harbor with currents along the shore of the lake the most effective means of harbor flushing at many locations.

The nearshore currents in the lakes are driven chiefly by the shear stress of the wind, and both speed and direction of the currents are closely correlated with periods of high-energy input. The relation between the coastal currents and currents in the open lake needs to be investigated. Numerous investigators have shown that the lake currents are generated principally by the wind, although the current patterns reported are more complex than the conformal currents usually envisaged in lakes. The nearshore currents observed at the harbors investigated are certainly related to a wind-driven circulation of the entire lake basin. The results of the current studies in the vicinity of Great Lakes coastal structures are felt to be applicable to similar structures on the ocean coasts. The lakes provide the opportunity to describe those currents caused by wind, and uncomplicated by tidal flow along the shore.

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