SHORE PROPERTY STUDIES &

TIDES, CURRENTS & WATER LEVELS

CENTRAL REGION

"A STUDY OF THE LAKE HURON STORM SURGE OF AUGUST 22, 1971"

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TABLE OF CONTENTS

ABSTRACT

This study is undertaken in an attempt to update storm stage damage information and to determine the temporal and spatial scales of the meteorological fluctuations in water level, as a consequence of the storm surge on Lake Huron on August 22, 1971.

Stage damage to the Sarnia city and township nine mile shoreline resulted from intense erosion and not from inundation - on the order of 60,000 cu yds of sandy material were eroded and only 25,000 cu yds were re-deposited onshore.

The generation of a squall line superimposed on a cyclonic circulation induced basically three dominant spatial and temporal scales in the water level fluctuations. The breaking of wind generated surface waves - on the order of 5 to 10 seconds and 5 to 10 feet - was mainly responsible in conjunction with the rise in water level for the erosive scouring of the onshore beach. The solitary wave generated by the motion of the squall line - on the order of 5 to 10 minutes and 5 to 10 miles - proceeded down the lake, registering significantly different amplitudes and periods at spatially diverse stations. The cyclonic wind set-up - on the order of 5 to 10 hours and 50 to 100 miles - showed similar changes in magnitude, due to the preponderance of a normal boundary, but demonstrated a greater temporal coherence not indicated in the squall surge. These three phenomena, along with resurgence and reflected surge waves, were all observed to be inherent scales of the storm surge process.

INTRODUCTION

On the evening of August 22, 1971 a low pressure system passed from west to east over the southern portion of Lake Huron, bringing with it localized squall conditions, superimposed upon fairly steady northerly winds blowing over the entire length of the lake. Preceeding the general cyclonic circulation a narrow but intense squall line, initiated by the southward advancing cold front on the western flank of the low and with winds peaking to 70 mph, moved rapidly down the Lake and onto the City of Sarnia and the Sarnia Township shoreline, perpetrating severe beach and inland damage (Clippings 1 and 2). Fortuitously, the authors were able to observe, a day after the storm, the horizontal extent and severity of the damage, as well as to obtain quantitative measurements of the erosion and water level fluctuations.

The motivation for undertaking such an in-depth study, as is presented here, is twofold. Updated storm stage damage computations are required on a continuing basis as input to the Canadian Methodology used by the I.G.L.L.B. to make a quantitative evaluation of the effects of lake level regulation on the shore properties of the Great Lakes. Analysis of the temporal and spatial scales of water level fluctuations caused by meteorological phenomena are required to ascertain the optimum geographical spacing and time sampling, for the prediction of hydrographic sounding reductions.

The former analysis is required in support of Central Region's newly formed Shore Property Studies unit, while the latter is required by the recently rejuvenated Tides, Currents and Water Levels unit. Because of significant scientific overlap, especially of causal effects, it was deemed appropriate to undertake a joint study by the two units.

In the ensuing dissertation qualitative analyses of the erosion observations, the meteorological wind and barometric data, and water level variations were undertaken. Quantitative computations were performed for the rates of erosion and accretion, as well as for the dominant periodicities and couplings in the wind and water level records. Finally the representativeness of the time series records was examined, and theoretical explanations of the onshore erosion and storm surge dynamics were advanced.

STAGE DAMAGE OBSERVATIONS

The major stage damage occurred when seventy mile per hour winds, eminating from the squall line, induced a two foot water level set-up along a nine-mile stretch of Lake Huron shoreline at Sarnia, Ontario. The severity of the wind damage can be observed in Plate 1, where numerous large oaks were uprooted over the narrow swath cut by the squall. Flooding of beaches and marine structures was also evident but the total inundation damage was light as the water soon receeded leaving the majority of the structures intact. However, as can be observed in Plate 2, some marine craft suffered damage, especially if the moorings snapped during the storm. By far the greatest stage damage resulted, not from inundation, due to the relatively high relief of the shoreline, but rather from onshore erosion. In some segments of the storm reach, upwards of ten feet of shoreline bank were lost - a very costly perdition considering the high price of lakefront residential property.

Photographs taken the day after the storm provided a qualitative "picture" of the extent of the onshore erosion damage (Plates 3 to 10). In Plate 3 it can be seen, by the exposure of the unpainted portion of the pole, that a half foot layer of sand, churned up by the uprush of the storm waves, has been scoured away during the downrush, leaving a layer of coarser sand and pebbles behind. The extreme penetration, by the storm generated waves, on this fairly wide beach is due to the storm induced two foot rise in water level. The extent of this penetration can be seen in Plate 4 by the exposure of tree roots far inshore and by the formation of a berm onshore - this horizontal deposit of beach material is normally found well offshore. In Plates 5 and 6, it can be observed that an eight foot wide sidewalk has been severely undercut by the erosion of the supporting sandy bluff causing it to collapse. Plate 7 demonstrates the effective design and placement of groynes for the long term accumulation of littoral drift, while Plate 8 illustrates the defficiencies of such systems, especially when a sloping onshore beach cannot be established. Plate 9 is an example of the slower rate of erosion of the more coehesive clay at the toe of the bluff, along with the more rapid scouring of the upper layer of sandy loam. Again the rise in water level facilitated the attack of wind generated surface waves in penetrating higher on the bluff. In plate 10 the effects of the most severe localized erosion can be seen. The concrete foundations for the boathouse have been completely undercut, tree roots have been exposed, causing trees to topple, and ten feet of sandy bank have been lost to erosion.

In order to simplify the analysis of erosion damage the nine mile stretch of shoreline, from the mouth of the St. Clair River to the Bright's Grove area, was divided into seven reaches (A - G), each with somewhat differing beach characteristics (Plans 1 to 9). Reach A presents a gently sloping offshore and onshore beach, typical of pre-storm equilibrium erosion conditions. Reach B, in contrast, has a rapidly sloping foreshore (as do the remaining seven reaches) and a steep narrow onshore beach. The latter condition, particularly susceptible to onshore erosion and longshore littoral drift, explains the high density of groynes in the area. In the eastern sector of the reach, a pronounced littoral drift from the east is indicated by the accumulation of beach material on the eastern side of the groynes (Plan 3). Reach C is a stretch of very wide and gently sloping beach, built up during long periods of normal wave action. During the storm, it provided enough horizontal extent for the wave to break, thus dissipating its erosive energy before excessive penetration could be achieved. The remaining reaches D, E, F and G embody the characteristics of the previously mentioned areas and will not be discussed in detail here - generally, the width of the beach narrows and the height of the bluff increases, from west to east. However, it should be pointed out that on reach G (Plan 9), because of the narrow beach and ten foot high bluff, the surface wave, elevated by the rise in water level, frequently impacted directly on the face of the bluff and dissipated its power in the erosive scouring of the sandy loam material.

STAGE DAMAGE COMPUTATIONS

Eight erosion stations, installed originally by the Lake Huron Task Force of the International Great Lakes Levels Board along the ten mile stretch of Sarnia and Sarnia Township shoreline, were re-levelled by our shore properties unit shortly after the storm (Figure 1). Unfortunately, stations 1 and 2 were rendered invalid when fill was placed on these areas prior to the storm. As a result of a discrepancy in levelling, station 5 also could not be used in the analysis. Levelling was performed using standard survey techniques with an accuracy of ± .1 ft. in the vertical and ± .5 ft. in the horizontal.. Profiles of the five operative erosion stations, along with the 1969 profiles prepared by the Lake Huron Task Force were plotted to scale in Figures 1 and 2. The delineation, High Water Level (H.W.L.) represents the two foot, storm induced rise in water level over the mean level (M.W.L.) for that day. Even though the 1969 profiles were measured two years previous, an in situ evaluation a month before the storm indicated that little conspicuous alteration of the profile had occurred over this period. Thus it is not unrealistic to assume that the 1969 profile is representative of the pre-storm condition, at least within the accuracies of the post-storm measurements.

The areas enclosed by the 1969 to 1971 profiles were measured by planimetry (Table 1, column "CU YD/YD"). Reasonable estimates of the volumetric erosion, for the various reaches discussed earlier, were computed by multiplying the above erosion and/or accretion values, per unit width of shoreline, by the appropriate reach length (Table 1, column "CU YD"). Therefore, the total erosion of 59,000 cu yd and accretion of 24,000 cu yd for the storm reach was computed as a summation of the representative erosion station values, each weighted by a length of reach with somewhat similar erosion characteristics.

Erosion station profiles 3, 4 and 6 exhibit almost equivalent erosion and accretion quantities, while profiles 7 and 8 indicate greatly increased erosion but only negligible accretion. The strong variability of these values, especially at stations 6 and 7 which are separated by only 2,000 ft., indicates the localized nature of onshore erosion and deposition. Differing offshore relief and onshore slopes, varying porosity and grain size of the shore material, and diversification of cusps, scarps and berms all contribute to the variability. At station 3 (Figure 1) the rise in water level superimposed on a gently sloping beach enabled a deeper penetration of the breaking waves (witness the high degree of erosion inshore) and at the same time, a normal or non-breaking wave climate over the beach strip (witness the equal degree of deposition on the beach). A similar situation existed at station 6. At station 4 the more steeply sloping beach caused the waves to penetrate and dissipate on the bluff. Similar, but even more severe conditions existed at stations 7 and 8, where the offshore slope was greater and the offshore protection of berms was reduced.

The extreme variability of the erosion and accretion values from station-to-station suggests that a reduced spacing and increased number of erosion stations would produce a more reliable estimate of the total storm stage damage. On the other hand, the significant change in shoreline as a result of the storm surge, and the lack of appreciable alteration for two previous years would suggest that the present sampling rate is adequate, that is the sampling period need encompass a single storm only. To calculate a rate of erosion, the frequency of occurrence of significant storm surges, as well as the normal wave climatology must be taken into consideration. However, an approximate value can be obtained using total figures from Table 1, and a two year sampling period. For the Sarnia and Sarnia Township shoreline the mean rate of onshore erosion is 30,000 cu yd per year and the mean rate of onshore deposition is 12,000 cu yd per year. The discrepancy between erosion and accretion is due to the fact that a significant amount of the eroded material is deposited offshore, beyond the limits of this study.

METEOROLOGICAL ANALYSIS

In the late afternoon and early evening of August 22, 1971, the centre of a rapidly intensifying low pressure system moved from the west-northwest across the southern portion of Lake Huron at a speed of approximately 50 mph. The cyclonic circulation around the low produced a southward moving cold front on the western flank and a northward moving warm front on the eastern flank. With the centre of the low to the east of the lake, a fairly steady wind out of the north-northeast blew along the longitudinal axis of the lake, with a fetch almost 2/3 the length of the lake and a speed averaging 30 mph. The wind vectors and isobars plotted in Figure 3a indicate very strong geostrophic agreement. Sometime prior to 1800 hours the deceleration of a portion of the rapidly advancing cold front produced a rarefaction wave or pressure jump of limited horizontal dimensions (approximately 20 miles by 5 miles for the most intense portion). This squall line, initiated in the northern sector of the lake, with winds peaking to 70 mph - far in excess of the steady surface wind pattern - sped down the lake from the north-northeast and onto the Sarnia and Sarnia Township shoreline, cutting a ten mile swath inland.

The meteorological data employed in this study are mainly wind speed and direction, and barograph, at one spatial location - Sarnia, supplemented by wind velocity data from the Great Lake's Research Station at Baie du Doré. The locations of the stations are given in Figure 3b. Greater spatial coverage of the meteorological data would be desirable, but additional stations, with sampling more frequent than one hour - a necessity due to the small temporal scale of the squall line - do not exist for the southern portion of the lake. However, as this paper is mainly interested in studying the meteorological effects on water level variations at a boundary normal to the wind axis, the data at Sarnia is more than adquate, at least for a temporal correlation. These overland winds, while not entirely representative on the microscale fluctuations of say, fractions of a minute, due to the difference in surface roughness, nevertheless can be assumed on the larger mesoscale variations, to be indicative of the nearshore over-water winds. The continuous recording wind speed and direction instrumentation, at the Sarnia Airport Weather Office, was inoperative during the storm surge and thus alternate sources of such data had to be investigated. Barographic data was obtainable from this source, however. Ultimately, wind speed and direction time series data were obtained from the Grace Church Station operated under private contract by Ontario Research Foundation. Impeller and vane sensors, mechanically linked to electrical generators, which in turn were electrically connected to strip chart recorders, had a full scale response time of 0.5 and 1.0 minutes, respectively. This electro-mechanical system was used to obtain analog records of wind speed and direction. Anemographic records with continuous hourly integration of wind speed and direction were supplied from Baie du Doré.

At this point the representativeness of the time series data, abstracted from the above analog records, should be examined. In the case of the Grace Church wind speed and direction data, a visual five minute running mean was applied to the analog record, thus filtering out all high frequency processes greater than or equal to .2 cycles/minute. This filtered series was then digitized once every five minutes, thus giving a Nyquist Frequency of .1 cycles/minute.

The Nyquist Frequency is the highest frequency that can be resolved by the analysis, and is also the aliasing frequency, or that frequency about which the high frequency energy spectrum is folded into the low frequency spectrum. With the application of the .2 cycles/minute low-pass filter, the lack of adequate damping of the sensor can be overcome and aliasing need not be considered serious. The major time scale process, that must be resolved in this storm surge analysis, is the one hour period associated with the squall line. Thus, the duration of measurement must be an order of magnitude larger - in this case 26 hours was chosen. Since the barographic data and Baie du Doré wind data are used basically as qualifying information and are not subject to quantitative analysis, these data were plotted as received, without attempting to analyze the sampling characteristics.

In Figure 4 the approach and recession of the low pressure system as measured by the barograph at Sarnia can be observed. However, the most significant feature depicted was the sudden 4.5 mb jump in pressure at approximately 1800 hours, marking the passage of the squall line.

In Figure 5 the integrated hourly values tended to smooth out short period high amplitude fluctuations, thus reducing the impulse-like character of the actual squall passage at 1630 to a step-like form with diminished magnitude and increased temporal scale. It should be noted that the squall line, travelling at approximately 70 mph, took nearly 1½ hours to cover the 100 miles from Baie du Doré to Sarnia. This would explain the time shift in the occurrence of the squall in the graph of Figures 5 and 6. The onset of the relatively steady wind, however, occurred almost simultaneously at both the Grace Church and Baie du Doré meteorological stations, verifying the much larger spatial scale of this phenomenon.

In Figure 6 the passage of the low pressure system can be readily observed, as the wind, initially out of the south-southwest at 10 mph, starts to diminish at 1700 hours, decreasing to a negligible amplitude of 3 mph at 1900 hours, and then increases again at 2100 hours, reaching a maximum amplitude of 35 mph at 2100 hours, heading out of the north-northeast. This complete 180^{o} reversal in the wind direction would have been effected smoothly except for the generation of the squall line at 1800 hours, which during its passage, caused the winds to shift the 180^{o} suddenly and prematurely. The squall wind speed impulsed to 70 mph in a time scale of 5 minutes, but gradually tapered off to 3 mph in a time scale of just over one hour. Other distinct time scales can be observed in the wind speed time series data. The major short period fluctuations ranged from 10 to 20 minutes while the post-squall steady winds exhibited large period oscillations on the order of 5 to 7 hours. An auto-spectrum of the wind speed and direction data would give better insight into the important periodicities and the energy contained therein.

WATER LEVEL ANALYSIS

The water level data employed in this study are taken from permanently installed float actuated gauges operated by the U.S. Lake Survey Centre at Detroit, Michigan and the Water Survey of Canada at Guelph, Ontario. The geographical locations of these gauges are given in Figure 3b. The analog record from the Water Survey gauge at Point Edward contained truncated peaks for the storm surge pulse due to a vertical restriction in the float movement, and consequently had to be replaced by the record at the U.S. Fort Gratiot station. The latter, in any event, was more representative of the open water conditions, as it was located on the coastline of the lake rather than on the banks of the St. Clair River. The spatial coverage afforded by the four water level records was quite adequate, but could have been enhanced by the addition of gauges on the Sarnia beach, to improve the erosion analysis, and at Kettle Point, to improve the detection of storm surge reflections. Even though the spatial separation between the gauges was not small enough to resolve the solitary wave produced by the squall line, excluding the Lakeport data, it was more than adequate for the evaluation of spatial coherence. The float actuated gauges, installed in stilling wells designed to dampen out the short period surface wave and ship's wake, demonstrated a response time of approximately five minutes. Thus the water level data, digitized at a five minute interval, would not incur any aliasing difficulties (the Nyquist frequency in this case is .1 cycle/minute).

In Figure 7 the water level records were plotted for the three stations, Harbour Beach, Goderich and Fort Gratiot on the same time scale as the wind data at Sarnia. The southward progression of the squall line can be observed in the water level records by the onset of larger amplitude oscillations at approximately 1630 for Harbour Beach, 1645 for Goderich and 1800 hours for Fort Gratiot. At the northern two stations the amplitude and period of the oscillations were significantly less than at the southern station, due to a combination of factors. Neither station was located at a normal boundary where piling up of water could occur. In addition, as a result of the narrow horizontal extent of the intense portion of the squall line (approximately 20 miles) the waters on the two shores of the lake, fifty miles apart, did not receive the full impact of squall winds. At both these stations the passage of the squall line induced high frequency oscillations in the water level with dominant periods of 20 to 30 minutes. Since the wind diminishes significantly for about one hour after passage of the squall line, the observed fluctuations must be either free oscillations (though their periods are too short for the excitation of all but the very high mode seiche oscillations), or the progression of a train of slowly moving long waves generated somewhat further north by the squall line. The onset of the steady wind appears to have dampened these high frequency oscillations as well as inducing a small magnitude water level set-up that can be correlated to the large scale wind field at Sarnia. Little distinct evidence of a reflected storm surge wave can be observed at the Goderich station, as the high frequency fluctuations tend to mask this phenomenon. Cross-spectra of the Goderich and Fort Gratiot stations would give a better indication of the existence of such a wave.

At the Fort Gratiot station the wind and water level records appear to be strongly correlated. The impulse rise in wind speed induces a corresponding, but more gradual rise in water level and one that is sustained longer due to the increased inertia of the water medium (10^3 greater density). During the lull in wind forcing, between 1900 and 2100 hours, two resurgence waves, the first with a period of 35 minutes and the second with a period of 55 minutes can be observed. Similar resurgence oscillations can be seen further on in the record but are superimposed on the mean wind set-up and thus appear to be somewhat distorted. The extreme water level change at the southern station is due to, both the effect of a normal boundary, and the effect of a reduction in offshore bathymetry. A simple regression formula, as proposed by Platzman (1963), could be formulated using the data in Figures 6 and 7, to give an operational method of relating set-up to the square of effective wind speed.

In Figure 8 the water level data at Lakeport and Fort Gratiot were plotted on an expanded time scale in an attempt to ascertain why the storm surge, and for that matter, the entire large scale wind set-up was only negligibly repor-duced in the Lakeport record. From geophysical considerations it can be deduced that the passage of the intense portion of the squall line over the Lakeport area brought with it a solitary storm surge wave that bowed out due to a change in bathymetry, but was not recorded on the Lakeport gauge within the period of record. The salient explanation might be that the recording instrumentation was malfunctioning, as the record terminated abruptly at 2215 - however, this defficiency can be attributed to the general electrical failure in the area following the passage of the storm squall. An alternate interpretation is that the water level sensor dampened the storm surge fluctuations due to significant fouling of the water intake port in the stilling well - this defficiency illuminates the need for additional information on the effect of port size variation on the response time of water level gauges. In Platzman's numerical model, however, (Platzman 1954) the records at two stations separated by only twenty miles show evidence of negligible reproduction of the storm surge at one and very significant reproduction at the other. Thus to fully resolve the situation additional field data in the Lakeport area are required and/or a hydrodynamical model of the Lake Huron storm surge must be formulated.

THEORETICAL CONSIDERATIONS

In order to fully describe the dynamics of the storm surge process the following vertically integrated, linearized, momentum and continuity equations must be employed:

$$\frac{\partial U}{\partial t} = -gD\frac{\partial \eta}{\partial x} - \frac{1}{\rho}D\frac{\partial P_a}{\partial x} + fV + \tau_x\big|_S - \tau_x\big|_B$$

$$\frac{\partial V}{\partial t} = -gD\frac{\partial \eta}{\partial y} - \frac{1}{\rho}D\frac{\partial P_a}{\partial y} - fU + \tau_y\big|_S - \tau_y\big|_B$$

$$\frac{\partial \eta}{\partial t} = -\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y}$$

(1) (2) (3) (4) (5) (6)

$$U = \int_{-D}^{\eta} u \, dz \qquad V = \int_{-D}^{\eta} v \, dz$$

This hydrodynamical model includes non-steady response (term 1) as is demanded by the temporal variations in the wind and pressure gradient forcing. Also variations in bathymetry are included as depth "D" is a function of x and y. The two-dimensionality of the above system of equations is absolutely necessary as the squall line has a limited horizontal dimension and moves at an angle to the longitudinal axis of the lake. The shoreline configuration, as demonstrated in Platzman (1954), must be brought into the solution of the above equations by setting the horizontal water transports (U and V) to zero at physically realistic lateral boundaries. The gradient of the free surface elevation (term 2) is the only internal pressure included in the formulation as the baroclinic effects are neglected in the vertical integration. The gradient of atmospheric pressure (term 3) is incorporated as a necessary part of the forcing, especially when an extreme hydraulic pressure jump is associated with the squall line movement. Coriolis forces (term 4) are added for completeness in the geophysical formulation but can be neglected in this scale of motion. The surface stress (term 5) formulated in terms of the square of the wind speed is the forcing mechanism responsible for the wind set-up and partially responsible for the squall surge. Finally, the bottom stress (term 6) has been employed even though its effect in the deep water environment of Lake Huron is marginal at most.

To arrive at an enhanced understanding of the dynamic interactions of the storm surge processes on Lake Huron the above system of partial differential equations must be solved, either analytically or numerically, for the response of the free surface to the various pressure and wind forcing regimes. Such a procedure is beyond the scope of this present study and is the subject of a further paper co-authored by T.D. Murty and N.G. Freeman. However, a simplified analysis of the mechanisms involved, can be accomplished by the segregation of the three donimant scales of motion. The first is the very small temporal and spatial scale of the wind generated surface waves - on the order of 5 to 10 seconds and 5 to 10 feet respectively. The second an intermediate scale, with periods on the order of 5 to 10 minutes and lengths on the order of 5 to 10 miles, results from the motion of the squall line. The third and largest scale process, a result of the cyclonic wind set-up, exhibits time scales on the order of 5 to 10 hours and space scales on the order of 50 to 100 miles.

The periods and heights of wind generated surface waves have been found, through empirical analyses, to be a function of wind speed, duration and fetch, with generally an increase in period and height accompanying increases in these three independent parameters. Employing the duration-oriented tables in Weigel (1964), and sectioning off significant wind intervals, the following typical surface wave heights and periods can be obtained;

Wind Speed (mph)	Duration (hrs)	Height (ft)	Period (sec)
7	7	0.6	2.6
25	3	2.5	5.9
15	4	1.9	4.0

From actual ten year wave climatoloy charts for the month of August, Pore et al. (1971), the most frequently occurring surface waves for Lake Huron can be determined;

Frequency of Occurrence	Height (ft)	Period (sec)
24%	1.6	≤ 5
18%	3.3	≤ 5
8%	4.9	≤ 5

Evaluation of both the above sources would suggest that a typical surface wave at the time of storm surge might have a period of 4 seconds and a height of 3 feet. The surface wave characterization, in itself, is not sufficient to understand the erosion dynamics. Actually it is the destructive kinetic energy of the breaking wave that is most responsible for onshore erosion. It has been found, again empirically, that breaking depth is linearly related to the pre-breaking height of the surface wave according to the formula,

$$Db = 1.28 H$$

thus giving a breaking depth of approximately 4 feet for the typical surface wave. The wave uprush resulting from a breaking wave on a continunous impermeable slope may be computed by the following equation, taken from Hunt (1959);

$$Hv = 2.3\ T\ H^{\frac{1}{2}}\ m, \qquad \text{for } m \leq H^{\frac{1}{2}}/T$$

where Hv is the maximum vertical displacement of the breaking wave above mean water level and T, H, m are the period and height of the wave, and the slope of the shore profile, respectively. Choosing a .1 slope, as is indicated by the station 4 profile, the maximum vertical uprush is 1.6 feet or 16 feet along the slope. As can be seen at station 4 this length of uprush, in conjunction with the mean water level, would permit only the leading edge of the near-dissipated breaking wave to contact the toe of the bluff, - basically a non-erosive condition. However, due to the storm induced 2 foot rise in water level the uprush takes place immediately adjacent to the toe of the bluff, thus dissipating most of the kinetic energy of the breaking wave (in the order of 10^3 foot-pounds for the typical wave) on the face of the bluff and effecting considerable erosion of the sandy material.

With the passage of the squall line a rise in water level develops and grows laterally, basically parallel to the line axis. When this wave, which can be modelled as a solitary long wave with phase speed $C = \sqrt{gD}$, advances into deeper water, where the free wave speed exceeds the squall line speed, the central section moves ahead of the squall line. Some typical long wave, phase speeds for the southern portion of Lake Huron are given below;

Dist. from shore (miles)	Depth (feet)	Phase Speed (mph)
10	60	30
25	120	42
45	240	60
70	360	74

As the speed of the squall line is approximately 70 mph, only in the central region of the lake does the middle of the squall surge bow out, thus distorting its shape from a straight to a convex surface. This bowed configuration could possibly account for the lack of detection of any significant storm surge at Lakeport, at least within the period of available record.

In discussing the scales of motion it might be opportune to examine the relative magnitudes of the two forcing terms (3 & 5) in relation to the intermediate and large scales, defined earlier. For the squall scale a very sharp rise in pressure of 4.5 mb (4.5×10^3 Dynes/cm^2) within 5 miles (8×10^5 cm) produces a pressure gradient at the deepest part of the lake (1.1×10^4 cm) of:

$$\left| \frac{1}{\rho} D \frac{\partial P_a}{\partial x} \right| = \frac{1}{1.0} \times 1.1 \times 10^4 \times \frac{4.5 \times 10^3}{8. \times 10^5} = 62 \left\{ \frac{cm^2}{sec^2} \right\}$$

With winds peaking to 70 mph (3.1×10^3 cm/sec) a quadratic wind stress law gives:

$$\tau_x /_s = C \frac{\rho_a}{\rho} V^2 = .003 \frac{x}{1.0} 10^{-3} \times (3.1 \times 10^3)^2 = 29 \left\{ \frac{cm^2}{sec^2} \right\}$$

For the steady wind set-up scale the isobaric pressure gradient which is 4 mb (4.0×10^3 Dynes/cm^2) in 100 miles (1.6×10^7 cm), can be used:

$$\left| \frac{1}{\rho} D \frac{\partial P_a}{\partial x} \right| = \frac{1}{1.0} \times 1.1 \times 10^4 \times \frac{4.0 \times 10^3}{1.6 \times 10^7} = 3 \left\{ \frac{cm^2}{sec^2} \right\}$$

The surface stress for winds averaging 35 mph (1.55×10^3 cm/sec) can be computed as follows:

$$\tau_x /_s = C \frac{\rho_a}{\rho} V^2 = .003 \frac{x}{1.0} 10^{-3} \times (1.5 \times 10^3)^2 = 7 \left\{ \frac{cm^2}{sec^2} \right\}$$

The above calculations indicate that in the intermediate scale process the dominant forcing of the storm surge is the intense pressure gradient, while in the large scale process it is the wind stress that induces the long term set-up. However, in neither case does an order of magnitude separate the two forcing terms and thus both must be considered in the evaluation of the dynamics of the storm surge on Lake Huron.

CONCLUSIONS

The storm surge, over its short duration, caused the loss of almost 60,000 cu yds of sandy loam material due to erosion with only 25,000 cu yds re-deposited onshore. This storm induced erosion data provides validation of the theoretical approach to the stage damage computation in the Canadian Methodology for Great Lakes regulation, compiled by the I.G.L.L.B. It is recommended that, due to the variability along the nine mile stretch of Sarnia city and township shoreline, an increased number of erosion stations should be established, and because of the significant post-storm change in profile, a re-levelling should be carried out immediately following any significant onshore storm condition. Finally it is suggested that an advisory and/or co-ordinating function be established to assist shore property owners in the placement of protective structures, with a view to the overall attenuation of both, along shore littoral drift and storm surge erosion.

As a result of the meteorological storm conditions, various water level phenomena were generated, with a distinct temporal and spatial scale. These included surface waves, solitary waves, cylocnic wind set-up, resurgence waves and reflected waves. In order to resolve these scales in hydrographic sounding reductions, a five minute period should be considered to eliminate aliasing from the surface waves and a spatial scale of not more than 20 miles should be implemented to include major resurgence effects. Further it is recommended that a more quantitative analysis of the meteorological and water level data be undertaken to determine with greater accuracy the dominant (energetic) periodicities and interrelationships. These might include the following statistical analyses:

1) Autospectra of water level data

2) Cross-spectra of water level data

3) Bispectra of water level data

4) Correlation studies between wind and water level data

5) A regression analysis relating the water level rise to the square of the normal wind component

6) A numerical hydrodynamic model of the storm surge for the southern portion of Lake Huron

The recommendations suggested here should not be interpreted as only applying to Sarnia or Lake Huron, but rather they should be extended to the entire Great Lakes Basin.

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Sailboat Feared Lost, Trailer Camp Hard Hit

By SUSAN PADDELL
(Observer Staff Writer)

Fear was expressed today that an unknown number of persons aboard a sailboat may have been victims of the violent storm which cut a devastating swath through the city and to the north Sunday night. The craft was noticed off Bright's Grove as residents ran for cover to escape the roaring wind and rain, and falling trees and branches.

The big blow did widespread property damage, estimated at more than $200,000, flattening and toppling trailers, causing several fires including one at Bright's Grove's Kenwick-on-the-Lake, and disrupting utility services in various areas of the city and district. Crews working through the night and today, strove to complete the massive repair and clean-up operation in the wake of the storm, the second in this area in 13 days.

(see related storm stories and pictures on pages 13, 14 and 20)

Sarnia RCMP detachment said it received a call on a missing sailboat Sunday night, but said the investigation would be done by Sarnia township police, who were unavailable at press time.

The Marine and Rescue boat located in Bright's Grove could be searching for the boat today, but communication with the rescue unit was impossible because most lines to the Grove remain down today.

George Smith, a resident of Bright's Grove, said today he sighted a sailboat "about two miles off - shore just before the storm broke."

He said he took cover during the storm but when he returned to the lake shore after, there was no sign of the boat or anyone that could have been on board.

Coast Guard officials at Port Huron, reported assisting eight sailboats during the storm Sunday night. More than 15 calls for assistance were still waiting, said a spokesman for the squadron.

Most of the boats requiring aid, were beyond the 12 - mile buoy the last buoy in the shipping channel, and the coast guard were using three vessels to tow these boats into calmer waters.

OFFICIALLY IT WASN'T A TORNADO

Jerry Otterson, of the Department of Transport weather office at Sarnia Airport said today Sunday's storm "was definitely not a tornado". Mr. Otterson said "everything points to two funnel clouds touching down momentarily".

He said funnel clouds do not usually touch the ground, but when they do, there is only a small area which shows where the funnels have touched. "Had it been a tornado you would have been able to follow its path on the ground" he said.

INJURED

A 26 - foot cabin cruiser, whose owner was not determined, was forced to beach Sunday night, just east of Bright's Grove, north of Poplar Lane.

Passenger, 17 - year- old William Weaver of Dresden, was in good condition at St. Joseph's hospital today with lacerations to his thigh, that occurred when the boat was turned about twice from the high winds and rough water.

The cruiser's pilot said he was running the vessel "wide open" to try and keep the boat from running ashore - but was not successful.

Neither Sarnia hospitals reported serious injuries as a result of the storm.

Bright's Grove appears have been the target by the storm that knocked out all communication and hydro to the area, felled trees across streets, exploded gas mains and tore cottages from foundations.

AT KENWICK

Oscar Willis, of Forest, owner of Kenwick - on-the-Lake, said today there has been no estimate of damage as yet to the building.

He said a fire broke out, and there was wind and tree damage to the old dancing casino, located on the shore of Lake Huron.

Fire trucks were hampered in reaching the scene by blocked roadways, but succeeded in turning off the source of the gas, which cut off the fire's cause.

A lakefront cottage, owned by Thomas H. Wightman of Port Huron was lifted about six feet off the ground at one edge when a 30 to 40 - foot tall tree was pulled from the ground by the winds that have been estimated to have reached 80 miles per hour.

Damage at the Green Haven Trailer Park, on Highway 7, has yet to be totalled but at least six trailers were demolished, at an average cost of $10,000 each. One $14,000 trailer that had not yet been sold, was flattened from the damaging winds.

(see SAILBOAT page 2)

Storm Damage: $200,000; Fruit Crop Losses High

Mobile Trailer Locations. Cottages Hit Hardest

By Staff Reporters

Damage in Sunday night's violent squall is estimated at around $200,000 by F. G. Fellows, Emergency Measures co - ordinator for Sarnia - Lambton.

He points out that he hasn't had a chance to make a comprehensive assessment, however.

SIX TRAILERS

Destruction of six trailers (at Greenhaven) he put at $60,000 (an additional $50,000 damage was reported by Biltrite): $30,000 for an aircraft; five cars for a total of $20,000 and 200 - 300 trees on private property set at $100 each for a total of $20,000 - $23,000.

"I can't assess the labor," he adds. "Last time Hydro placed the cost at $3,000.

Mr. Fellows said rescue crews went into operation smoothly because they were still "teed up" from the last storm on Aug. 17.

NASTY SQUALL

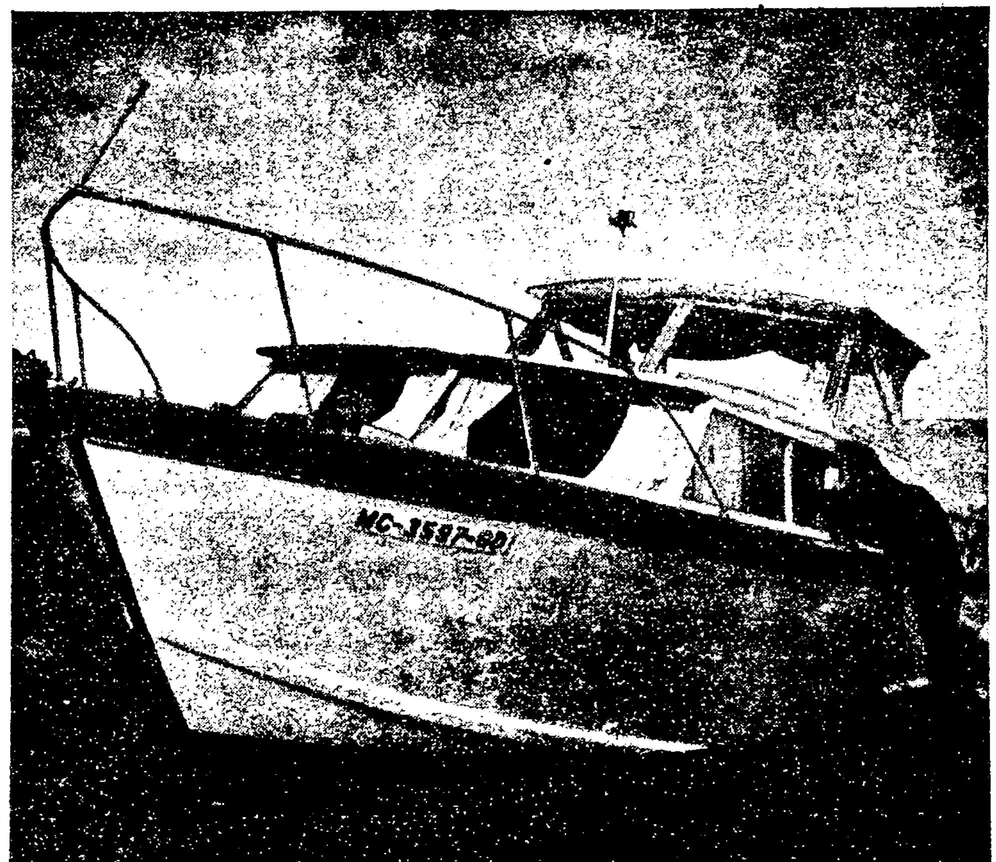
He said the storm, which he categorized as a "violent, nasty squall", was definitely not a disaster.

"Nobody was really hurt and no-one is without a home, although everybody's got problems," he points out.

A survey of hard - hit Bright's Grove showed a lot of trees down, cottages with shingles off and punctured rooves, he added.

Course was typical of such storms, he said.

Lakeshore waas hit heavily between Colborne and Blackwell, with little damage between there and Bright's Grove.



THIS 26-FOOT cabin cruiser lies in the aftermath of high winds, and high waves on the beach east of Bright's Grove. The city's only reported injury was a passenger on this vessel, 17-year-old William Weaver, of Dresden. Mr. Weaver received a lacerated thigh when the boat was spun around twice. According to witnesses at the scene early today, the boat fought the winds and waves, but was cast ashore. Mr. Weaver was rushed to St. Joseph's Hospital, where his condition is reported to be "good". (Observer Staff Photo)

Clipping 2

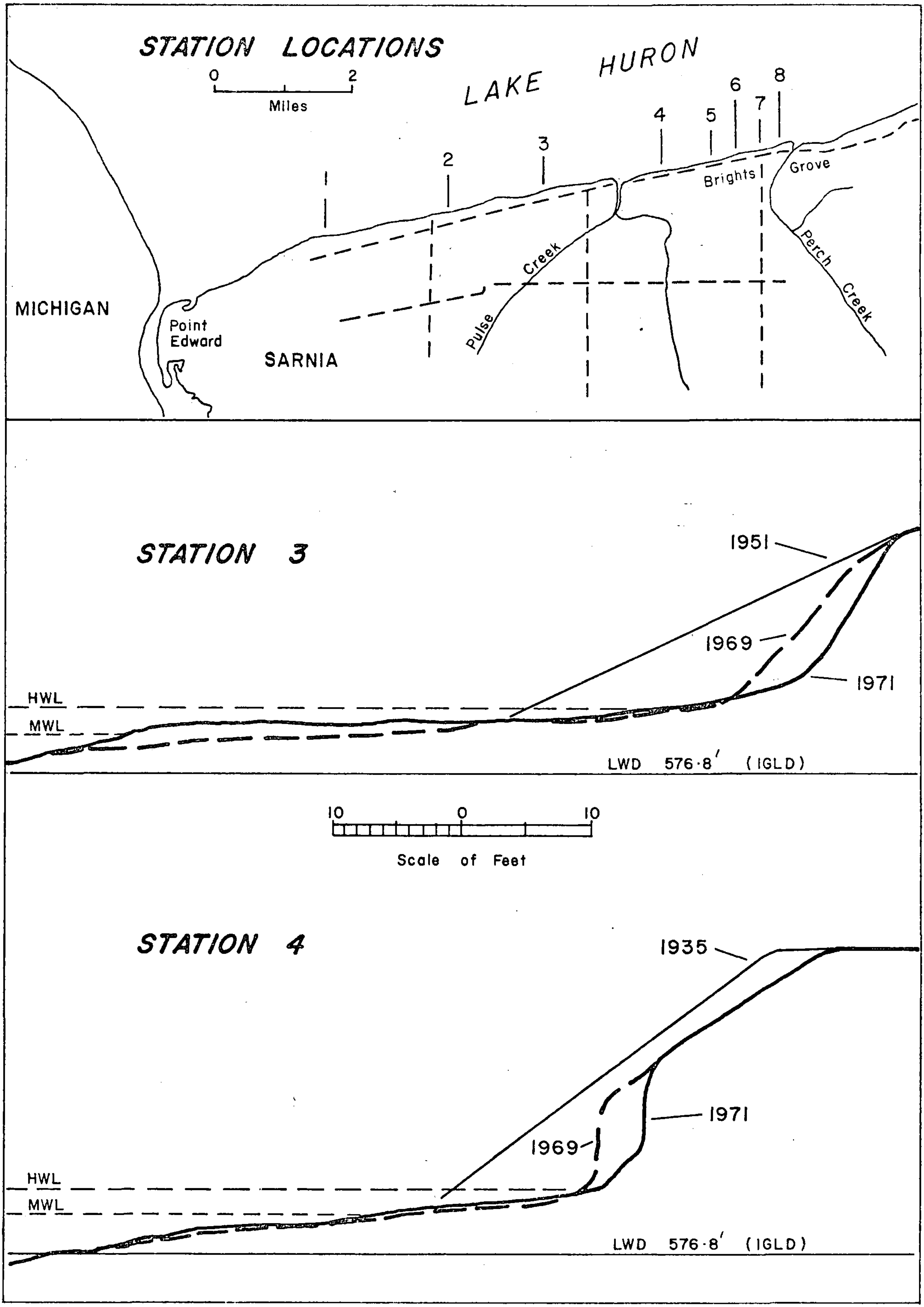


FIGURE 1 EROSION STATION LOCATIONS and PROFILES

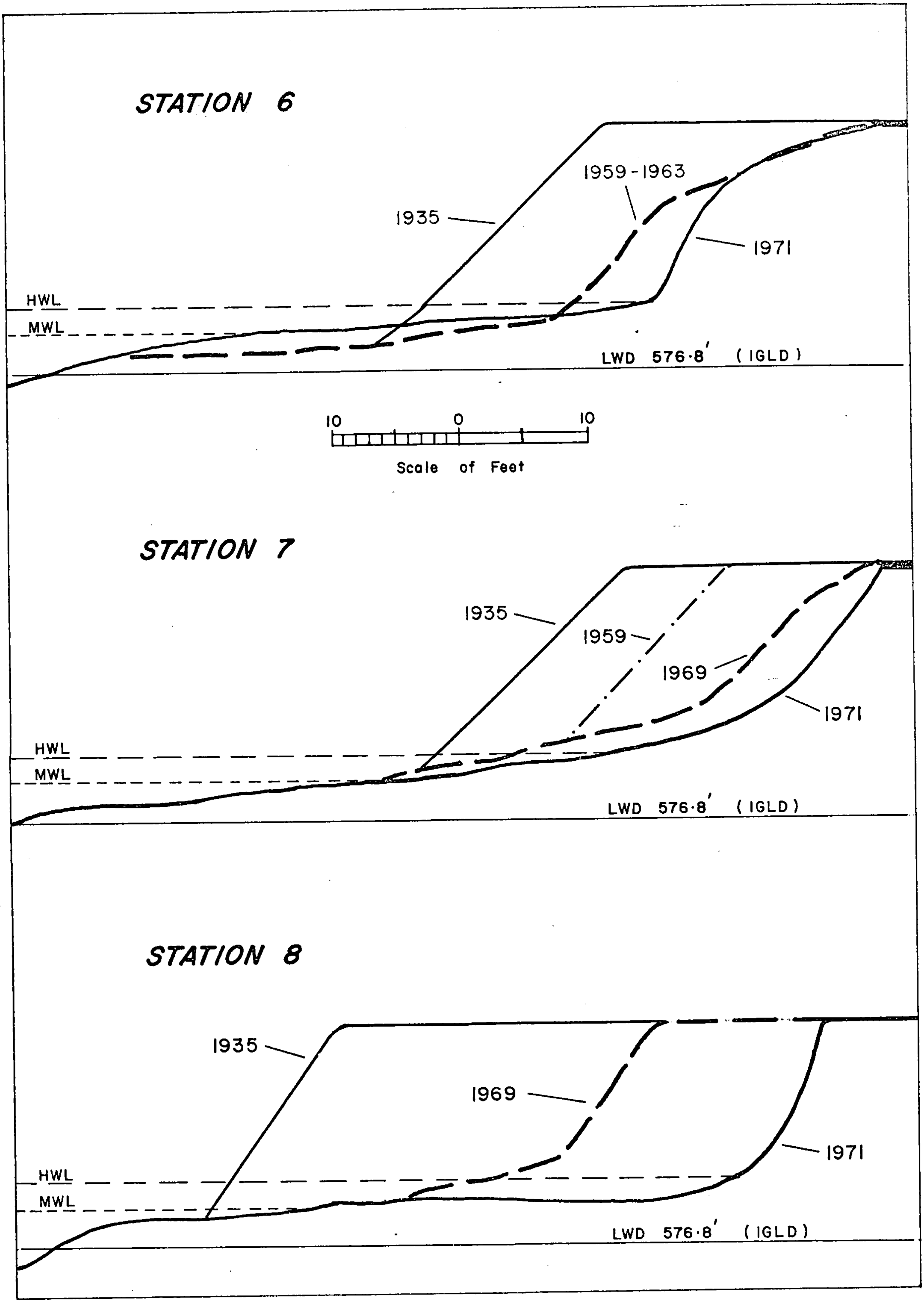


FIGURE 2 EROSION STATION PROFILES

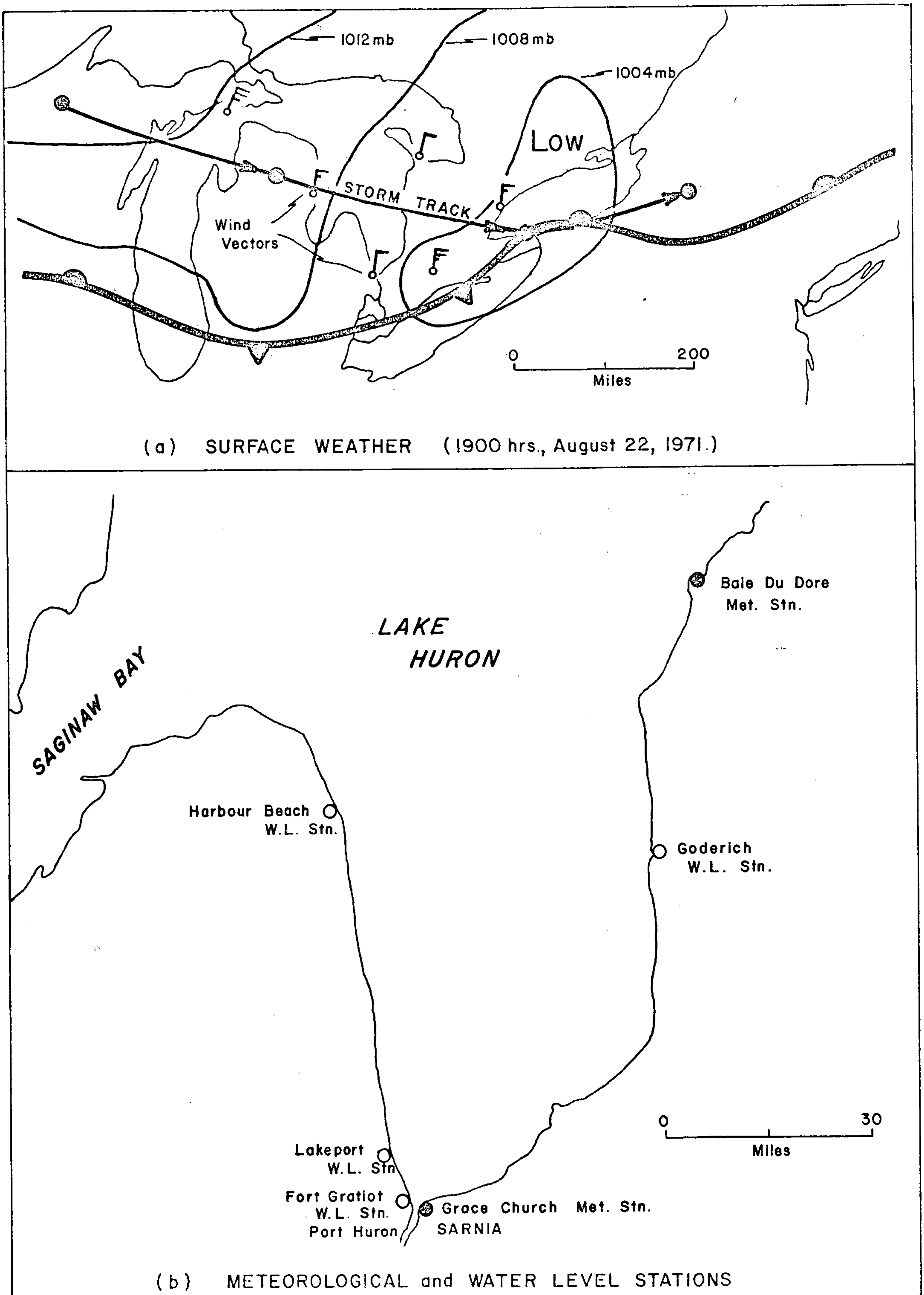

1012 mb
1008 mb
1004 mb
Low
STORM TRACK
Wind
Vectors
0
200
Miles
(a) SURFACE WEATHER (1900 hrs., August 22, 1971.)
LAKE
HURON
SAGINAW BAY
Baie Du Dore
Met. Stn.
Harbour Beach
W.L. Stn.
Goderich
W.L. Stn.
0
30
Miles
Lakeport
W.L. Stn
Fort Gratiot
W.L. Stn.
Port Huron
Grace Church Met. Stn.
SARNIA
(b) METEOROLOGICAL and WATER LEVEL STATIONS

FIGURE 3

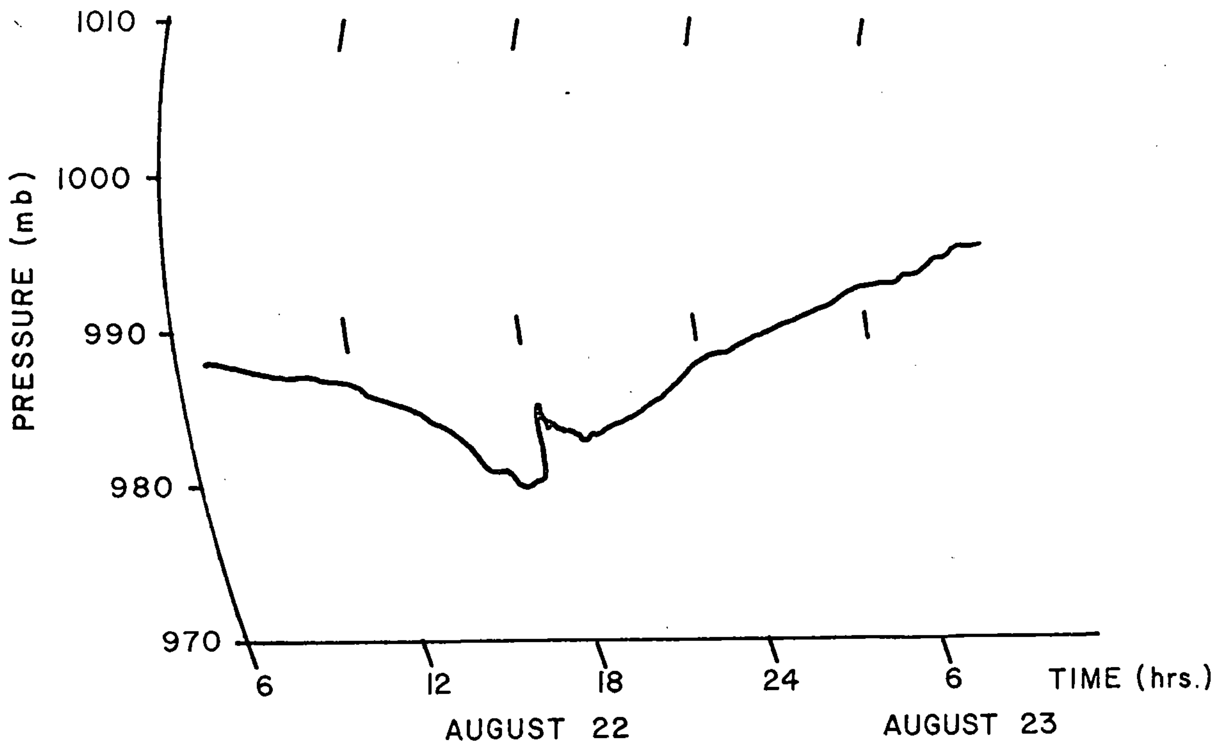


FIGURE 4 BAROMETRIC PRESSURE – SARNIA

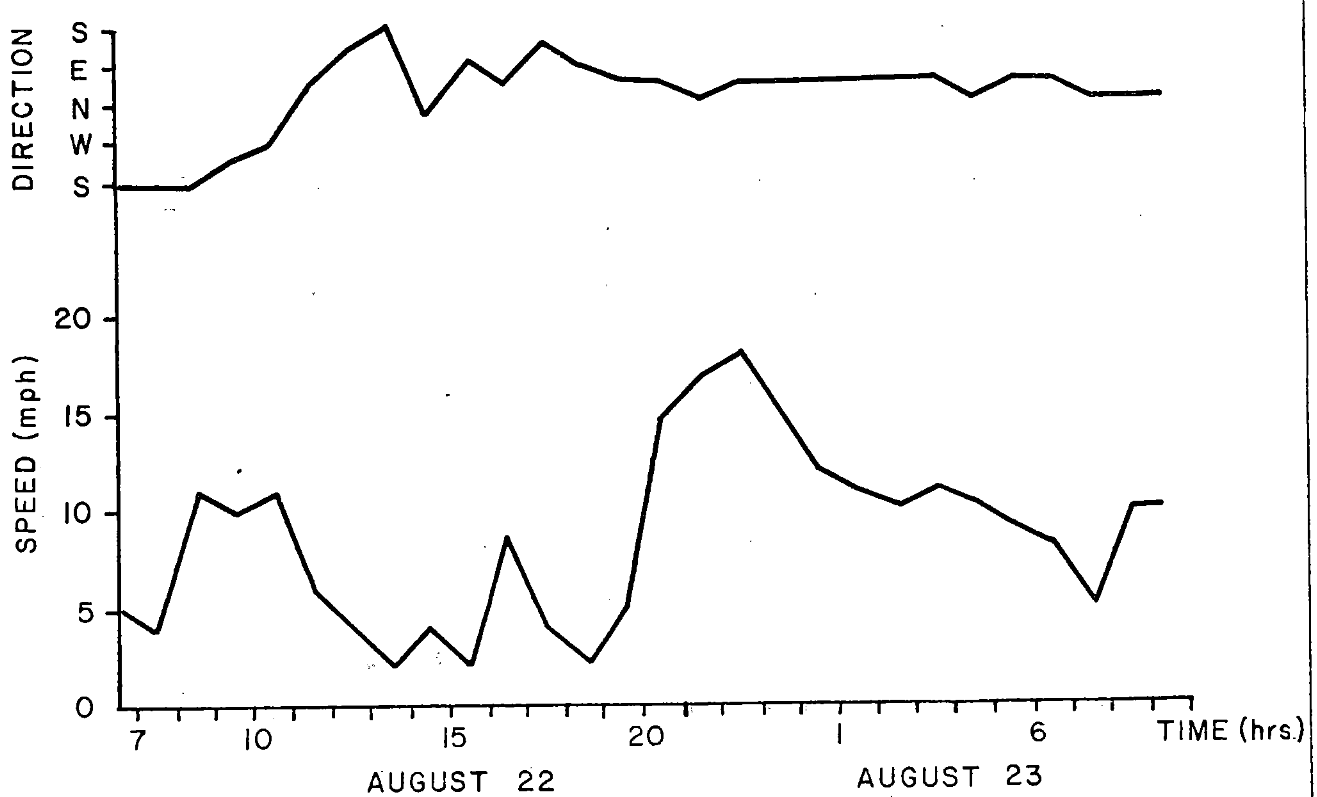


FIGURE 5 WIND VELOCITY – BAIE DU DORE

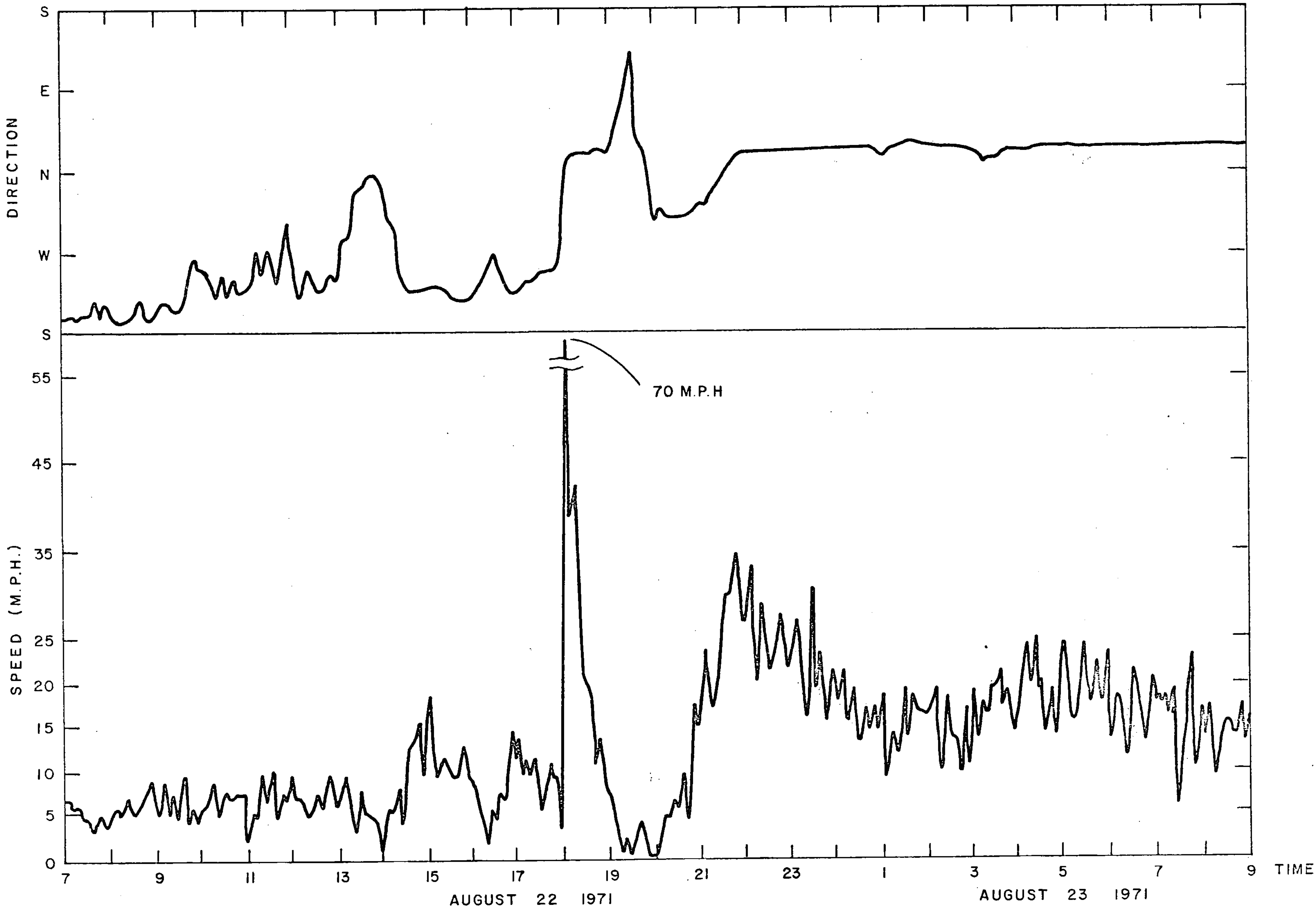


FIGURE 6 WIND VELOCITY — SARNIA (GRACE CHURCH STATION)

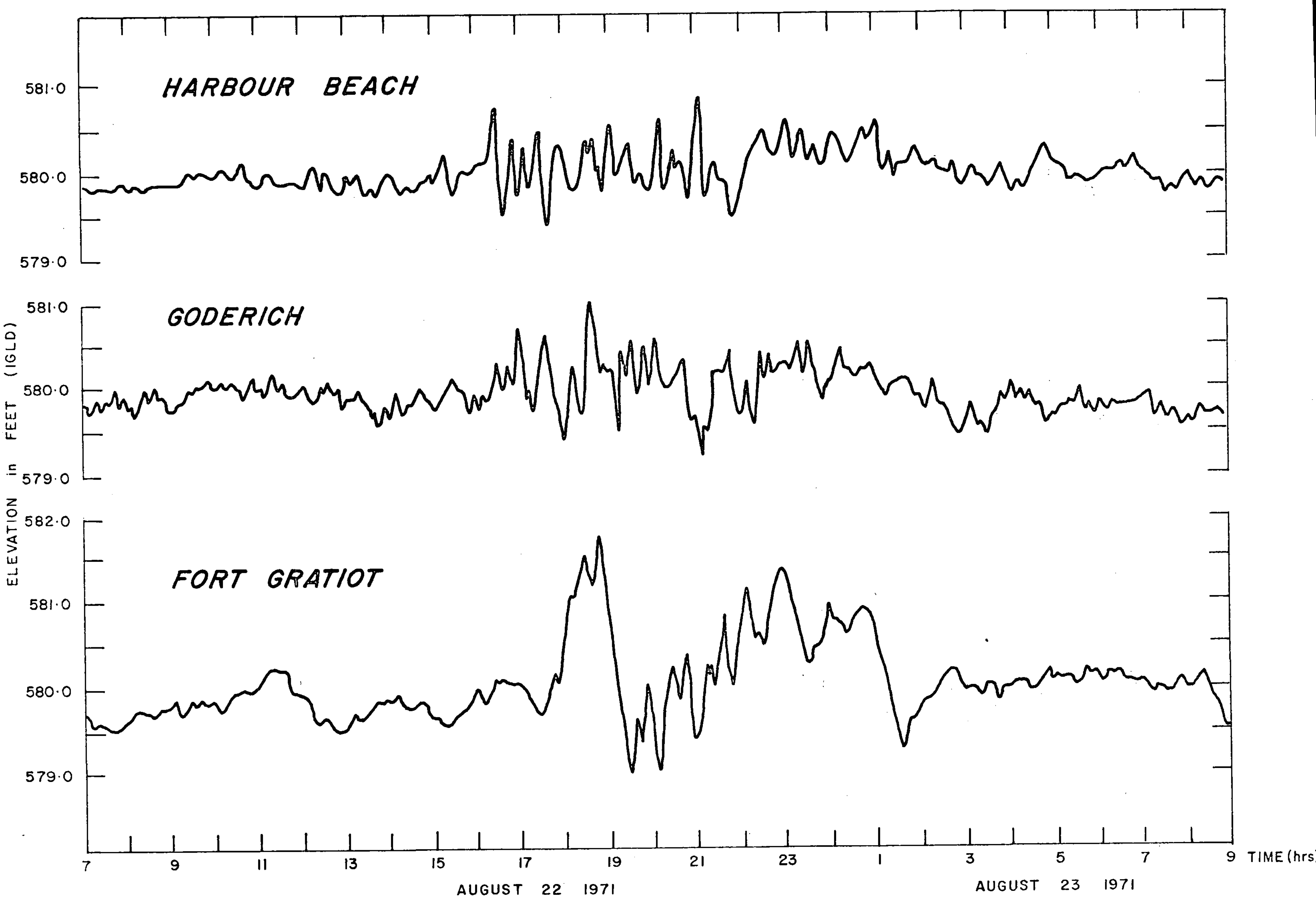


FIGURE 7 WATER LEVELS — — — — LAKE HURON

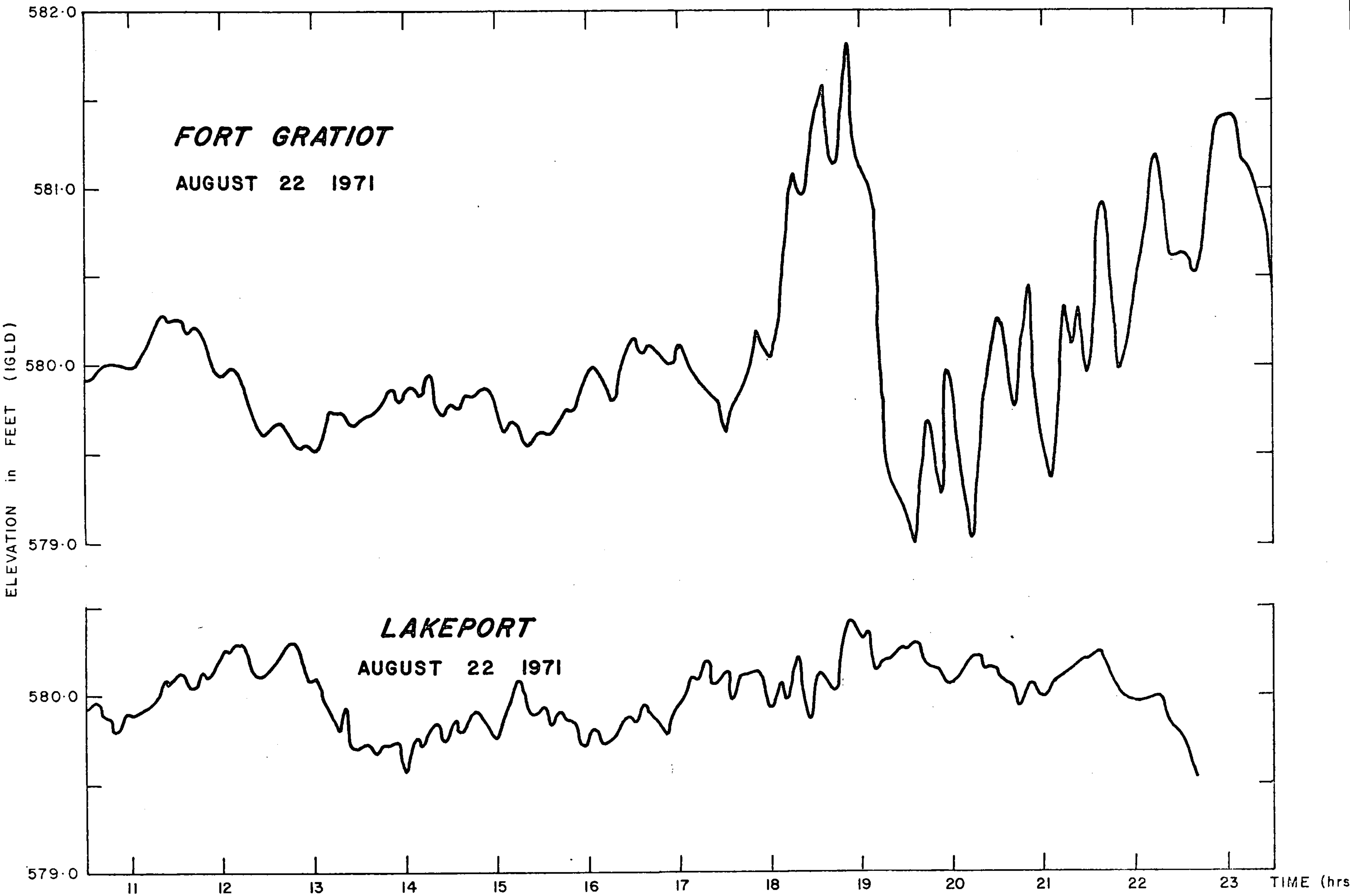


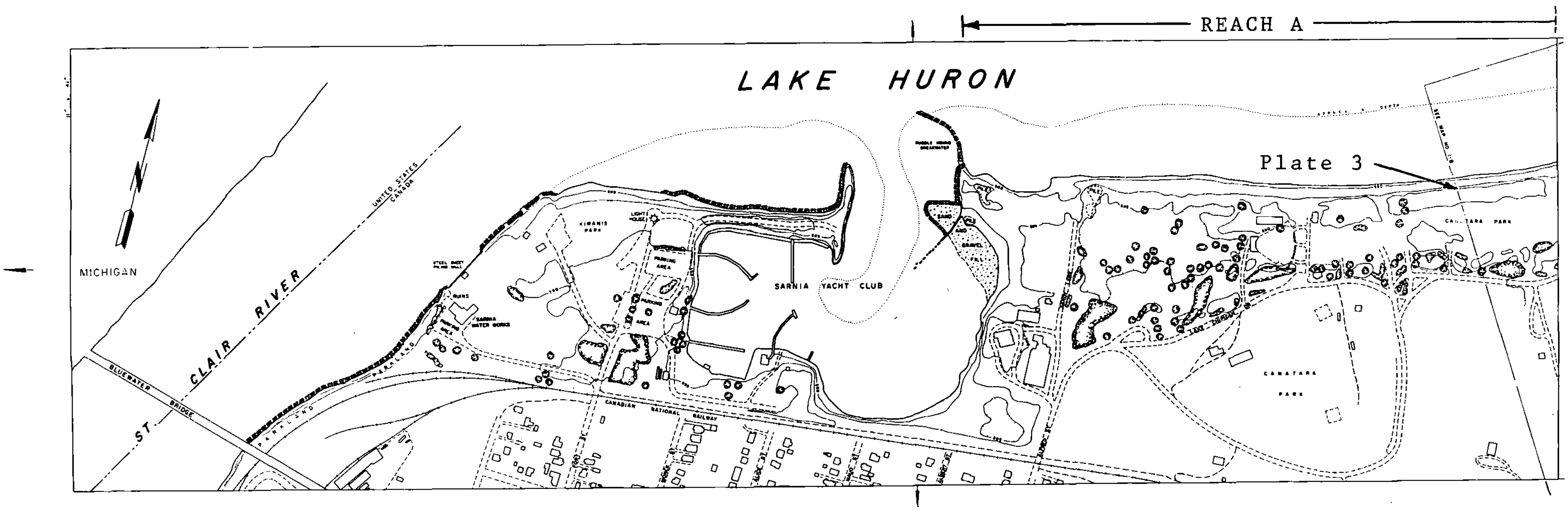
FIGURE 8 WATER LEVELS — — — LAKE HURON

TABLE 1

EROSION & ACCRETION APPROXIMATE VALUES

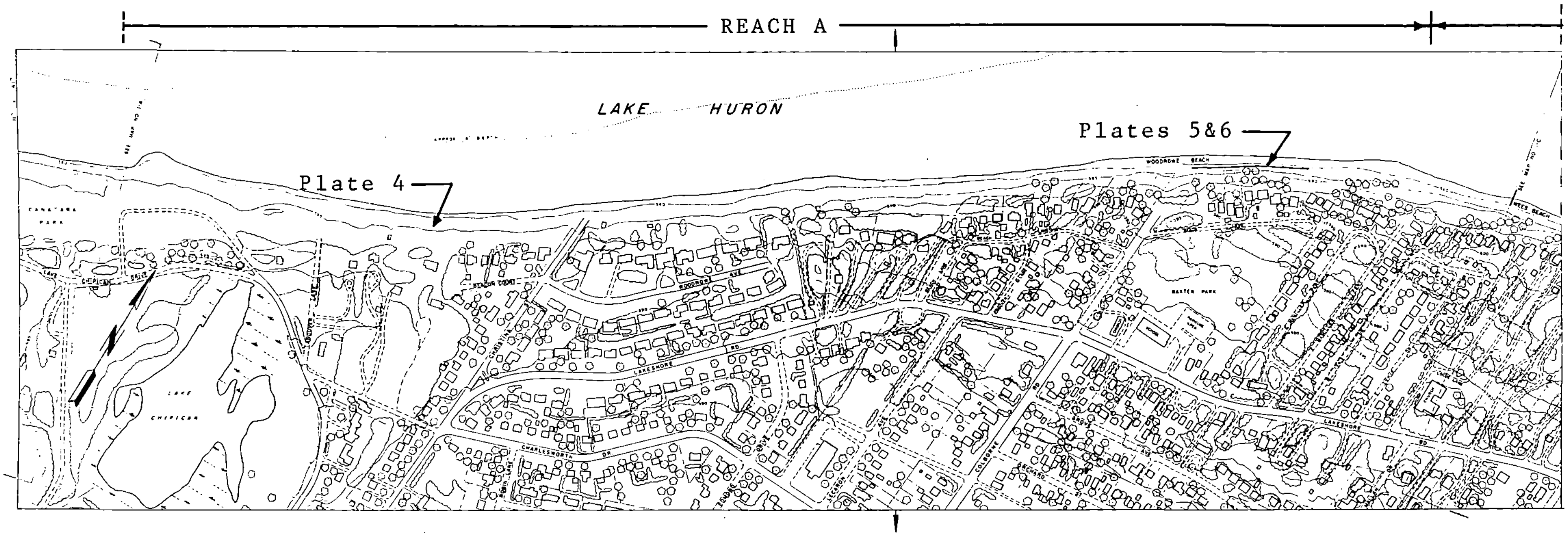
REACH NO.	REACH MILES	EROSION STATION	EROSION CU/YD/YD	EROSION CU/YD	ACCRETION CU/YD/YD	ACCRETION CU/YD	SOIL SAMPLES MECHANICAL ANALYSIS % SAND	% GRAVEL	% CLAY
A	1.60	0	1.1	3,100	0	0	99	1	
B	1.25		1.8[E]	4,000	1.5[E]	3,300	92	6	2
C	.91		0	0	0	0	100		
D	3.15	3	3.5	19,400	3.0	16,600	100		
E	.81	4	1.3	1,800	1.1	1,600			
F	.78	6 7	4.3 10.4	10,200	4.0 0	2,700	81	19	
G	.47	8	25.0	20,700	0	0	100		
TOTAL	8.97			59,200		24,200			

E - ESTIMATED BY COMPARISON WITH REACH D

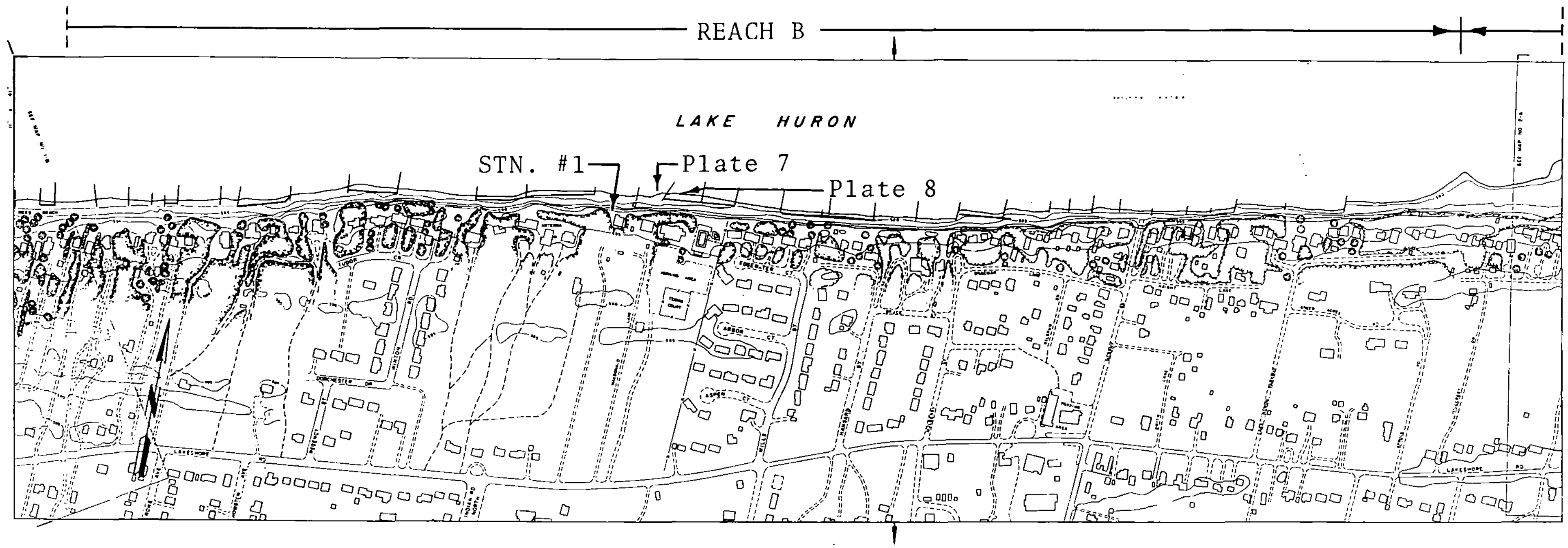


REACH A
LAKE HURON
Plate 3
MICHIGAN
ST. CLAIR RIVER
UNITED STATES
CANADA
SARNIA YACHT CLUB
CANATARA PARK

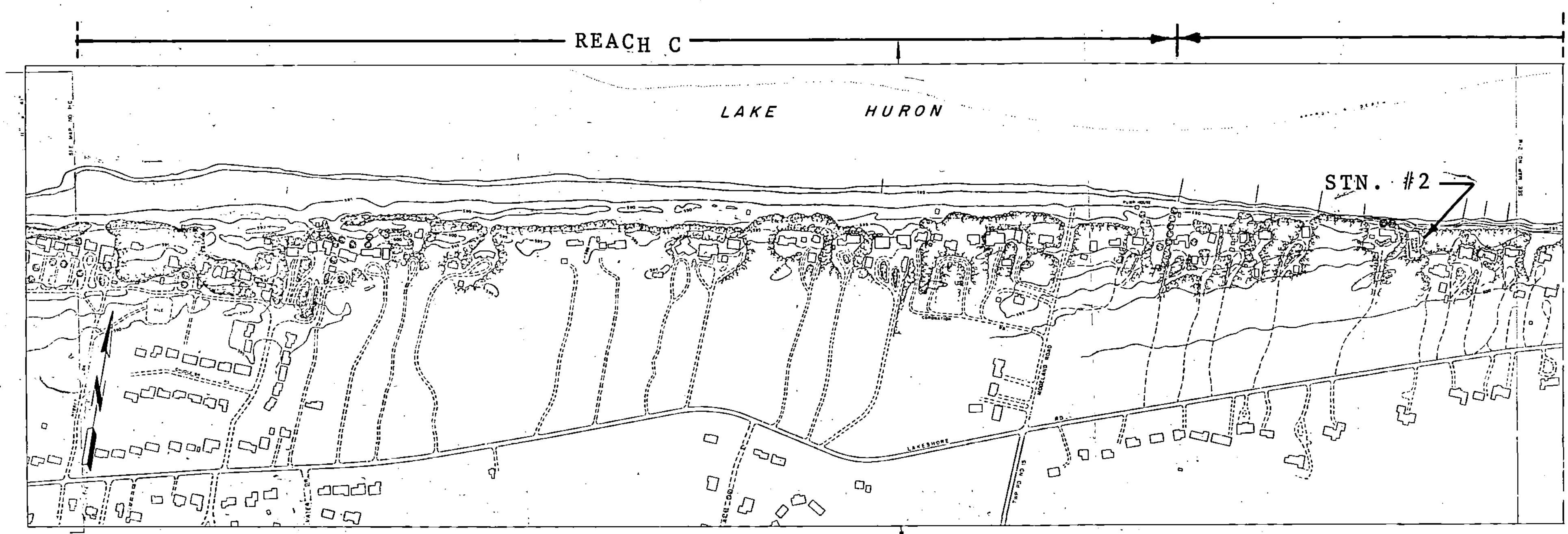
PLAN 1



PLAN 2

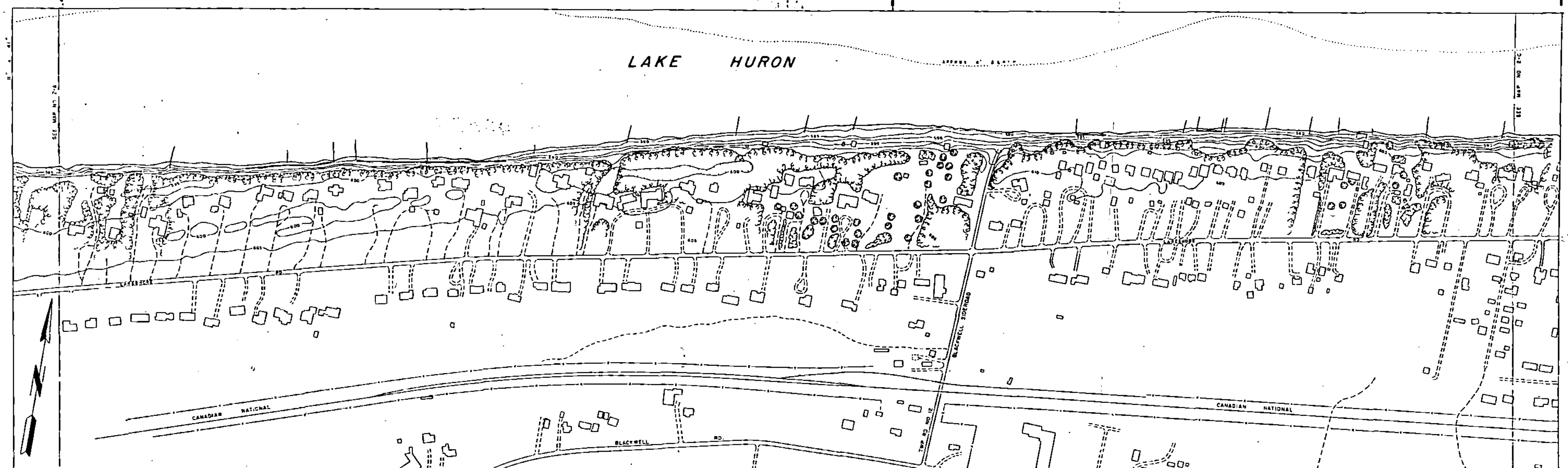


PLAN 3

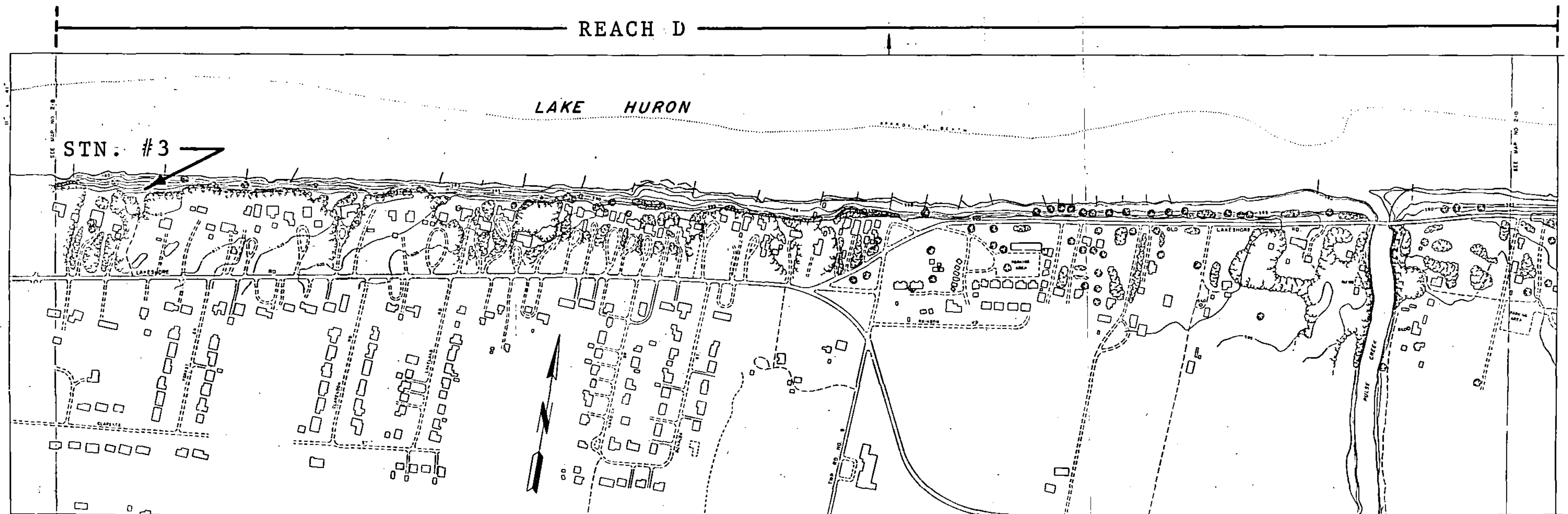


PLAN 4

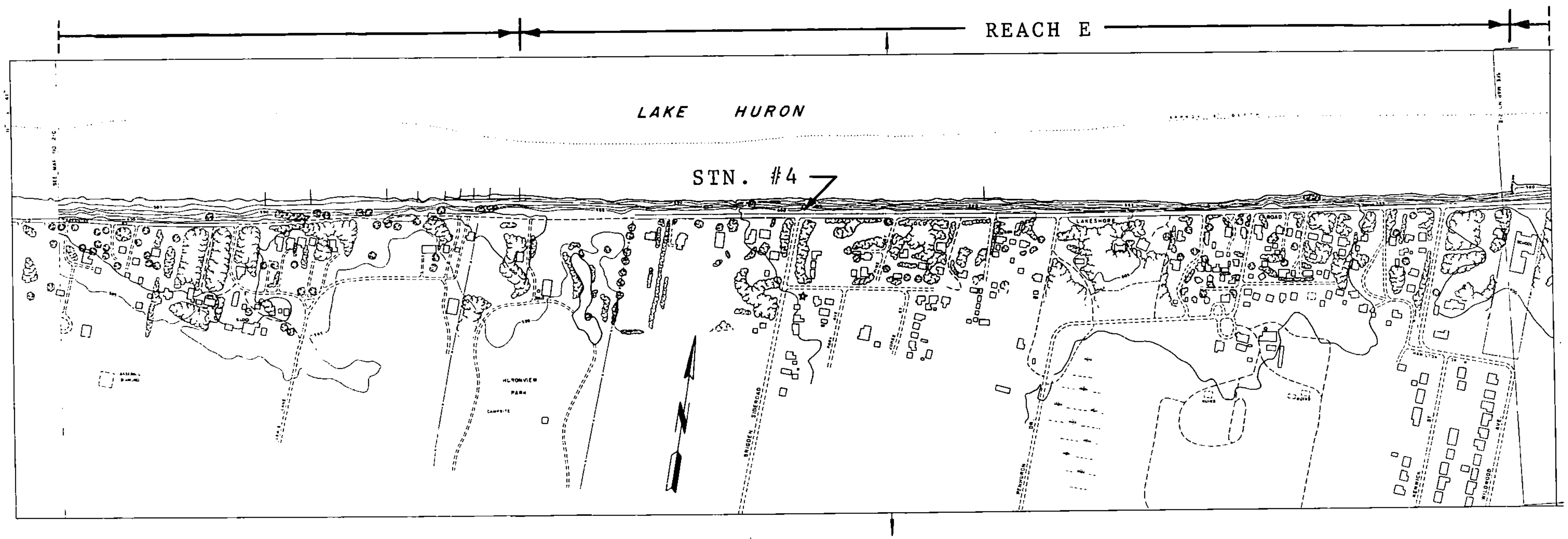
REACH D



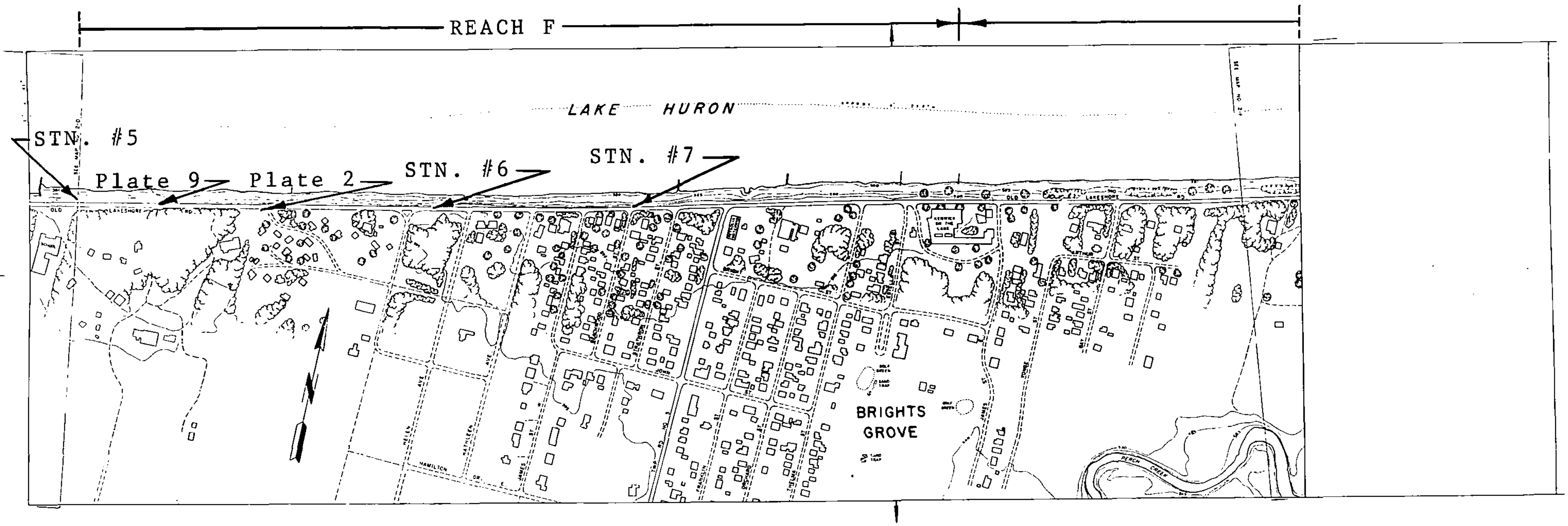
PLAN 5


REACH D
LAKE HURON
STN. #3
LAKESHORE
OLD LAKESHORE RD.
PULSE CREEK

PLAN 6



PLAN 7


REACH F
LAKE HURON
STN. #5
Plate 9
Plate 2
STN. #6
STN. #7
BRIGHTS
GROVE

PLAN 8

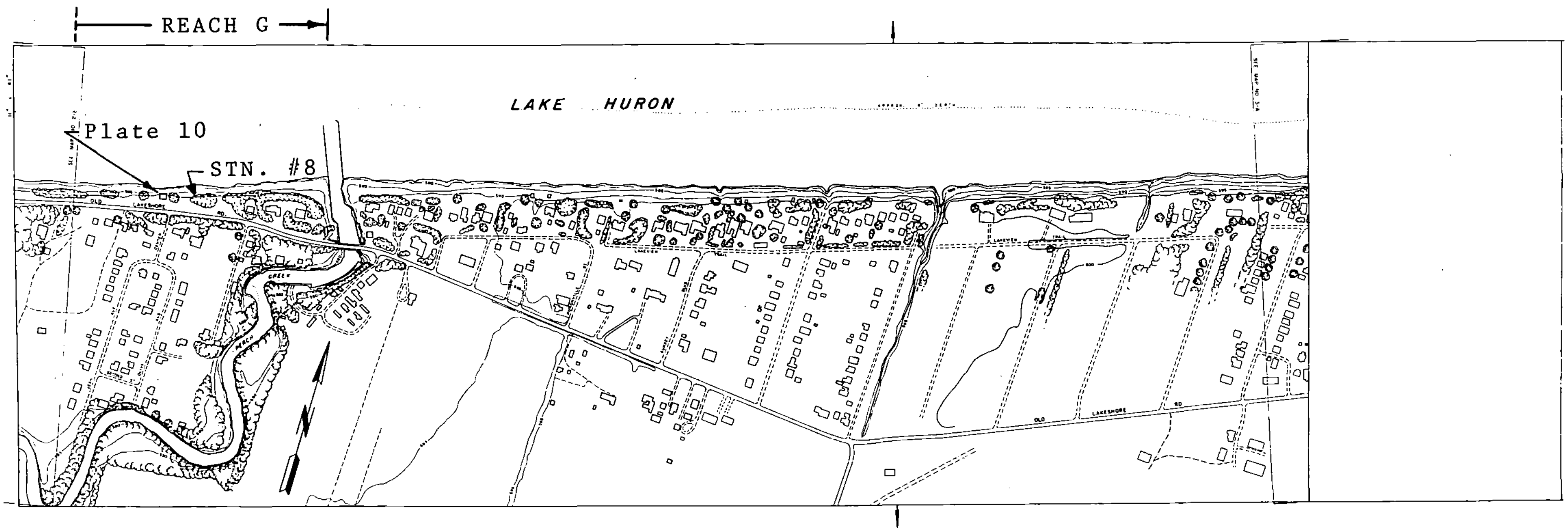

REACH G
Plate 10
STN. #8
LAKE HURON
OLD LAKESHORE RD

Plate 1

Plate 2

Plate 3

Plate 4

Plate 5

Plate 6

Plate 7

Plate 8

Plate 9

Plate 10