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THE HYDRODYNAMICS OF CHEDABUCTO BAY and ITS INFLUENCE ON THE "ARROW" OIL DISASTER

by

H. A. NEU

AOL REPORT 1970-6

MAY 1970

PROGRAMMED BY
THE CANADIAN COMMITTEE OF OCEANOGRAPHY

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ABSTRACT

Meteorologic and hydrodynamic factors which could have influenced the "ARROW" oil disaster are analyzed and described. It is concluded that a storm which prevailed over the Atlantic seaboard on 4 February, 1970, relatively large waves, and a wind driven surface current toward the N, may have contributed to the grounding of the "ARROW". Exceedingly low Low-Waters during the days following the grounding hastened the destruction of the ship. The oil which escaped from the wreck from 4 February to 12 February appears to have been largely contained in the Bay by the prevailing winds.

The results of a number of meteorologic and hydrodynamic surveys, made during the salvage operation, are analyzed and discussed herein. In addition to the latter surveys, a more comprehensive survey was conducted of the circulation and transport pattern in the Bay to gain a better understanding of the hydrodynamic features of the area and their overall effect on the disaster and their consequences. Due to lack of time, the results of only part of this survey are reported. The complete results will be the subject of a future report.

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1. INTRODUCTION

On 4 February, 1970, the oil tanker "ARROW" ran aground on Cerberus Rock in Chedabucto Bay spilling large quantities of oil into the Bay before sinking on 12 February, 1970.

It soon became evident that the movement of the oil escaping from the wreck was influenced primarily by the forces of the wind and tide. It was, however, difficult to forecast the movement of the oil or trace its course because of a lack of relevant wind and tide data. In addition, very inconsistent weather conditions frequently made wind drift and wave predictions impractical.

In an effort to solve some of these problems during the recovery of the oil from the undamaged compartments of the sunken ship, a team from Bedford Institute was placed at the disposal of the Task Force:

(a) to advise on hydrodynamic problems,

(b) to obtain wave data and current data by direct measurements in areas of interest,

(c) to obtain, through a more comprehensive survey, a better understanding of the circulation pattern due to the tide and wind shear forces.

The survey was begun on 26 February, 1970, and completed on 26 April, 1970.

In this report, wind, current, wave and tide conditions during the grounding and break-up of the ship, prior to the survey, are first reviewed and reconstructed by applying semi-theoretical methods with data obtained from the survey. Some of the data collected during the survey is then presented and analyzed.

A description of the predicted movement of an oil-spill which occurred on 25 March, 1970, is also included.

2. GENERAL DESCRIPTION

Chedabucto Bay, which includes the Strait of Canso and George Bay, formed a system connecting the Gulf of St. Lawrence with the Atlantic Ocean and separated Cape Breton Island from the mainland of Nova Scotia (Figure 1). Before the Canso Causeway was constructed in 1955 the currents through the Strait were strong and during the winter, great quantities of ice were carried from the Gulf into Chedabucto Bay. The Causeway has stopped the flow of water and ice, providing, on the Atlantic side, ice-free, deep-water harbour facilities.

Chedabucto Bay extends from the Canso Causeway at the western end to a line joining Point Michaud and Canso Head on the Atlantic seaboard at the eastern end (Figure 1). It includes Lennox Passage and Bay of Rocks. The total area is approximately 1200 square miles. The depth of water at the entrance to the Bay is 300 to 400 feet, or about the depth generally found over the Continental Shelf. West of the entrance the depth decreases gradually, with deeper water on the south side than on the north. The south shore is straight and steep while at the north side, where Lennox Passage forms the shore line, relatively shallow water prevails. The passage, connecting the north-eastern section of Chedabucto Bay with Inhabitants Bay at the entrance to the Strait of Canso, is more than 3000 feet wide at its narrowest section and averaging more than 20 feet deep. The south shore of the Passage is composed of a group of islands and a number of secondary channels. Petit-de-Grat, Isle Madame and Janvrin Island are the three largest islands.

South of Isle Madame there is a group of shoals stretching from east to west over a distance of six miles; the average depth over this

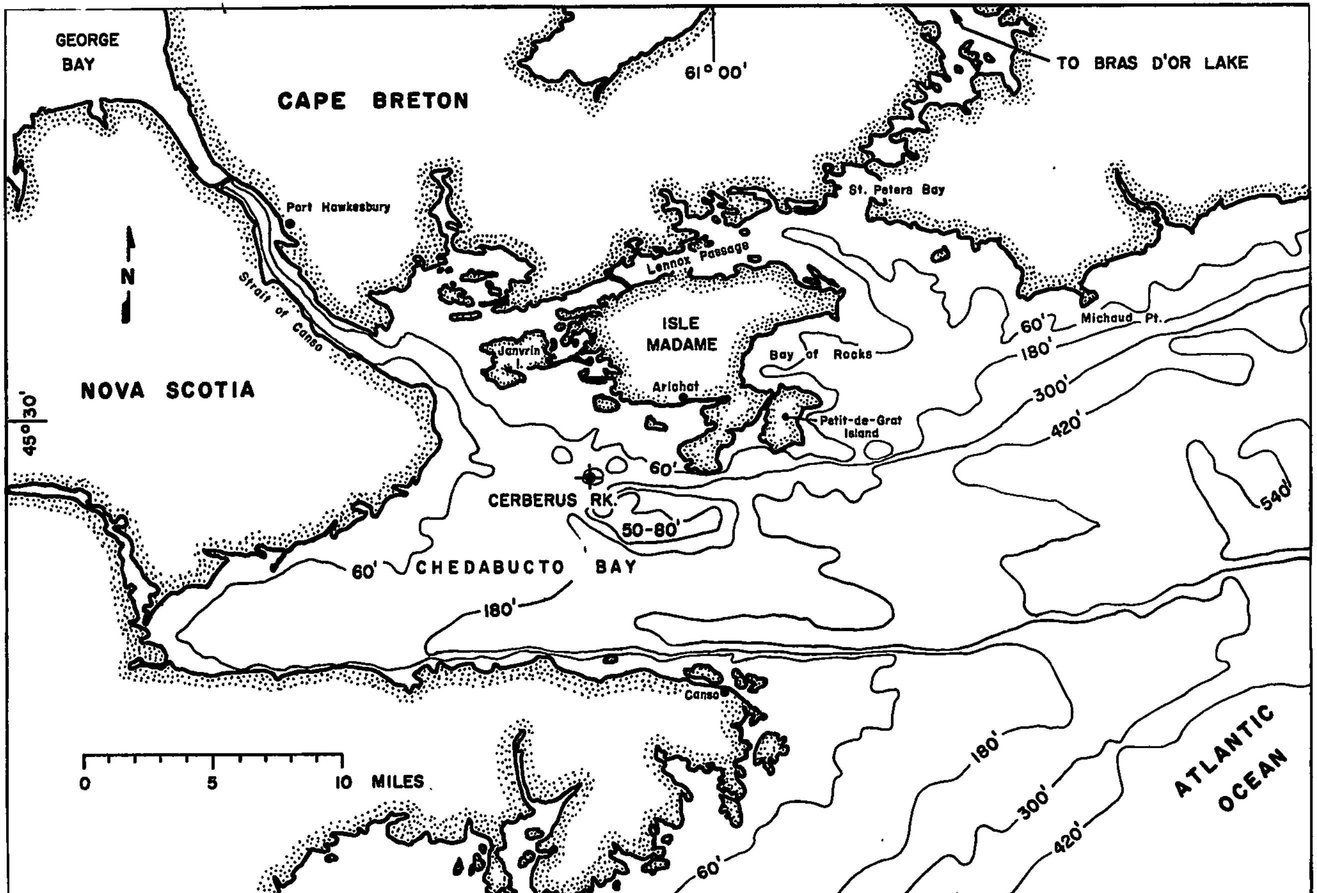

Fig. 1. Map of Chedabucto Bay

area being of the order of 50 to 80 feet. Cerberus Rock, an outcrop on one of these shoals, is located in the western section of this shallow area and according to Hydrographic Chart No. 4308, the Low-Water depth over the top of the rock is 1 foot.

3. WIND AND HYDRODYNAMICS DURING GROUNDING AND BREAKING UP OF TANKER "ARROW"

The 11,379-ton oil tanker "ARROW" enroute to Point Tupper, N. S., loaded with Bunker "C" oil, ran aground on Cerberus Rock, 4 February, 1970, at 0935 hours local time, during a storm having average winds of 40 knots from the south. The waves were of appreciable size at the time and increased after the ship had run aground.

On 8 February, 1970, the ship broke into two sections and on 12 February at 1030 local time, during another storm from the SW, the stern section sank into 90 feet of water. With the exception of the winds, which were recorded at the Canso wind station, no other local data were recorded. However, the state of the sea over the open ocean and the Continental Shelf is recorded twice daily on wave charts published by the Canadian Navy Weather Service in Halifax and from this information the nature of the waves at the entrance to the Bay was obtained. The amount of energy entering the Bay and propagating towards the wreck was determined by applying the Refraction Principle with the aid of a computer. With this method, the state of the sea near the ship was estimated.

Winds not only generate waves, but also drive the surface layer of the water on which oil is floating. In addition to the wind-induced current, the surface layer is also influenced by the tide which during its cyclic rise and fall, moves water in and out of the Bay. An analysis of these two forces provided some indication of the movement of the oil during and after the disaster.

3.1. Wind

Two sources of wind information were available for Chedabucto Bay, the atmospheric pressure gradient from which the geostrophic wind was obtained and records of direct wind observations. Before 5 March, Canso Weather Station was the only station in operation. At this time, several more stations were placed into service, the locations of which are shown in Figure 2.

The geostrophic wind is an approximation in which it is assumed that it is the result of two forces, the pressure-gradient force and the force due to earth's rotation. This assumption applies to the air movements 1500 to 3000 feet above the ground. In the layer below, the wind is retarded by friction. By descending to the surface of the earth, the strength of the wind decreases as the friction effect increases. At 20 to 30 feet above the ground, where wind observations generally are made, it is only about half of that of the upper layer. This decrease in speed is associated with a deviation of the wind to the left of the geostrophic wind direction.

The reduction in wind speed and the deviation in direction depends not only on the height above but also on the roughness of the surface, being smaller over open water and larger over rough land. Subsequently, it must be assumed that the wind over the open water of Chedabucto Bay was generally greater than observed at the wind stations on land.

On Figure 3 the geostrophic and observed winds are plotted for the periods from 3 February to 12 February and from 15 March to 24 March. It can be seen that the observed winds deviate from zero to forty degrees to the left of the direction of the geostrophic wind and that the recorded winds are up to 50 percent smaller than those derived from the atmospheric pressure. In a number of cases the geostrophic wind was smaller than the surface wind.

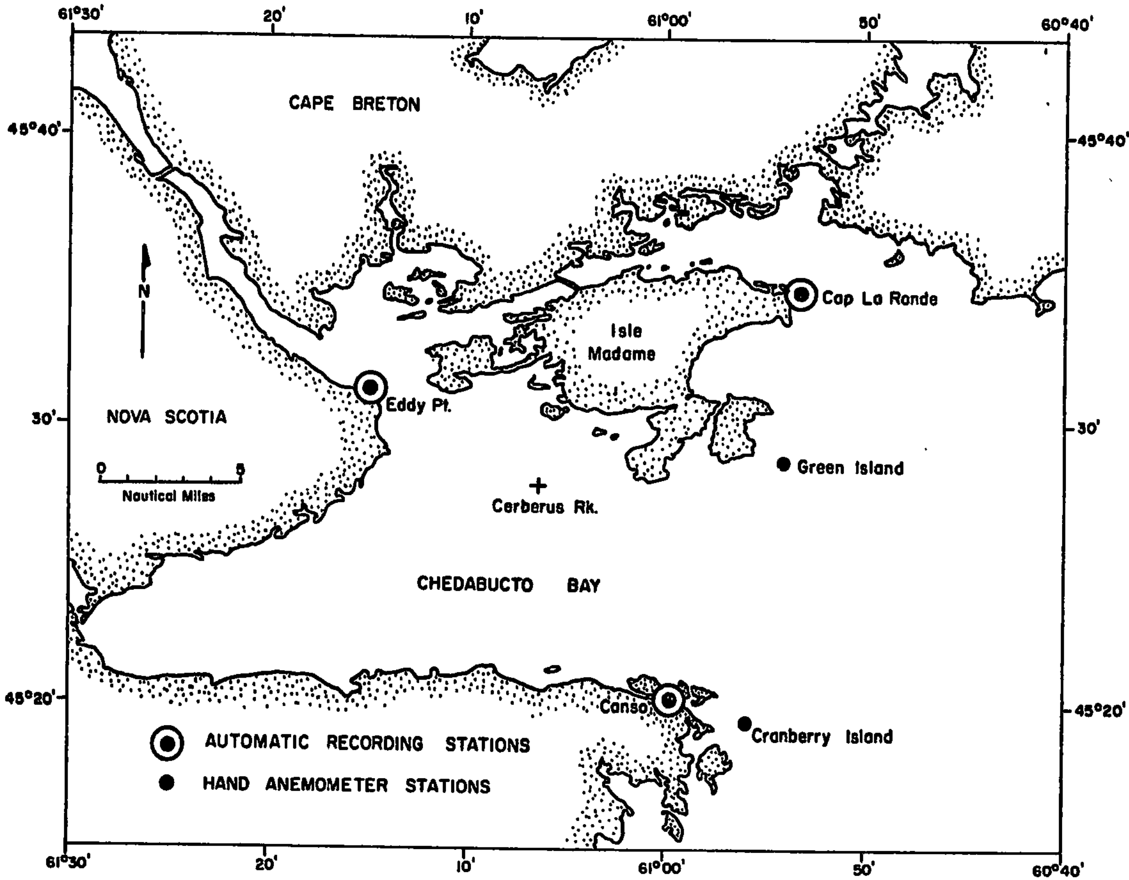

Fig. 2. Location of Wind Observation Stations

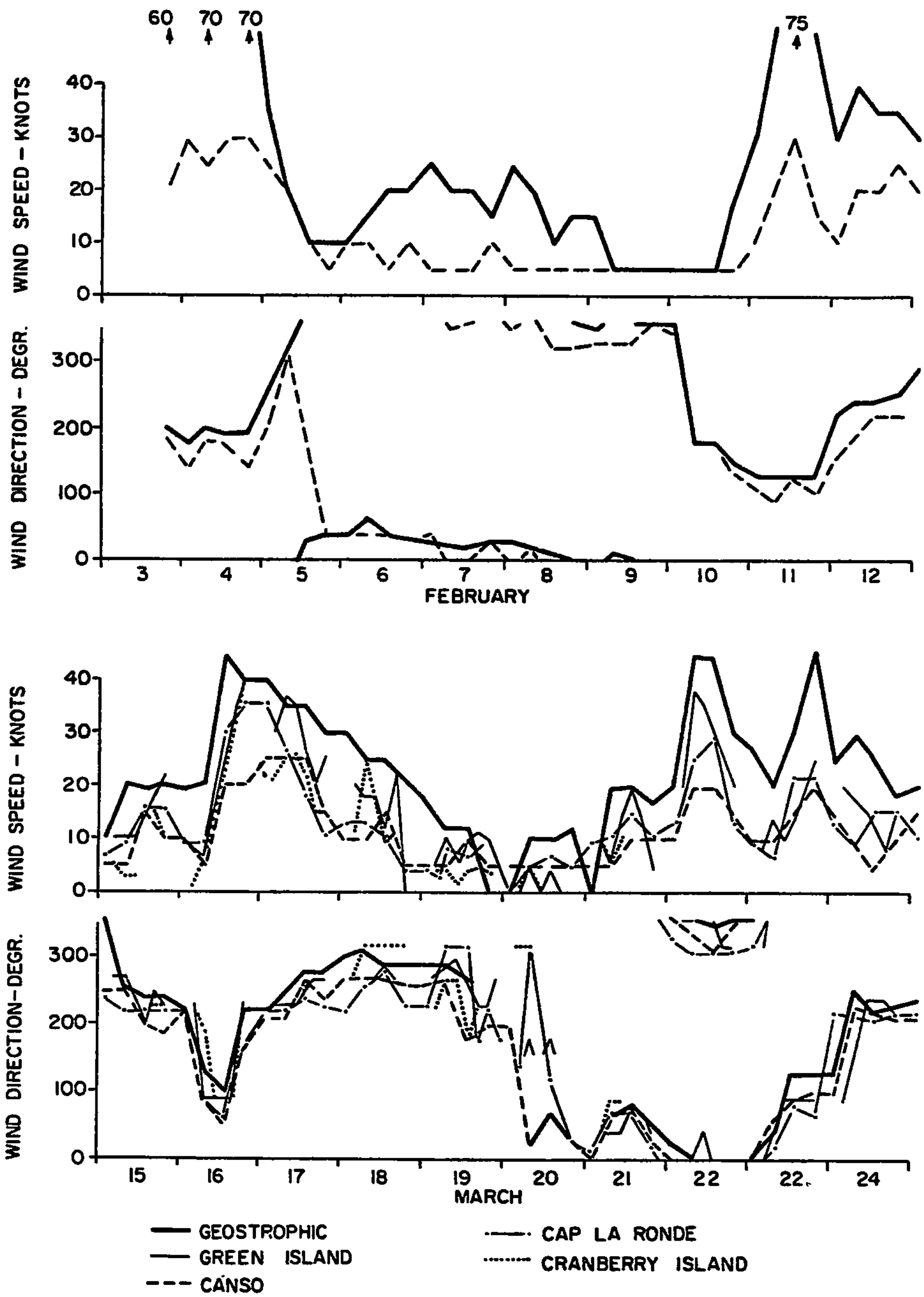

Fig. 3. Geostrophic and Observed Winds in Chedabucto Bay

Dexter* investigated the relation between the surface wind and geostrophic wind off the coast of Nova Scotia. The results of Sambro Lightship off Halifax are plotted on Figure 4. They indicate that between the two winds there existed a somewhat linear relation which can be expressed in the following approximation:

$$W_R = 10 + 0.43\ W_G$$

W_R and W_G are the wind speeds in knots for the surface layer wind and geostrophic wind respectively.

This relationship was used to obtain wind data which were assumed to be independent of ground features and therefore more representative of the open Bay. In addition, the direction of these winds was modified by 20 degrees toward the left of the geostrophic wind direction.

In this report, winds obtained this way are referred to as "reduced geostrophic winds".

On Figure 5, the vectors of the reduced geostrophic wind for six-hourly and daily intervals are plotted for the period from 3 February to 12 February, 1970. During the early hours of 4 February, and at the time the ship grounded, the wind was from the south with an average strength of 40 knots. During the following day the wind strength decreased and its direction changed to West and later to North. On 11 February, a new disturbance developed with winds of 30 knots, first from the ESE and later from the Southwest.

As stated previously, oil which spilled into the bay drifted under the influence of the wind and tide. The movement of water surface layers in response to shear stress has been widely studied but is not

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* R. V. Dexter (1959). Preliminary Report on Winter Wind Speed Versus Pressure Gradient at Sea Off the Nova Scotia Coast. Meteorological Branch, Department of Transport, Canada. CIR-3213, TEC-304; 10 June, 1959.

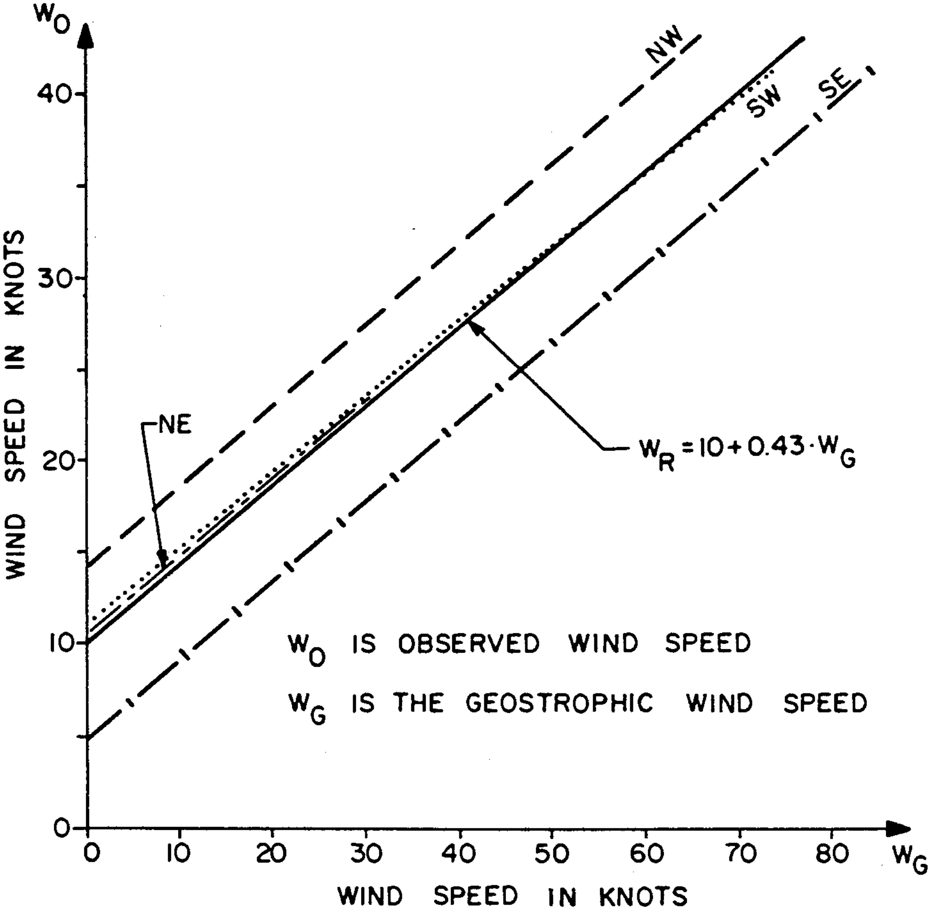

Fig. 4. Relation between Geostrophic and Observed Wind Speed at Sambro Lightship

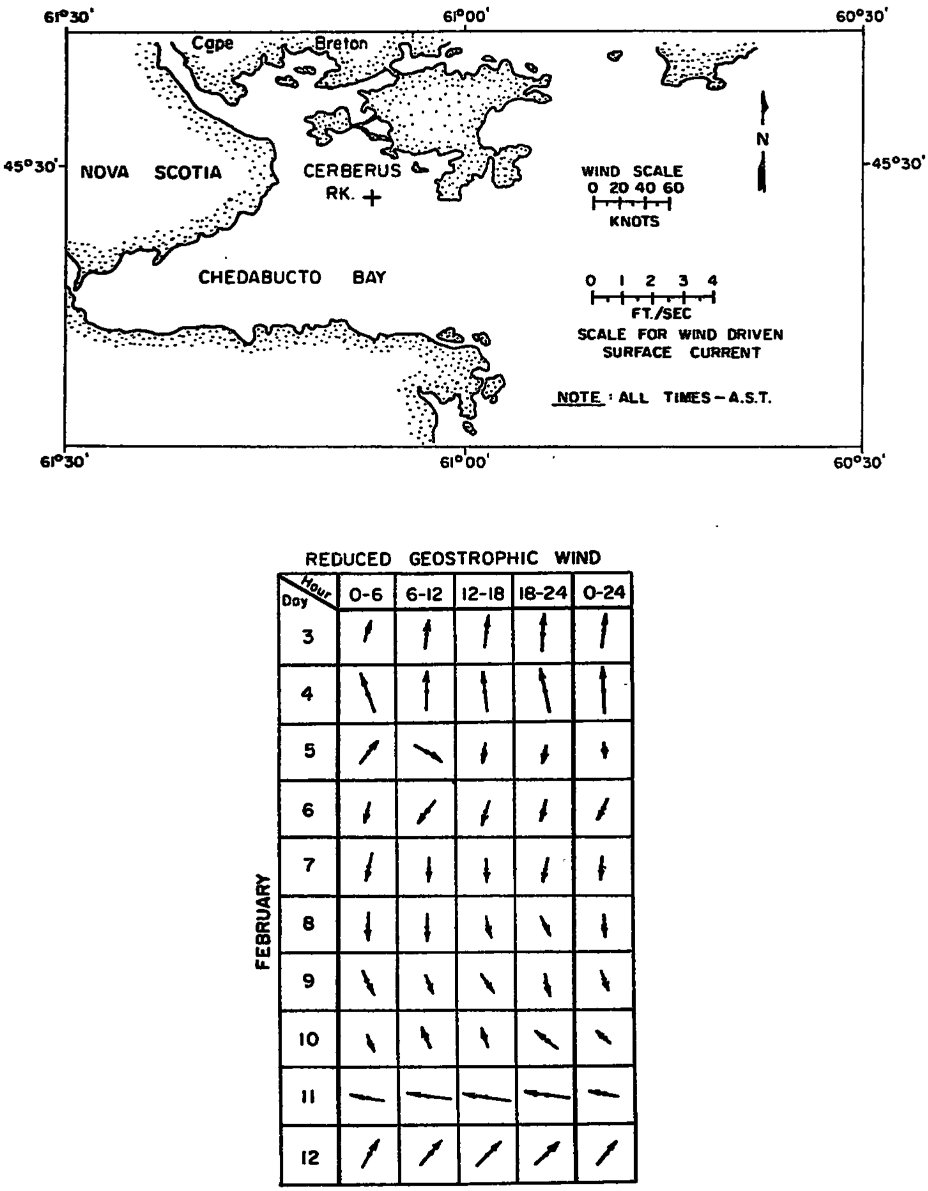

Fig. 5. Mean Wind Vectors from 3 February to 12 February, 1970.

well understood. There are many factors which warrant consideration in applying the theory, particularly in confined waters. For example, in a rectangular bay which is closed at one end, like Chedabucto Bay, there generally is, for continuity, a return flow in a lower layer to counterbalance the surface current. This causes a two-layer flow system in which the speed of the surface layer is affected by the counter current and thus by the depth of water. Many more factors come into the picture, such as the state of the sea, the temperature of air and water, the earth's rotation, etc., which make the theory quite complex for routine field application.

Observations conducted in Chedabucto Bay and in the Strait of Canso indicate that the surface layer moves with an average speed of about 2.5% of the wind speed measured 30 feet above the water. This generally agrees with observations reported by Wiegel*. It is therefore decided to use this simplified relationship for estimating the wind-driven surface current from the reduced geostrophic wind vectors (Figure 5). It should be noted that the effect of tidal motions is neglected. The behaviour of oil with respect to the sea water on which it floats has not previously been sufficiently studied. In the present case it was assumed that a heavy oil slick floating on sea water moves with the same speed as the water environment; the effect of a different wind shear stress factor for oil and the spreading due to gravity and surface tension being neglected. These factors may become important over long stretches, e.g. to Sable Island, but it was felt that they could be disregarded for comparatively short distances as in Chedabucto Bay.

The distance from Cerberus Rock to Isle Madame and Janvrin Island is about 20,000 feet, to the west shore about 30,000 feet and to the south shore of Chedabucto Bay approximately 40,000 feet. Under the effect of 25 knot winds (neglecting the effect of the tide), the escaping oil reaches the shores of the islands, and the west and south

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* R. L. Wiegel, Oceanographical Engineering, Prentice-Hall Inc., 1964. pp 317-321.

shore of the Bay in about 5.5, 8.2 and 11 hours respectively.

From the magnitude and direction of the wind vectors--which may also be considered as surface current vectors--(Figure 5), it seems that the oil which escaped from the wreck during grounding and during the following 24 hours was transported primarily towards the islands north of Cerberus Rock, Arichat Harbour and Petit-de-Grat Harbour. It appears that on the evening of 5 February the escaping oil started drifting slowly toward the south shore of Chedabucto Bay; but on 11 February, the wind changed direction and the newly escaping oil then moved with a speed of more than 1 ft/s into the area adjacent to Janvrin Island and Inhabitants Bay. After 12 February, the oil movement was mainly directed towards Arichat and Petit-de-Grat.

From this type of surface current analysis it is apparent that most of the oil which escaped from the wreck between 4 February and 12 February was contained in Chedabucto Bay by the action of the wind. It can be assumed therefore that during this period little escaped into the open ocean except that which was released from the shore at a later date or which was transformed into droplets, which then sank and became entrained in an outflowing deeper layer.

3.2. Waves

The orientation of the major axis of Chedabucto Bay relative to the prevailing winds, indicates that waves of any considerable height or period (i.e. greater than 7 feet or 8 seconds) are probably not generated locally. For instance, to the northwest the fetch from Cerberus Rock is limited to approximately 12 miles while to the southwest it is limited to 17 miles (Figure 1).

Waves generated by storms over the North Atlantic may, however, propagate into the Bay. Those approaching from the south and southwest may be refracted by Canso ledge which extends some 20 miles east of Canso, as a subsurface extension of the south shore of Chedabucto Bay. This ledge will refract waves having periods longer than 10 seconds; however, some energy from waves with shorter periods may be diffracted into the Bay.

A large shoal area, having average depths of 60 feet, extends southeast from Cerberus Rock. With depth exceeding 180 feet on all sides of this shoal, it is conceivable that it may focus the energy of 8 to 12 second waves from the east to southeast sector on Cerberus Rock, similar to a lens concentrating a beam of light.

The tanker ran aground during a storm over the Atlantic whose fetch and duration was long enough to develop a considerable sea. These waves have been a factor in the fate of the ship.

3.2.1. Average Ocean Wave Statistics, December - May

(a) Average wave characteristics (energy and period) for the months of December to May are given in Figures 6 and 7. The energy units are relative but take into consideration the frequency distribution of waves of a particular period.

It can be seen that most of the wave energy occurs in the 7 to 12 seconds period band, propagating from SSW to WNW. There seems to be a small change in direction of approach towards the north in Spring without any appreciable increase in energy.

(b) Using the synoptic weather charts from the Department of Transport and the Wave Climate Charts published by the Canadian Armed Forces, some wave hindcast calculations were made using the method of Bretschneider*. The estimated significant wave height, period and direction of propagation outside Chedabucto Bay are given in Table 1.

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* C. L. Bretschneider (1952). Revised Wave Forecasting Relationships, Proc., 2nd Conf. on Coastal Engineering; Council on Wave Res., Engin. Foundation.

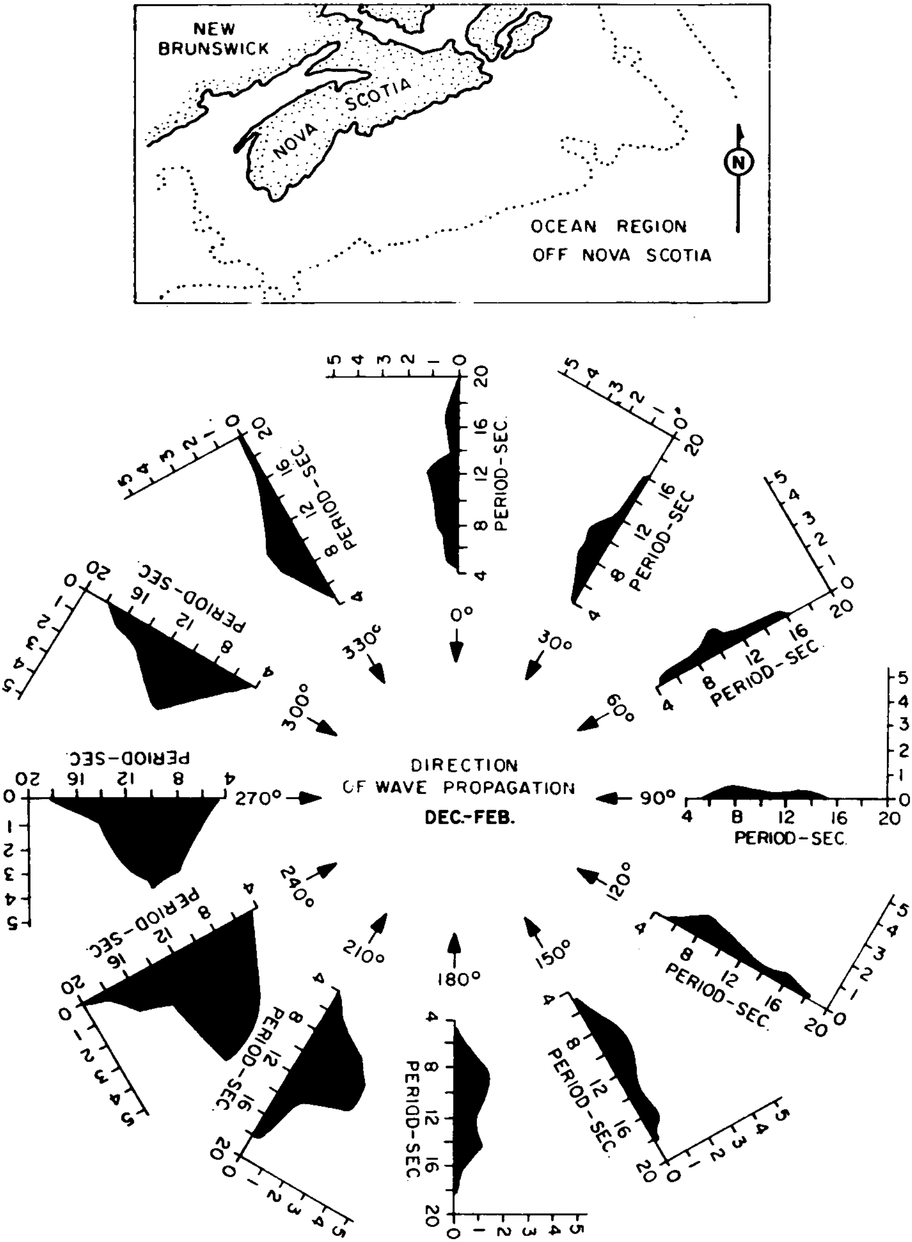

Fig. 6. Wave Energy Spectrum over the Continental Shelf, December to February

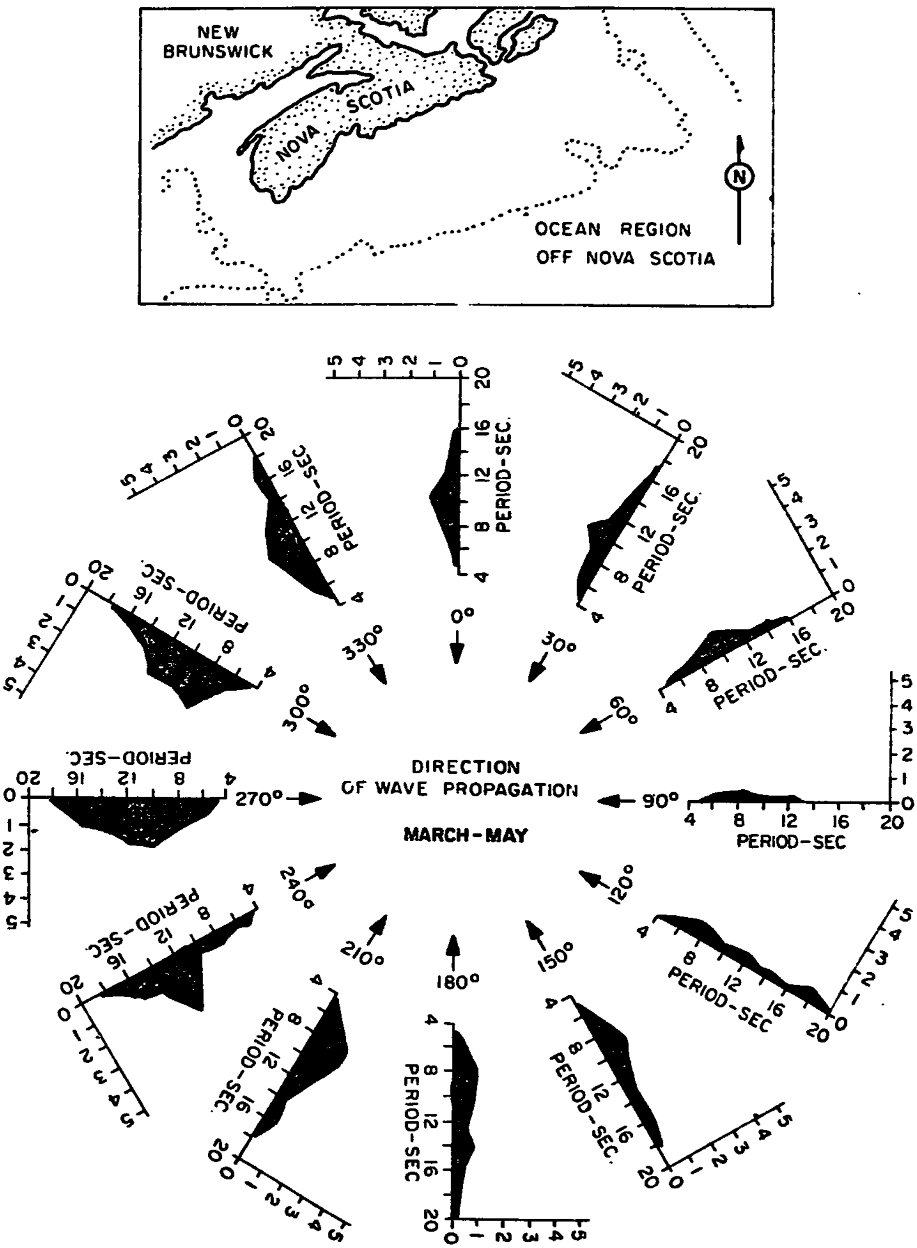

Fig. 7. Wave Energy Spectrum over the Continental Shelf, March to May

TABLE 1

SIGNIFICANT WAVE HEIGHT, PERIOD AND DIRECTION

OUTSIDE OF CHEDABUCTO BAY

DATE	TIME (AST)	HEIGHT (ft)	PERIOD (s)	DIRECTION
3 Feb	2000	18-20	8	SW
4 Feb	0200	20-21	8-9	SW
4 Feb	0800	20-22	11	SW
4 Feb	1400	20-22	12	S
4 Feb	2000	20-21	12-13	S
5 Feb	0200	15-16	12	S to SW
5 Feb	0800	8-10	12	S
		(Also some locally generated waves from NW)		
5 Feb	1400	6-8	12	SW
5 Feb	2000	6	12	SW
		(Also some locally generates waves from E)		
6 Feb	0200	6-8	9	ESE
6 Feb	0800	8-9	9-10	S
6 Feb	1400	8-9	10	E
6 Feb	2000	8	11	E
7 Feb	0200	4-6	12	ENE
7 Feb	0800	4-6	12	ENE
7 Feb	1400	8-10	8-9	NE
7 Feb	2000	8-10	8-9	NE
8 Feb	0200	6-7	10	NE
8 Feb	0800	6	10-11	NE
8 Feb	1400	6	10-11	NE
8 Feb	2000	4-6	11	NE
9 Feb	0200	4-5	11	NE
9 Feb	0800	2-4	10	NE
9 Feb	1400	2-4	9	NE
9 Feb	2000	2-4	9	NE
10 Feb	0200	2-4	8	NE
10 Feb	0800	2-4	8	NW
10 Feb	1400	4-6	9	SE
10 Feb	2000	8	4-5	SE
11 Feb	0200	15-18	6-7	SE
11 Feb	0800	18-20	9-10	SE
11 Feb	1400	20-21	11	SE
11 Feb	2000	20-22	11-12	SE
12 Feb	0200	22	12	SE
12 Feb	0800	22	12	SE
12 Feb	1400	20-22	10-11	SE

Ship grounded on 4 February, 1970, 0935 Atlantic Standard Time

It should be noted from Table 1 that prior to and after the grounding, there were rough seas over the North Atlantic which produced waves propagating in directions favouring their arrival at Cerberus Rock.

3.2.2. Wave Refraction Diagrams

A wave refraction diagram is a graphical representation of the change in direction of a wave front as it moves over an area of variable depth where its velocity is not constant. Thus, when travelling over increasing depths the wave front tends to diverge and conversely, converge over shoals and ridges.

In studying wave refraction, it is assumed that Snell's law applies, e. g.

$$\frac{\sin\alpha_1}{\sin\alpha_2} = \frac{C_1}{C_2}$$ where α_1 and α_2 are angles

between adjacent wave front positions and the respective adjacent bottom contours (Wiegel, 1964). C_1 and C_2 are the respective wave velocities at the two points and may be obtained for given water depths and wave periods by $C = \frac{g\tau}{2\pi} \tanh \frac{2\pi d}{L}$ where d = water depth, τ wave period, and L wave length.

Refraction diagrams (Figures 8 to 11) were constructed using a numerical technique developed by Wilson (1966)* and adapted to the Institute's CDC 3100 computer. The diagrams are shown in terms of wave rays or orthogonals, which are lines perpendicular to the wave crest. This type of presentation is useful for it can be shown that constant energy is transmitted between any two orthogonals. From this, it is possible to estimate variations in wave height due to refraction.

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* W.S. Wilson (1966). A Method for Calculating and Plotting Surface Wave Rays, U.S. Army Coastal Engineering Res., Dept. of the Army, Tech. Memo No. 17

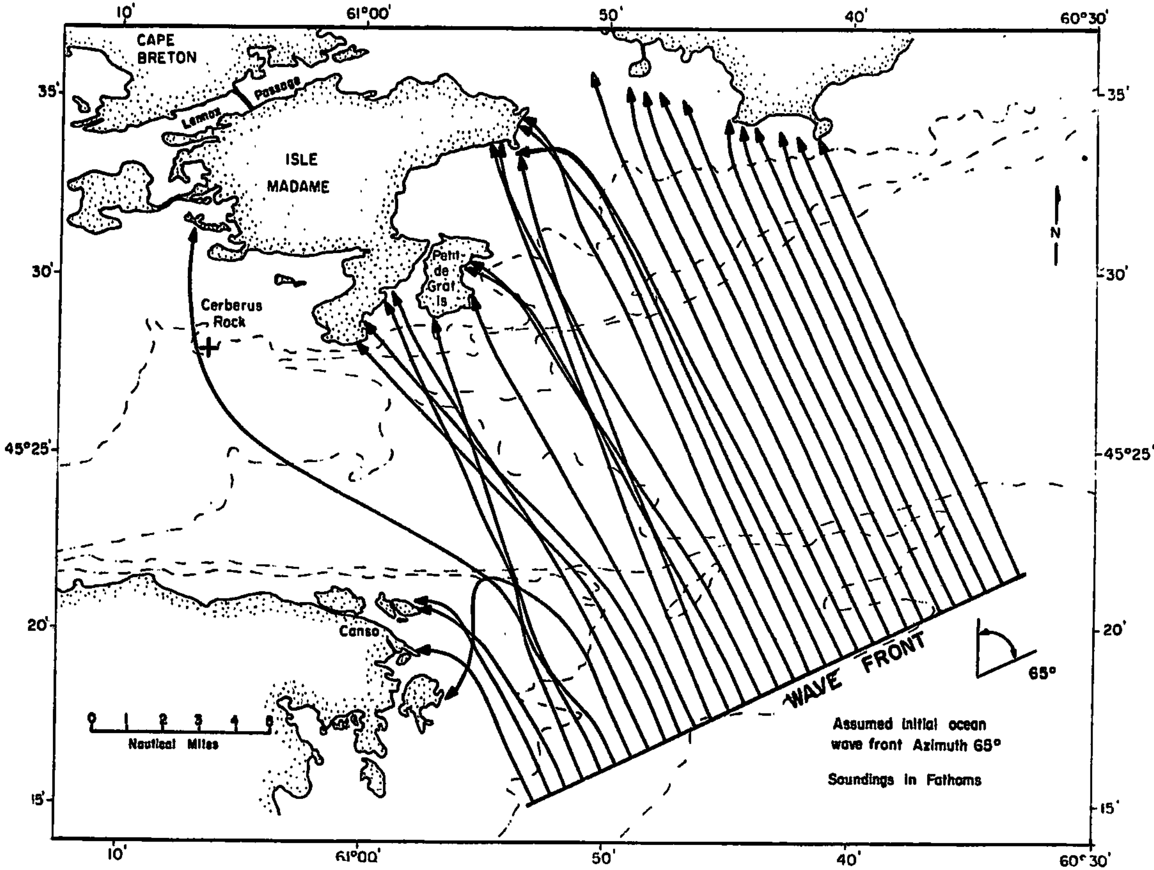


Fig. 8. Wave Refraction Diagram of a 10-Second Wave Train in Chedabucto Bay - 65⁰ Wave Front

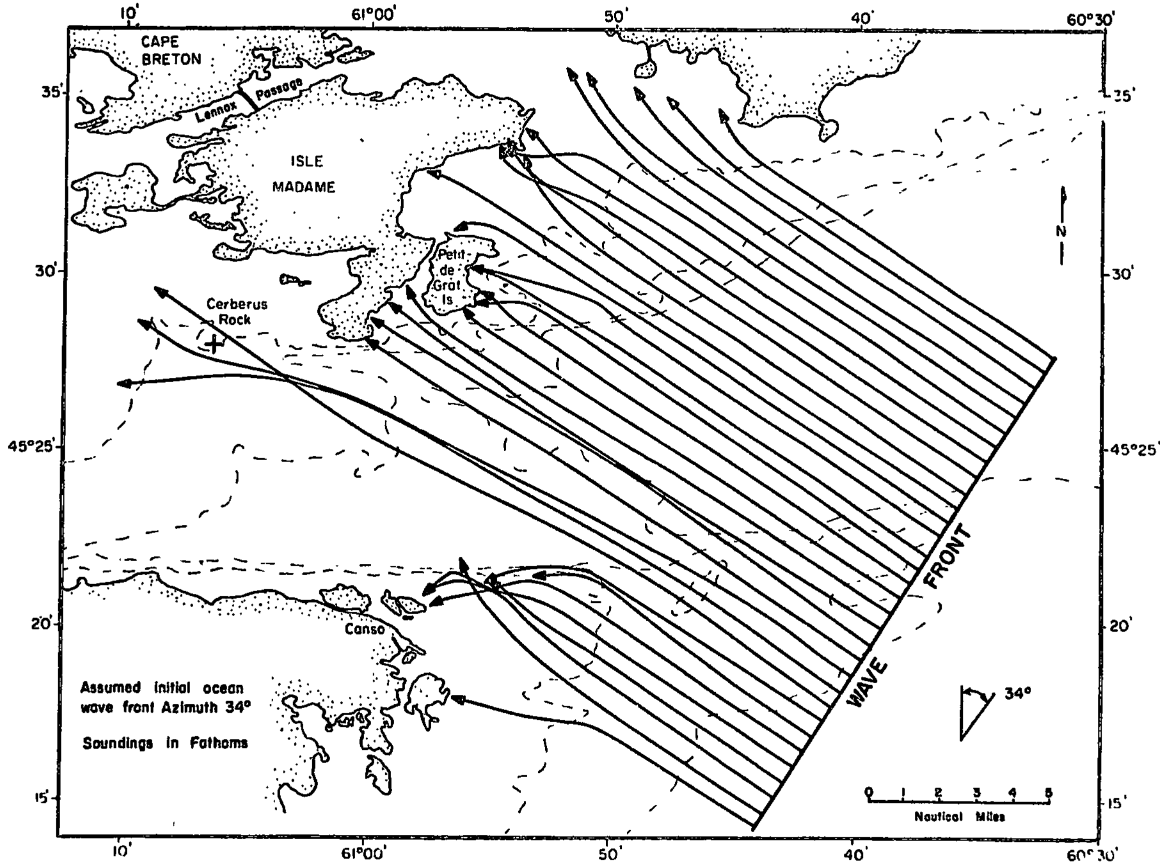


Fig. 9. Wave Refraction Diagram of a 10-Second Wave Train in Chedabucto Bay - 34° Wave Front

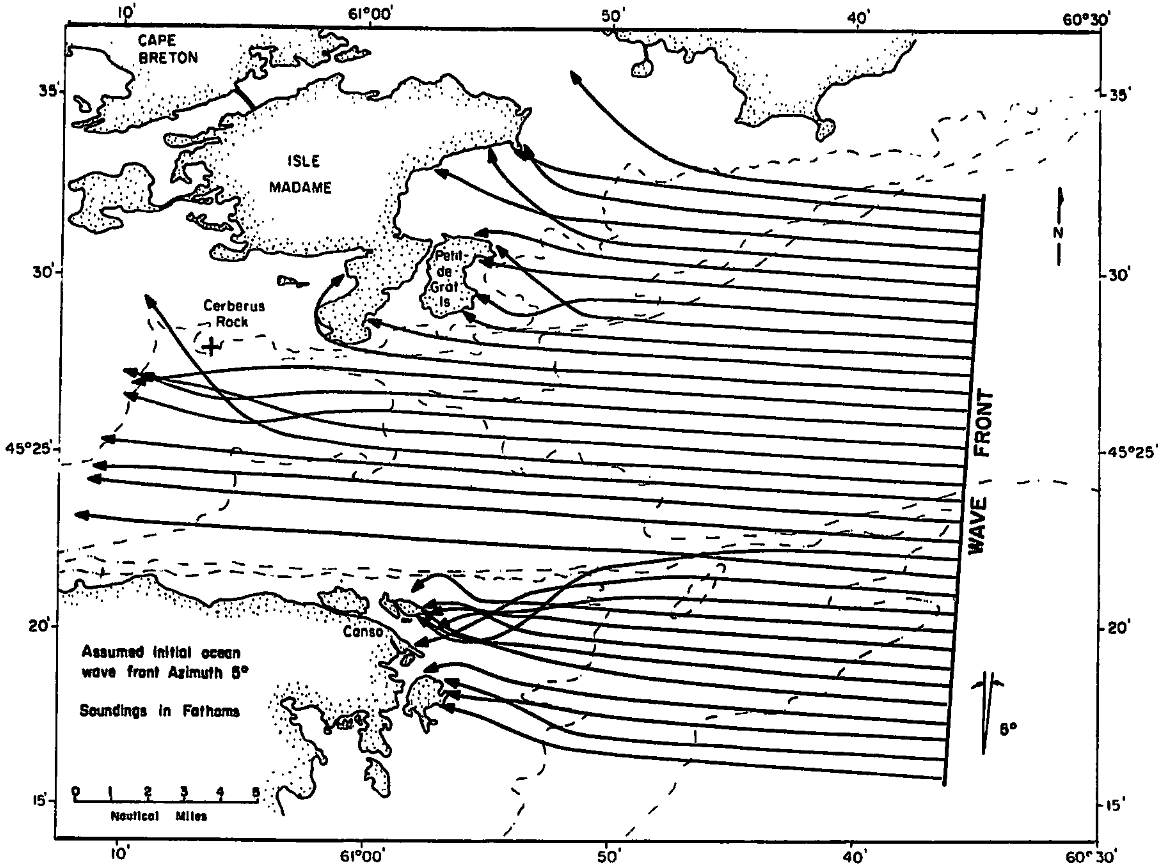


Fig. 10. Wave Refraction Diagram of a 10-Second Wave Train in Chedabucto Bay - 5^0 Wave Front

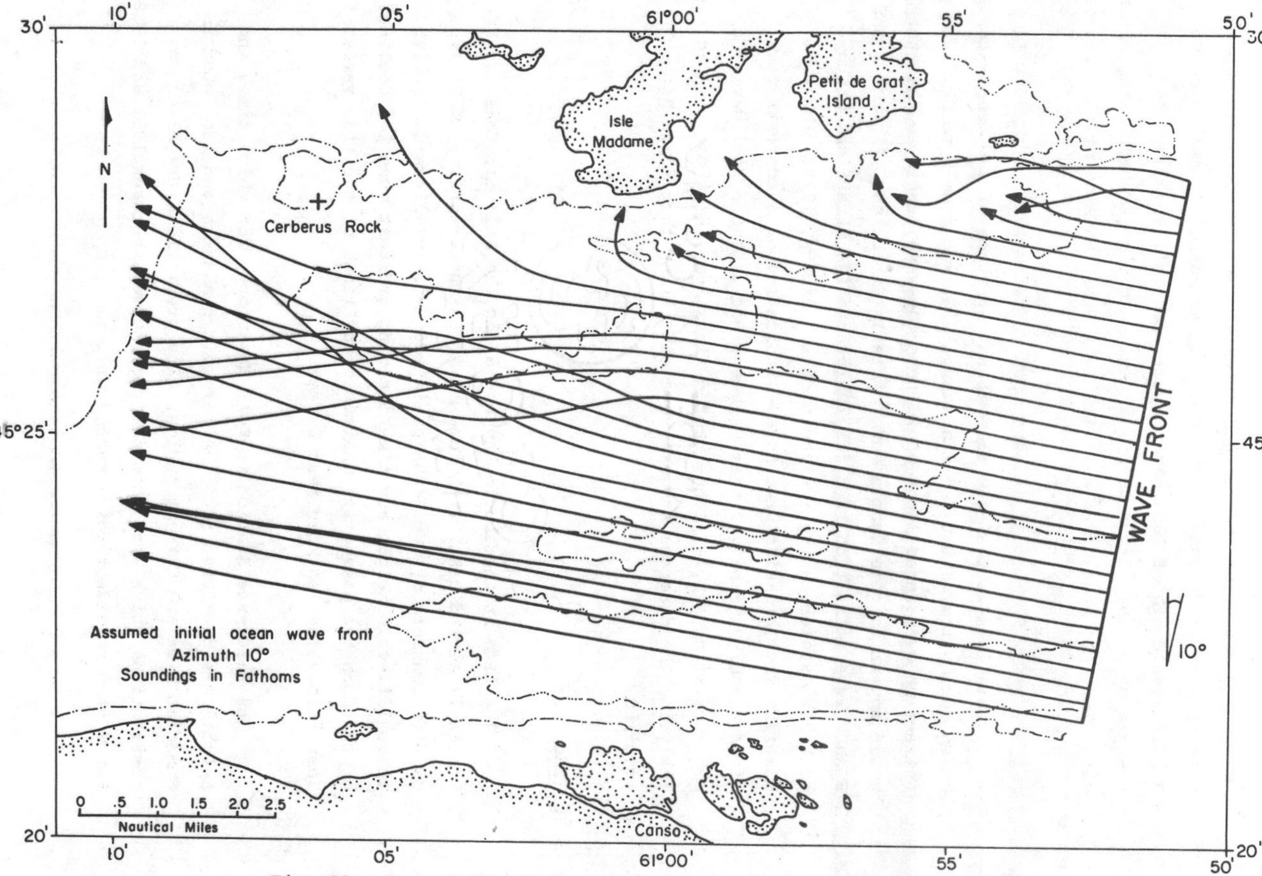


Fig. 11. Wave Refraction Diagram of a 14-Second Wave Train in Chedabucto Bay - 10^0 Wave Front

Waves having periods of ten seconds were considered as representative of conditions at the time of grounding. These waves have a half-wavelength of 250 feet and are thus influenced by the topography of the bottom before entering Chedabucto Bay. The initial wave front has been drawn as a straight line, an assumption which is probably reasonably correct.

Table 1 shows that the predominant approach of the deep water waves during the period 4-5 February, 1970, was from S to SW. Refraction over Canso ledge would turn the wave fronts so that they would appear to come from a more easterly direction. Figures 8 and 9 show wave refraction rays for representative directions which probably existed during the storm of 4 February, 1970. These diagrams show crossing wave rays-- indicative of a concentration of wave energy or height near Cerberus Rock. While real waves do not consist of single, long-crested sinusoids like those used in the analysis, the diagrams suggest wave conditions that could have occurred.

3.3. Tide

The tide in Chedabucto Bay and along the Atlantic Coast of Nova Scotia is semi-diurnal with some mixed characteristics. This type of tide consists of two High-Waters and two Low-Waters daily with inequalities in height and time becoming greatest when the declination of the moon has passed its maximum. The range of the tide varies from less than 2 feet to more than 6 feet.

The Reference Station is Port Hawkesbury for which times and heights are predicted from the harmonic constants and tabulated in the Canadian Tide and Current Tables. The predictions are based on observations which were obtained from surveys between 1952 and 1968. Since then no tide records were acquired.

The meteorological disturbances which may modify the mean water level by several feet and cannot be predicted in advance are not included in the forecast. There were no recordings of the actual water levels from the time the "ARROW" grounded. Estimated levels were obtained by introducing the meteorological fluctuations observed for the period at Halifax.

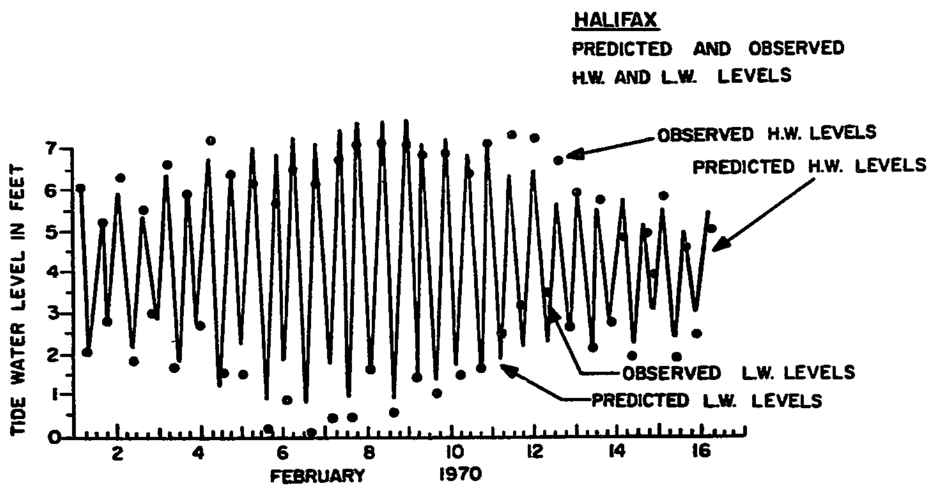
3.3.1. Tide During Grounding and Break-up

On Figure 12 the predicted and observed H.W. and L.W. levels at Halifax and the predicted and estimated H.W. and L.W. levels at Port Hawkesbury are shown. From the Halifax data, it can be readily seen that the tide range predictions were generally correct but that meteorological fluctuations of the mean water level were superimposed on the tides. Transferring these fluctuations onto the predictions at Port Hawkesbury Station, it appears that on 4 February, the day of the grounding, the water level in the Bay was slightly higher than predicted--in order of 0.3 foot for both H.W. and L.W.

The ship grounded 0935 A.S.T., halfway between H.W. and L.W. The tide range was approximately 4 feet. As shown in Figure 12, in the days following, the predicted tide range increased;the L.W. levels decreasing and the H.W. levels increasing by about one foot. In addition to this predicted drop of the L.W. level the mean sea level fell another 1 to 1.2 foot due to the subsidence of the weather disturbance and changing wind direction.

This combination of circumstances which caused exceedingly low L.W. levels was most unfortunate for the "ARROW". From the later part of 4 February to 8 February, at each L.W., the rock penetrated further into the ship's forward section of the hull. During the salvage operation the stern section became separated from the forward section which then remained on the rock.

On 11 and 12 February, another storm moved through the area



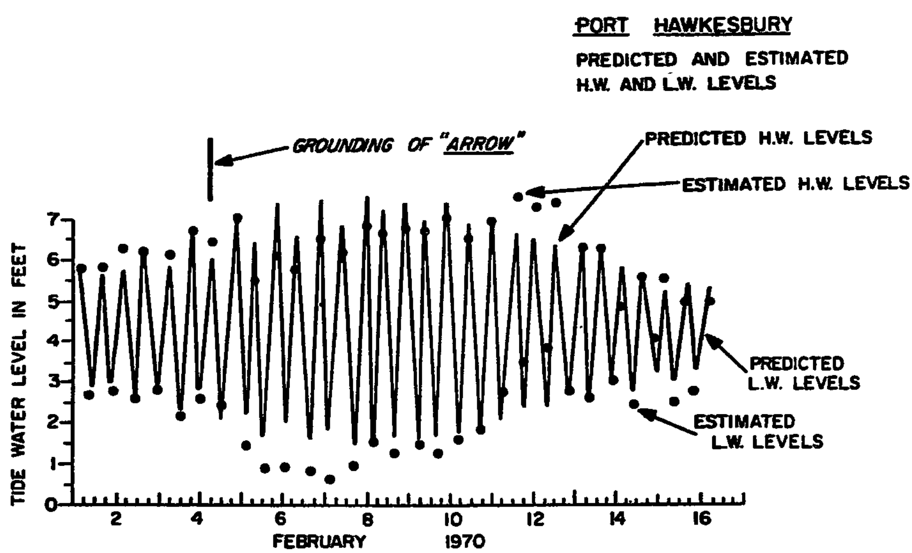


Fig. 12. Tide Levels of Halifax and Port Hawkesbury,
2 February to 12 February, 1970.

giving gale force winds and relatively heavy seas, first from S and then from SW. Mean water levels were more than 1.5 feet above predicted heights. These factors may have contributed to the final foundering of the stern section on the 12 February.

3.2.2. Current Structure near Cerberus Rock

The topography around Cerberus Rock is irregular (Figures 10 and 11) with a number of shoals and channels. These features increase the complexity of the current structure.

The tidal currents at Cerberus Rock during and after the disaster were reconstructed from a current survey which was conducted by the Canadian Hydrographic Service in June, 1968. (Figure 13). For a period of 17 days, a current meter was installed 9 feet below L.W. and 4,000 feet south of Cerberus Rock where the water is about 160 feet deep. While the currents at this location are not fully representative of those at Cerberus Rock, they give a general indication of the currents in the area. (Figure 14).

On Figure 15 are plotted the predicted tides (without meteorological influences), representative wind vectors, and current velocities in the westerly and southeasterly directions. It is readily seen that the current structure is quite confusing. The residual motion cannot be related to the prevailing winds; there must also be other meteorological influences and probably long period ocean surges in existence.

However, during Half-Falling Tide with tide ranges in the order of 4 feet and winds from a generally southerly direction, the currents were with a few exceptions, either flowing southeasterly or there was a slack-water. The strength of the currents did not exceed 0.8 ft/s (0.47 kn) and averaged 0.2 ft/s (0.12 kn).

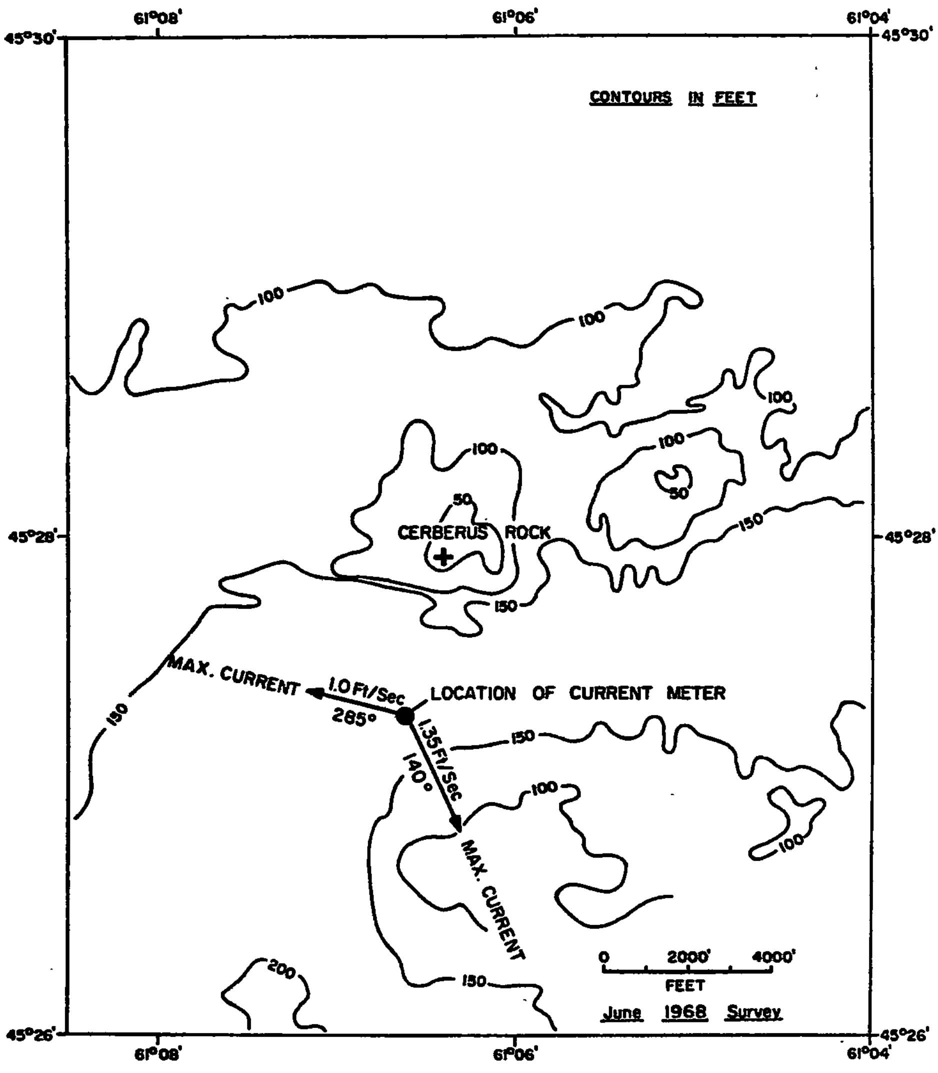


Fig. 13. Location of Current Meter and Maximum Currents Near Cerberus Rock; June 1968 Survey.

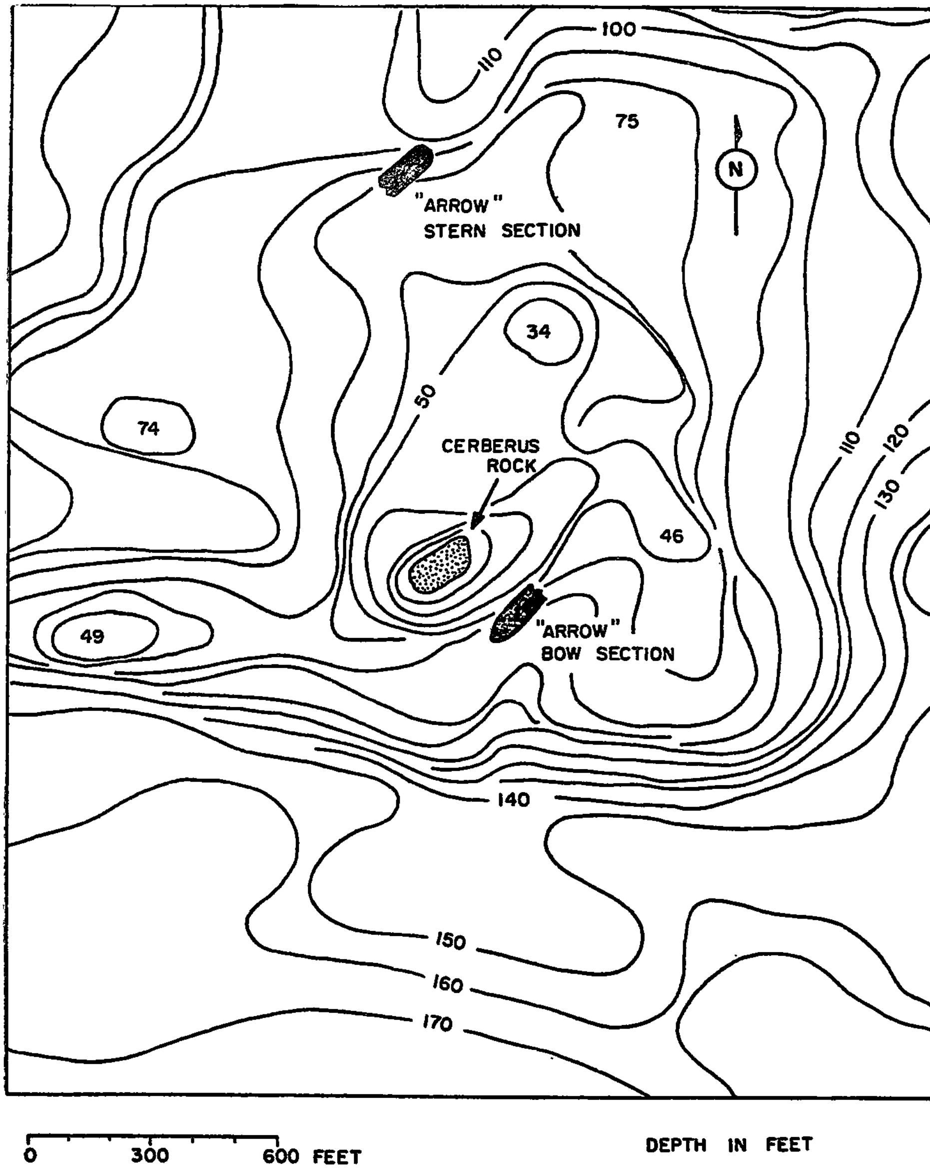


Fig. 14. Cerberus Rock and Sections of the "ARROW"

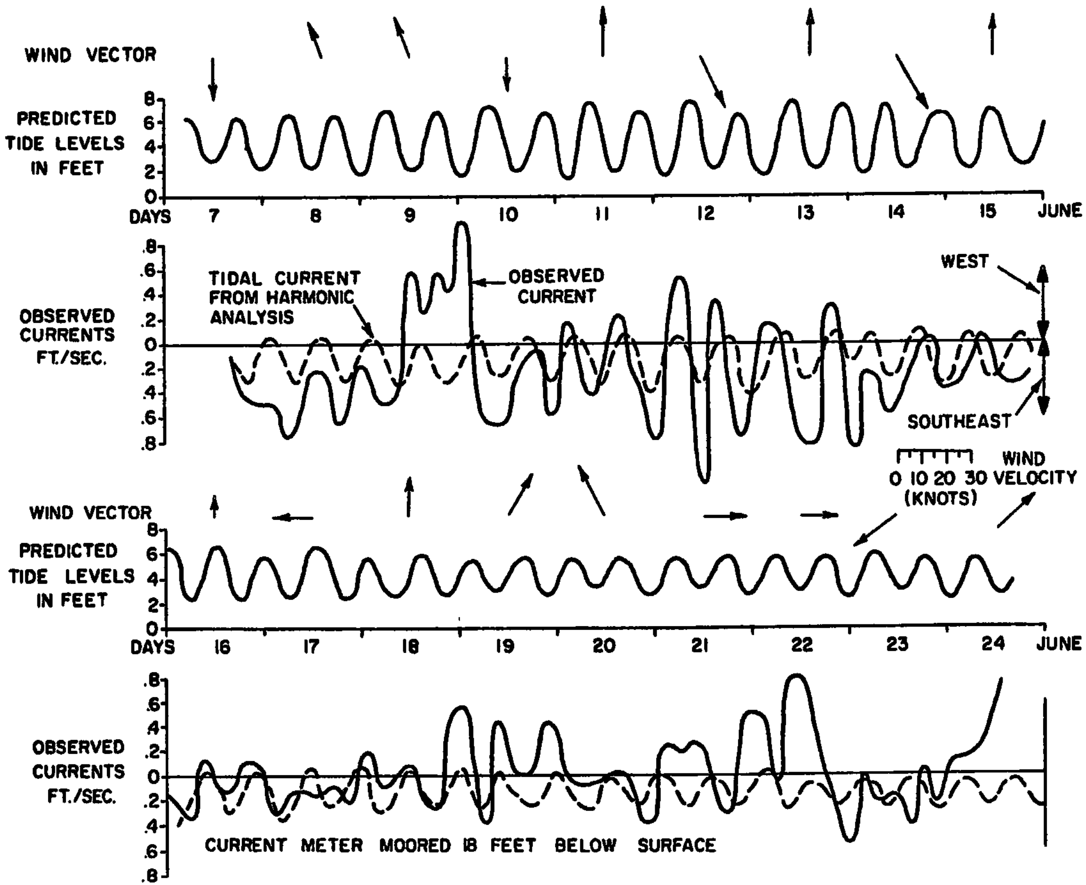


Fig. 15. Tide and Currents Near Cerberus Rock; June 1968

At the time the ship grounded, there was a south wind of 40 knots with a surface drift current of approximately 1.5 ft/s. This wind-induced current decreased quickly with depth so it can be assumed that the average wind driven current acting on the ship was not higher than about 0.8 ft/s (0.35 kn) in northerly direction.

Thus, it appears that the resultant current, due to the tide and the wind, was between the limits of zero and 0.8 ft/s northerly toward Cerberus Rock.

3.4 Conclusions

(1) At the time the "ARROW" ran aground there was a storm with average winds of 40 to 50 knots over the Continental Shelf and Chedabucto Bay.

(2) The maximum wave heights were in the order of 25 to 27 feet on the open sea while refraction studies and a later survey indicate they were probably more than half these values at Cerberus Rock.

(3) At the time of the grounding, the currents near Cerberus Rock were probably no greater than 0.8 ft/s, and flowing in a northerly direction. In evaluating the forces on the ship, the effect of the wind on the superstructure of the ship should not be neglected.

(4) Large waves on 4 February and exceedingly low Low-Waters during the following days were the major factors in the quick destruction of the ship.

(5) Most of the oil which escaped from 4 February to 12 February appears to have been contained in the Bay by the prevailing winds. After the stern section sank on 12 February, the wind became more westerly and it is probable that part of the oil which escaped during the sinking of the stern section was carried out to sea.

4. WIND, WAVE AND TIDE OBSERVATIONS DURING THE SALVAGE OPERATION

To obtain a better understanding of the environmental forces under which the oil recovery had to be performed, the geostrophic wind data for the area were analysed and a floating wave tower was built and moored near the wreck to obtain wave information. In addition three temporary tide gauges were installed.

4.1. Wind

For the period of the operation, the Atlantic Weather Central in Halifax provided geostrophic winds from synoptic weather charts which were converted to surface winds as discussed under 3.1. The vectors of these winds are plotted on Figures 16, 17, 18 and 19.

A review of the data clearly indicates that the winds after 12 February were generally more from the west than before. Had these wind fields prevailed during the major oil spills from 4 February to 12 February, much of the oil which was deposited on the shores of the Bay would have drifted out to sea.

The wind vectors also give an opportunity to track the oil movement during certain periods.

4.2. Wave Survey

To provide wave information for operations at the salvage site, a wave recording station was installed on 15 March, 1.48 miles south-east of the wreck in 150 feet of water. After the oil had been removed from the wreck, the station was moved on 15 April, for scientific reasons, toward Jersyman Island into about 100 feet of water. The recording of waves lasted from 17 March to 23 April, 1970, with an interruption from 4 April to 13 April.

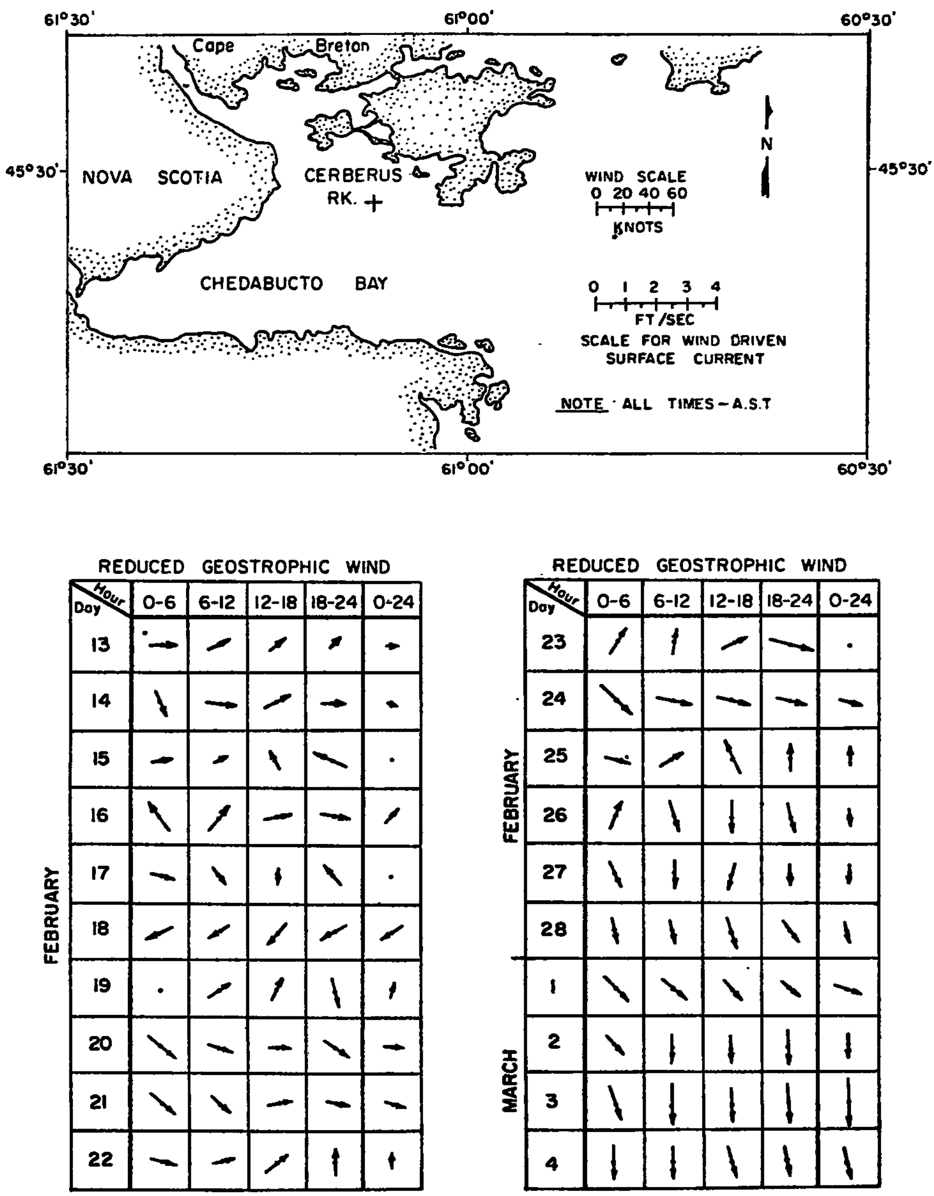


Fig. 16. Mean Wind Vectors from 13 February to 4 March, 1970

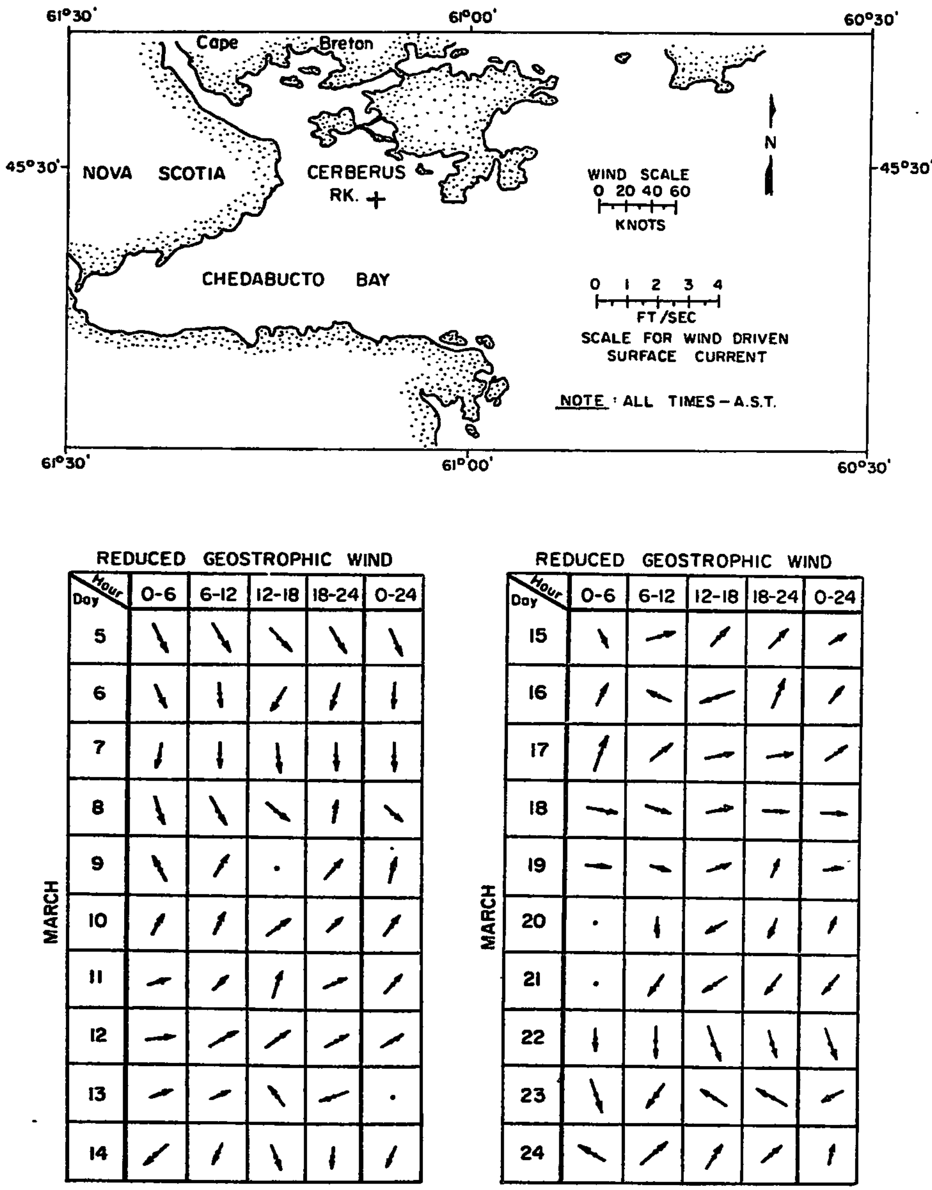


Fig. 17. Mean Wind Vectors from 5 March to 24 March, 1970

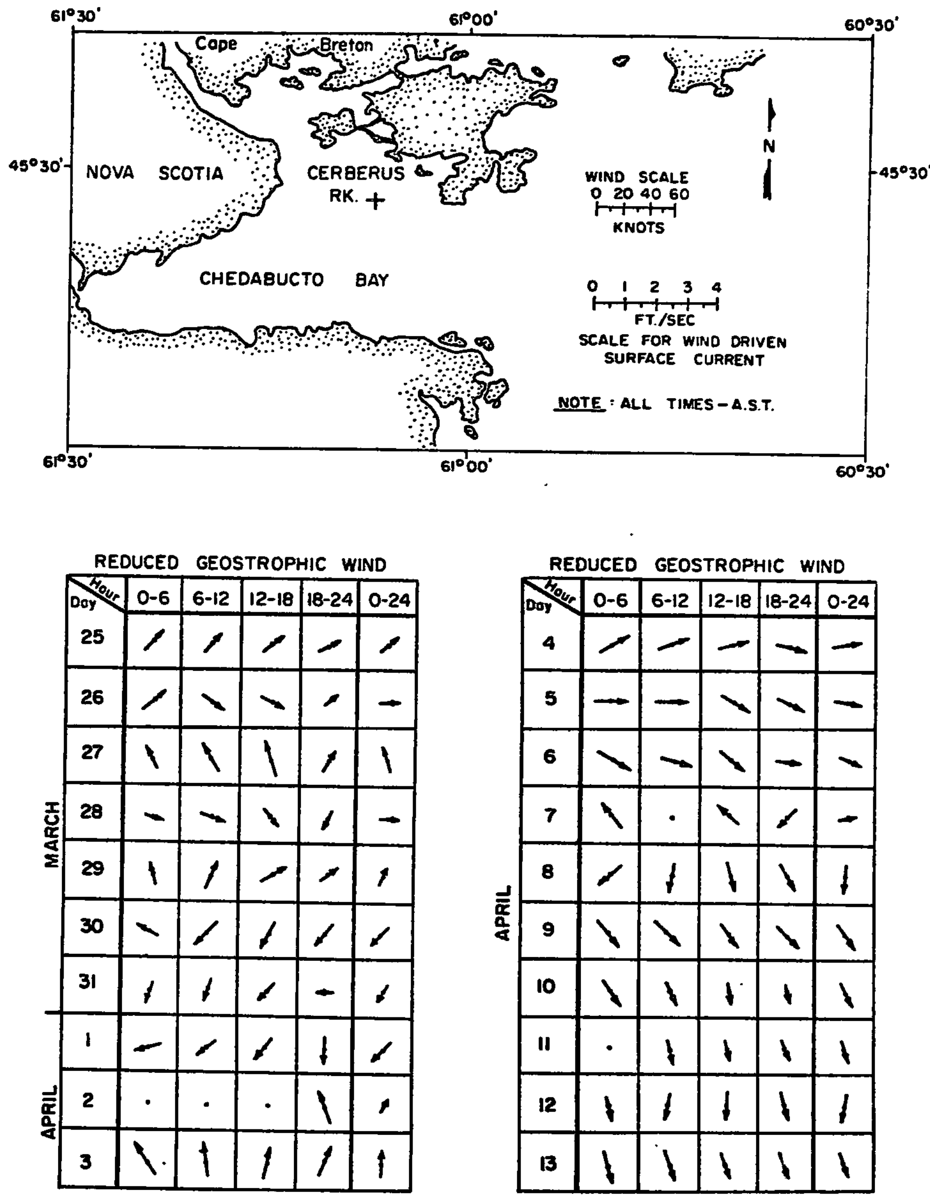


Fig. 18. Mean Wind Vectors from 25 March to 13 April, 1970

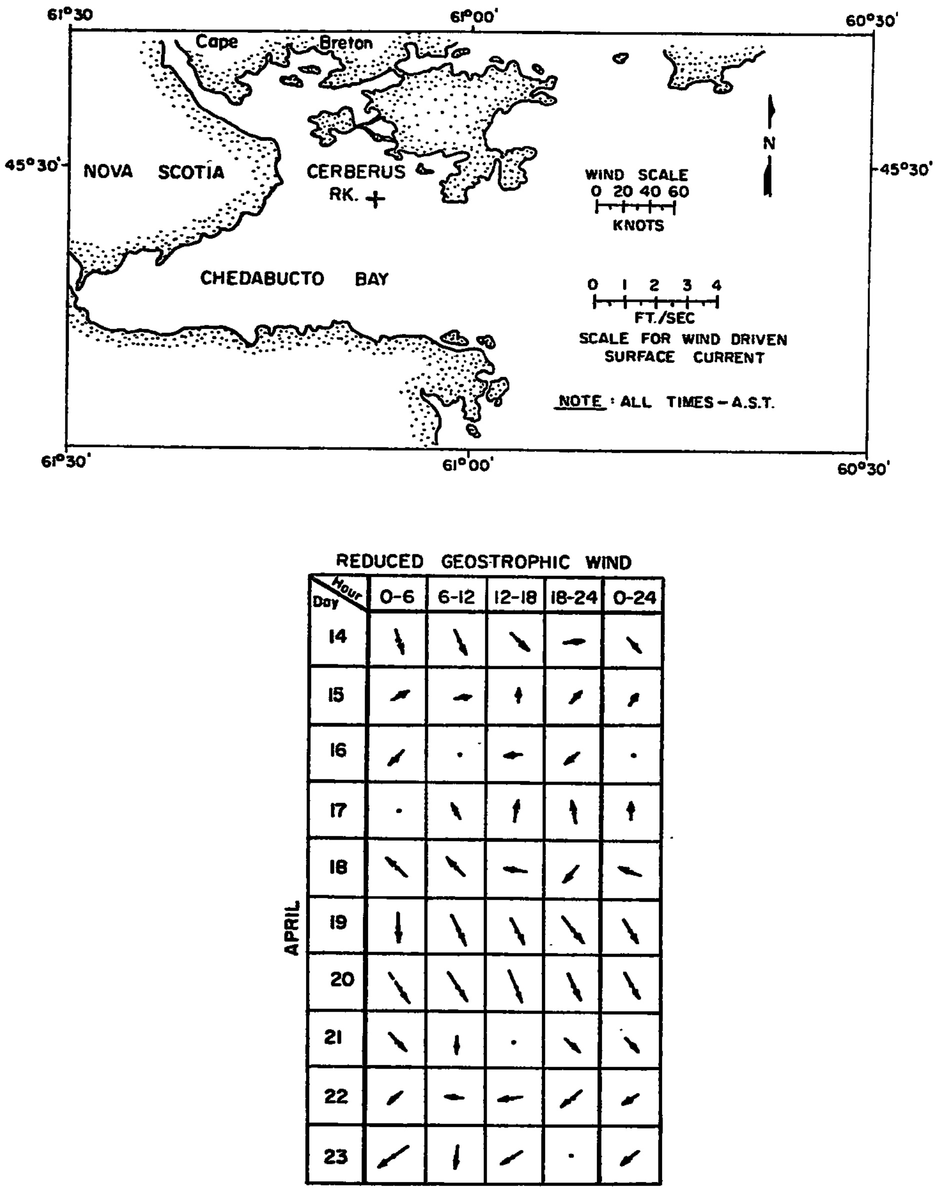


Fig. 19. Mean Wind Vectors from 14 April to 23 April, 1970

The recording system consisted of a portable tower to support sensors and telemetry equipment, and a central receiving station for recording and processing the wave information.

4.2.1. Wave Measuring Equipment

The wave measuring tower, which was especially designed and built for this survey, consisted of three 20 foot sections of 6 inch diameter Schedule 40 aluminum pipe and one 15 inch section of 8 inch diameter Schedule 40 pipe (Figures 20 and 21). Six 5 foot lengths of 4 inch diameter pipe were welded to the larger pipe, just below the water line, to provide additional buoyancy. A 12 foot length of 2 inch diameter pipe was bolted to the top of the tower to give the antenna a height of 24 feet above the water line. The tower, with a buoyancy of 400 lb. was moored in a vertical position by a taut line connected to a 1400 lb. bottom anchor.

Two sensors were used; a ± 10 PSID pressure transducer placed 20 feet below mean sea water and a 35 foot spirally wound wave staff. The outputs from the two devices existing as I.R.I.G. (Inter Range Instrumentation Group) channels, were multiplexed and applied as a modulating signal to a 200 mW f.m. transmitter operating at 250.2 MHz. The electronic circuits were powered by a lead acid battery pack placed at the bottom of the sea.

The recording station was located at Arichat 4.85 miles to the NNE of the tower. The strip chart recorders operated automatically and recorded wave heights for 15 minutes every three hours or continuously when required. The information from the pressure transducer was also processed in an analog computing manifold which continuously displayed the instantaneous square wave height and the wave energy averaged over a 10-minute time constant. The latter two recorders operated continuously at a speed of 3/4 inch/hour.

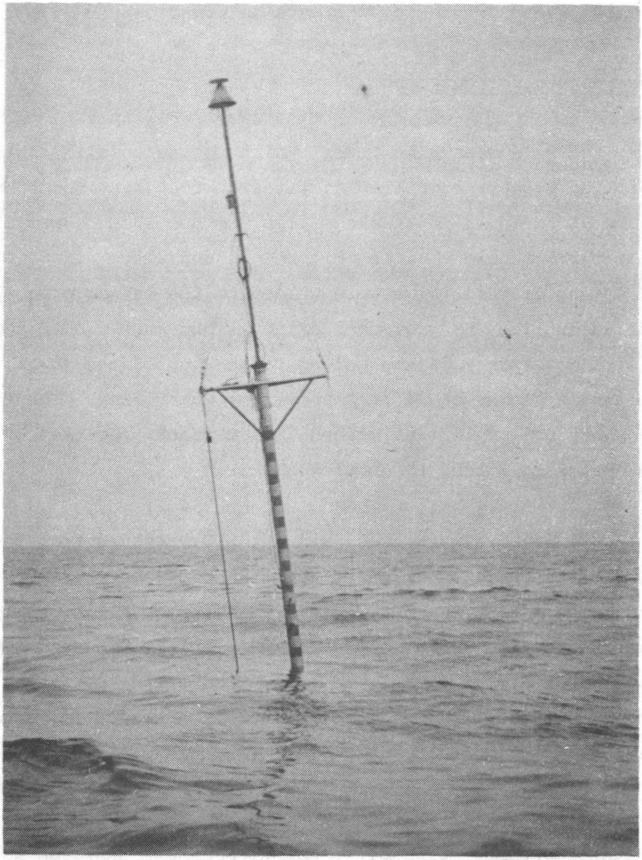


Fig. 20. Floatable Wave Tower at Chedabucto Bay

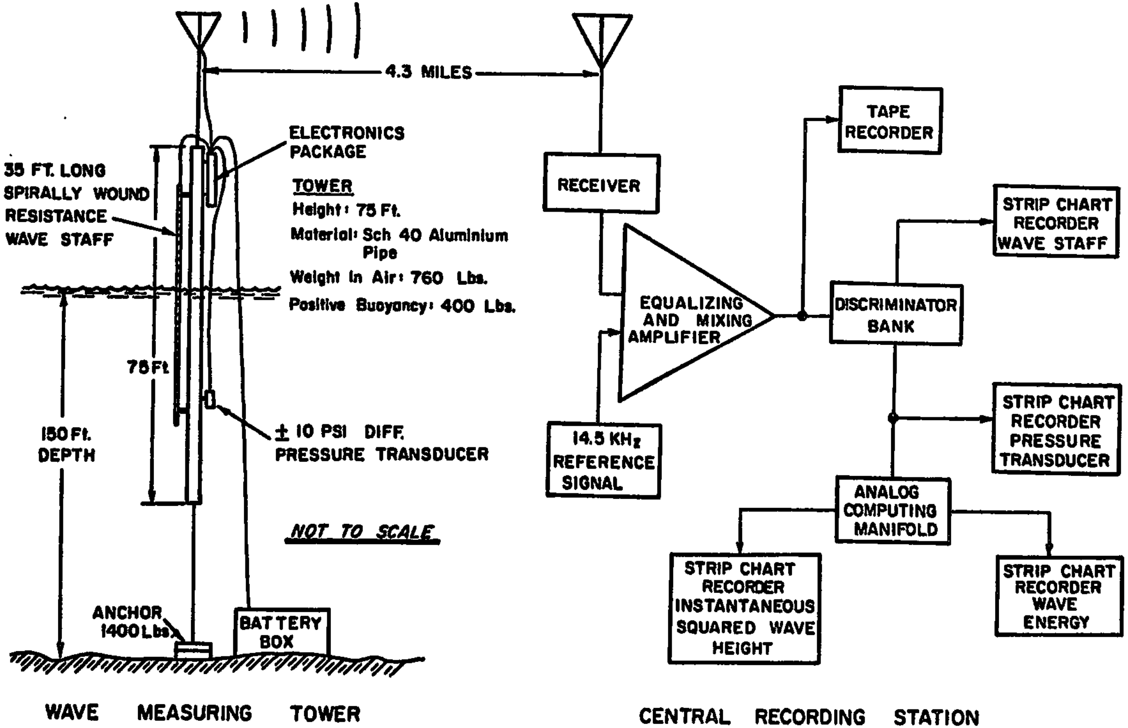


Fig. 21. Wave Measuring Installation at Chedabucto Bay

4.2.2. Wave Data

A time series of the maximum wave heights and the occurrence of winds, wave heights and periods are reported on Figure 22. The curves for wind and wave heights show some similarity, indicating that many of the waves were generated locally and over the Continental Shelf, except for those with periods longer than 9 seconds, which are ocean waves. These ocean waves prevailed 80% of the time and occurred with a wind field from E and SE. Ninety percent of the waves were higher than one foot and 15% were higher than six feet, with the highest on record being 9.5 feet. The longest waves had a period of 11 seconds and occurred 4% of the time.

On Figure 23, a representative section of a wave recording is shown. The upper curve is from the wave staff while the lower one is from the pressure sensor. The pressure sensor, which is placed 20 feet below mean water level, filters out waves of periods smaller than 3.5 seconds. The difference in wave heights from the two methods of measurement is due to pressure attenuation from the surface to the pressure sensor.

4.3 Tide Observations

As already mentioned, there was no record of the water level in Chedabucto Bay when the "ARROW" grounded. The Water Survey of Inland Waters Branch, Halifax, installed on 13 March, three temporary tide gauges, the first at Canso, the second at Guysborough, and the third at Port Hawkesbury. From the records the phase lag of the three stations, the speed of the propagation of the tide wave, the modification to height and shape of the curve, and the basic data for an analytic investigation into the tidal transport, based on the difference method will be obtained.

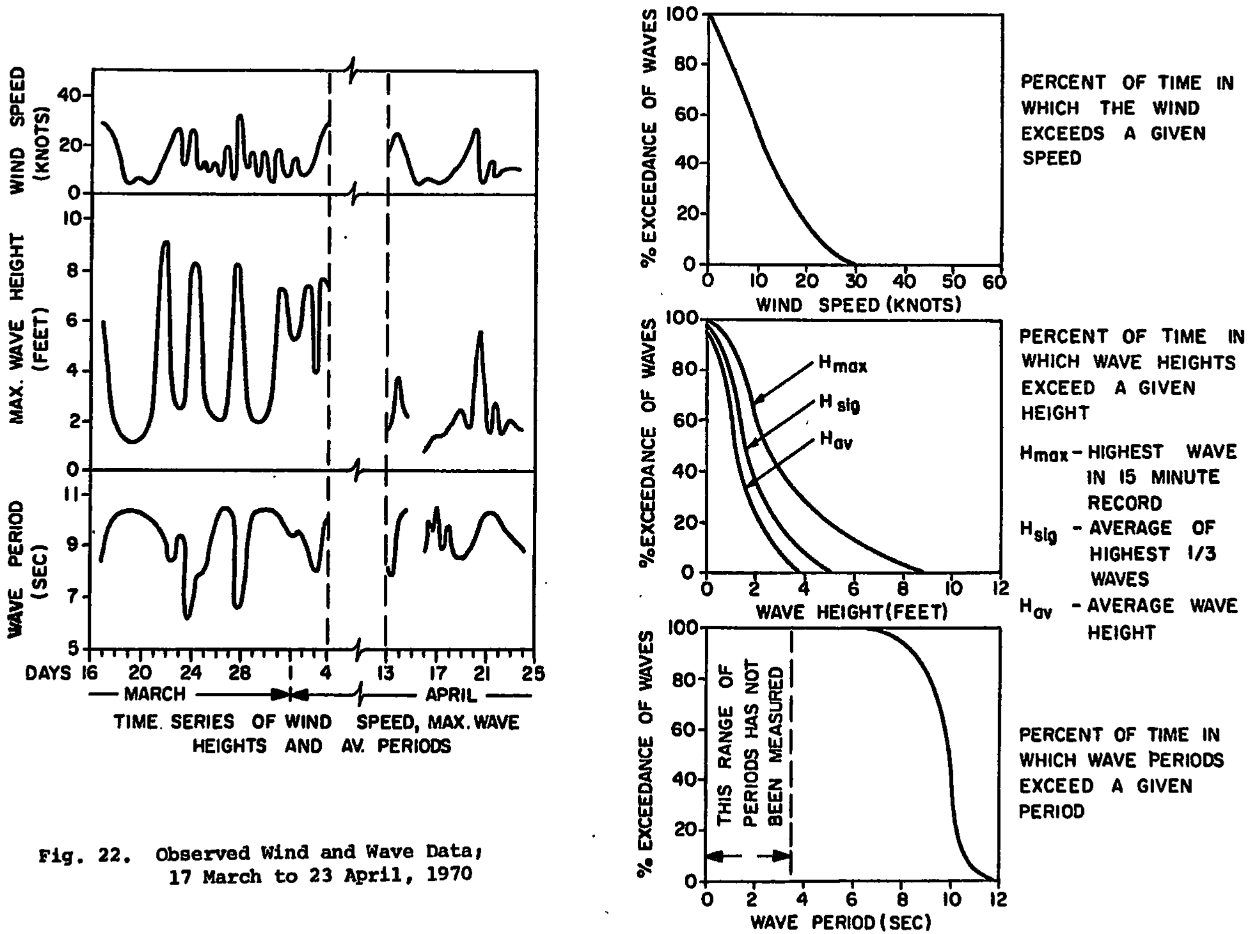


Fig. 22. Observed Wind and Wave Data; 17 March to 23 April, 1970

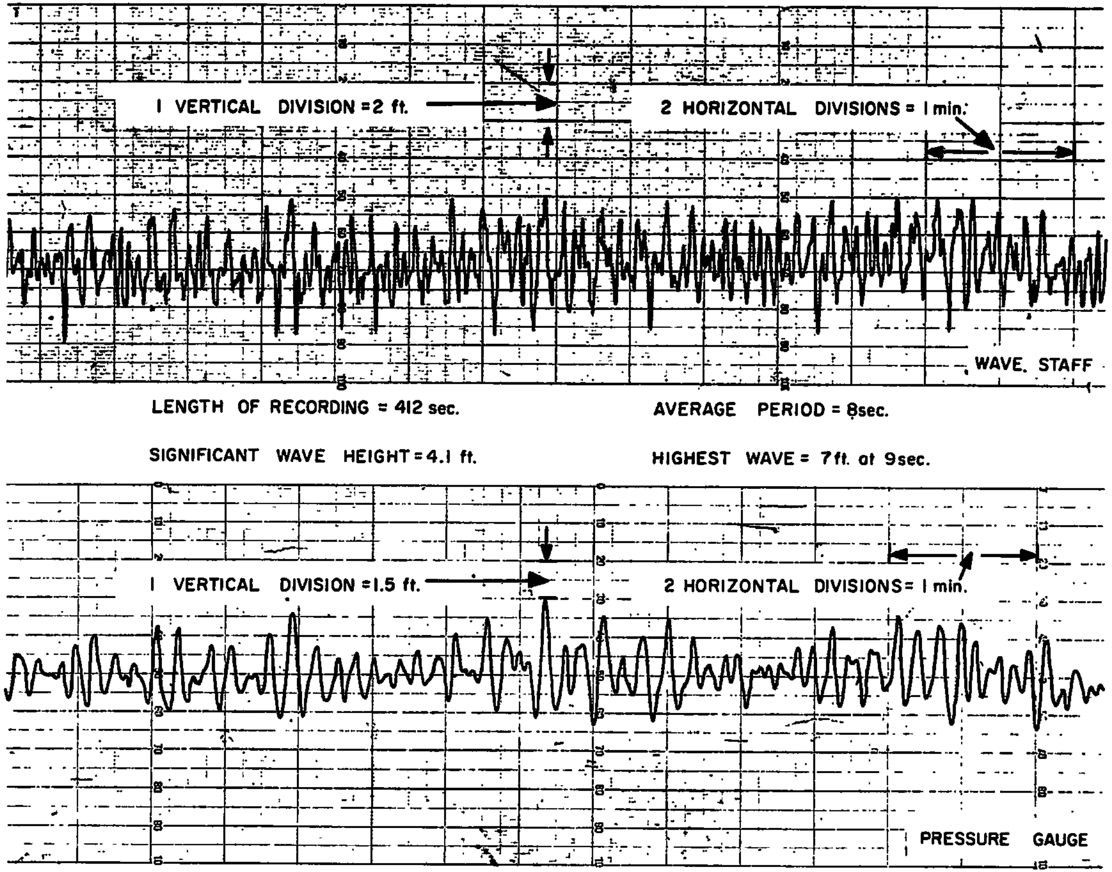


Fig. 23. Wave Recording in Chedabucto Bay

Due to lack of time, the data have not been fully processed. A brief review of the records indicates that distinct short period surges are superimposed on the tide levels. The surges at the different stations, however, do not seem to be related to each other.

5. HYDRODYNAMIC SURVEYS DURING SALVAGE OPERATIONS

During the field studies, a number of surveys were conducted. They included current surveys in Lennox Passage during the construction and closure of a dam, followed by an observation of the water levels on both sides of the dam after completion and studies of the currents and properties of the inlets of Inhabitants River, Guysborough River and Petit-de-Grat. A more detailed survey of the circulation pattern in the Bay was performed using 18 current meters. Other observations were made from ships anchored near the shores. Only part of this survey can be reported since there has been insufficient time to analyze the data. They will be dealt with in a separate A.O.L. Report.

5.1. Lennox Passage Survey

Lennox Passage is a protected waterway connecting the Strait of Canso with St. Peter's Bay and Bras D'Or Lakes.

It was observed that there was a substantial amount of oil held back by ice at the western end of Lennox Passage. Damming of the Passage would prevent the oil from moving into the eastern part of the Passage and St. Peter's Bay particularly during the early spring when the ice is moving out. It was therefore decided to close off the Passage at the bridges to Isle Madame Island.

The question arose of the nature and strength of currents which would be encountered during the construction and closure of the dams.

5.1.1. Currents during Construction of the Dam

A view of the dam site is shown on Figure 24. The sequence of construction of the two dams is demonstrated in the cross section at the top of Figure 25. At the bottom of the latter graph the current velocities at the centre of the channel are plotted during tide cycles of 5 March, before any restrictions were applied to the channel and, of 10 March and 15 March during the construction of the dam. From the figure, it is readily apparent the gradual closure of the channel resulted in a corresponding increase in velocity. Furthermore, as shown on the current pattern of 15 March, the currents became unstable, changing their direction completely within an hour and without any apparent relationship to the rising or falling tide. The reason for this will be explained in the next chapter.

5.1.2. Water Levels at the Dams

As the dams neared completion, it became apparent that the water levels on both sides were behaving differently from the water levels arising from the tidal fluctuations in Chedabucto Bay.

Three gauges were installed to observe these fluctuations in water level--two tide gauges, one on each side of the larger dam, and a highly sensitive differential manometer gauge for detailed measurements.

As shown on Figure 26, the newly separated bodies of water generally rose and fell with the tide, but fluctuated intermittently in opposite directions with amplitudes up to one foot and periods of about two hours or less.

This phenomenon is commonly known as a "seiche". It describes longer-period natural oscillations of partly or totally enclosed

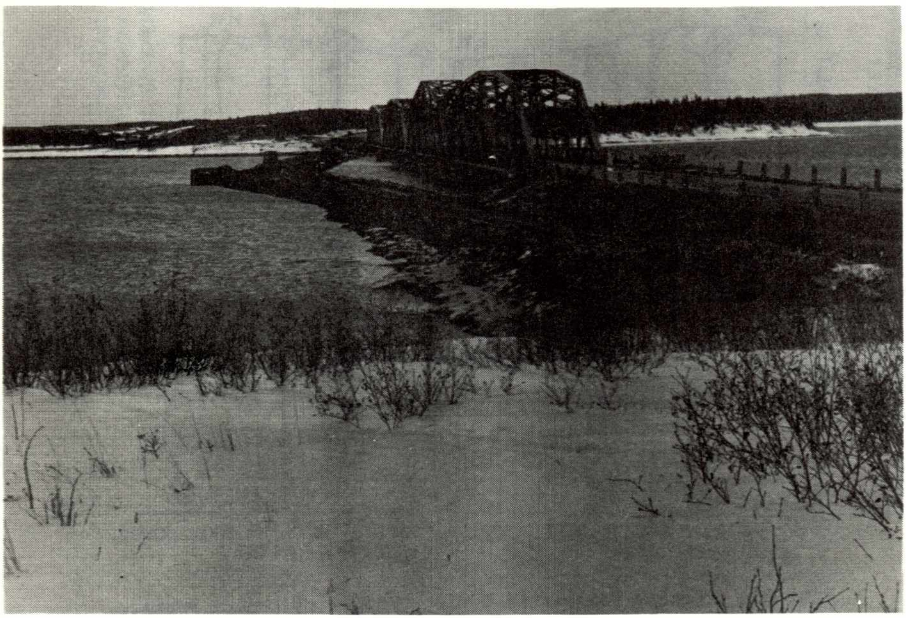


Fig. 24. View of Lennox Passage with dams under construction.

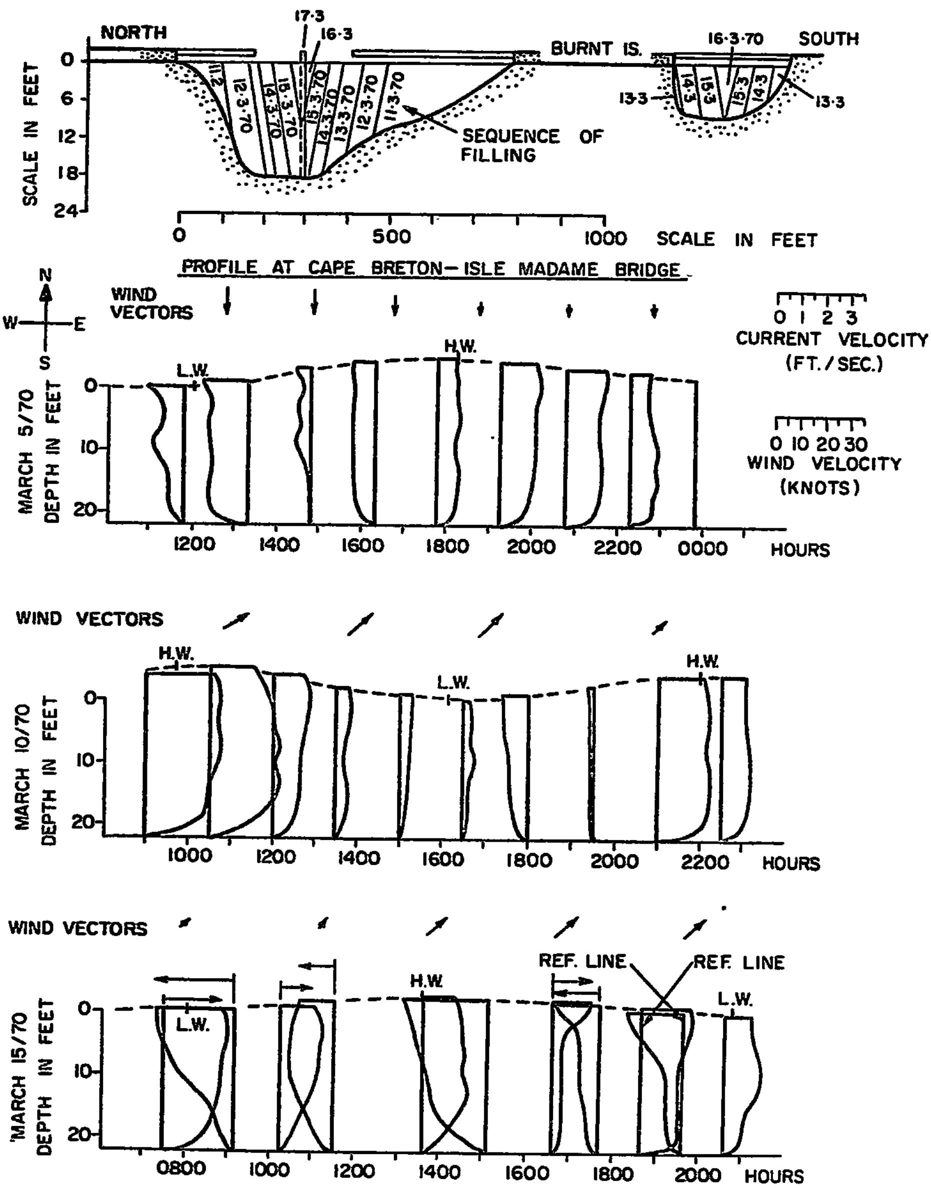


Fig. 25. Current Velocities during Closure of Lennox Passage

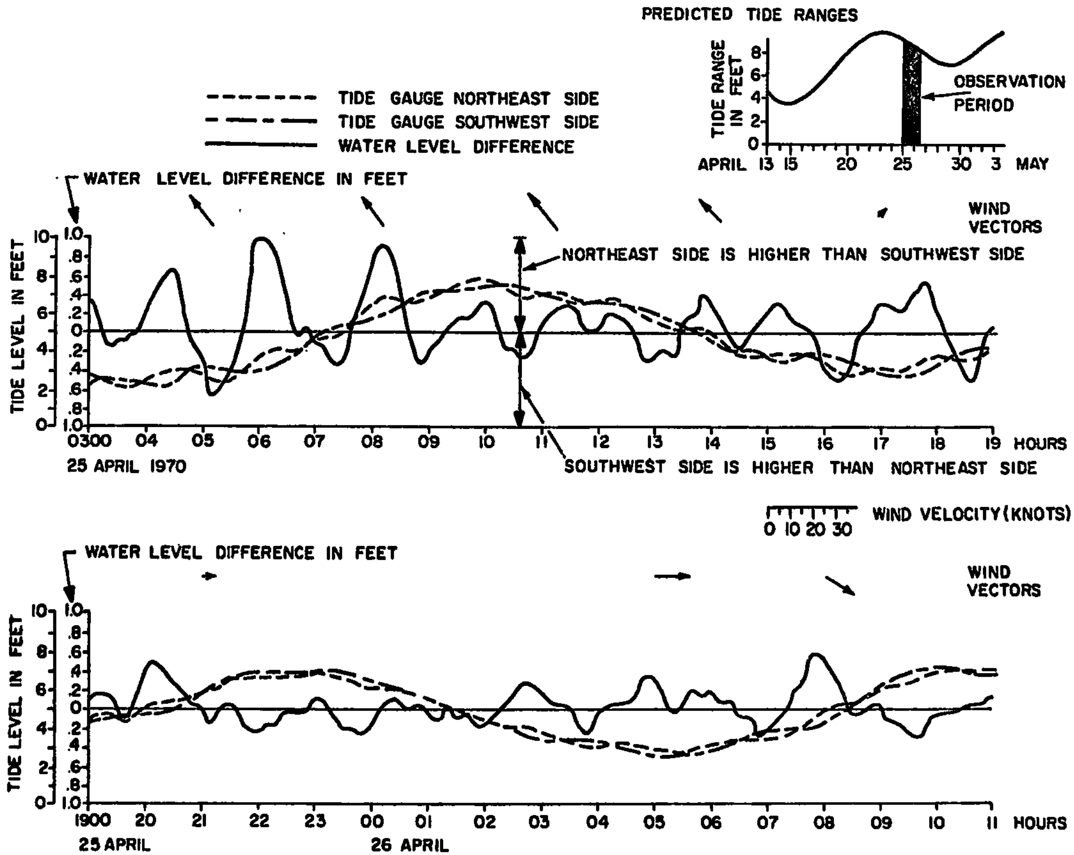


Fig. 26. Tide Levels and Water Level Differences at Lennox Dam

bodies of water which are caused by occasional disturbances such as winds, sudden changes in barometric pressure or ocean surges.

The physical dimensions of the basins, whose natural periods of oscillation would agree with those observed, have not been determined with certainty. It is, however, interesting to note that the tide curve of Port Hawkesbury shows similar oscillations, while the secondary oscillations of the tide gauges of Canso and Guysborough are of different character.

5.1.3. Currents of Lennox Dam Opening

Lennox Passage is a navigable waterway which is to be re-opened after the clean-up operation has been completed. It was decided that the opening in the dam shall not be wider than required for safe and unrestricted navigation.

For short distances, ships can usually handle currents which are larger than half their maximum cruising speed. Since fishing vessels and pleasure crafts are the prime users of Lennox Passage it can be assumed that they are able to manage currents of up to 6 ft. per sec (3.5 knots). The width of the opening must therefore be chosen so that its current does not exceed this value.

The currents in the Passage are controlled by tide, seiche and wind. Their respective influence on the flow structure was estimated from current observations and from the analysis of water level and wind data obtained during and after the closure of the dam. The results of this investigation are shown on Figure 27 where the relationship is plotted between the current and the size of the dam opening. The computations for these curves were based on a tide range of 5 feet, a seiche range of one foot and a wind of 40 knots blowing along the Lennox Passage. Second-power velocities were included to give an indication of the kinetic energies involved.

On Figure 27a, b and c are plotted the individual velocities of the tide, seiche and wind. For a 300 foot wide opening the respective velocities are 3.2 ft. per sec (1.9 knots), 3.5 ft. per sec (2.05 knots) and 2.6 ft. per sec (1.5 knots).

It is obvious that these currents occur more in composite form than singularly. The largest current occurs when tide, seiche and wind are acting together and are in the same direction. For an opening of 300 feet, this composite current is in the order of 5.5 to 6.0 ft. per sec, and is therefore within the limit specified.

The frequency of occurrence of these currents may also have some influence on the design of the opening. The regular tidal currents (Figure 27a) will be present about 50 percent of the time, the tide and seiche currents acting in the same direction (27d) 25 to 30 percent, and tide, seiche and wind of 40 knots acting in the same direction 5 percent of the time. The latter condition occurs only during gales, when navigation is coming to a halt. Furthermore, this kind of peak current will last no longer than 30 to 40 minutes at the most. Unfortunately, the time of occurrence of this high velocity cannot be predicted.

5.2 River Inhabitants

In the middle of March as the ice melted, Inhabitants Bay was seen to be heavily polluted by oil and consequently there was a danger--which later materialized--that oil would enter the river system. To determine the currents prior to installing a log-boom, a survey was conducted on 13 March, 1970. The locations of the two survey stations, a cross-section of the channel, and the results, are shown on Figure 28.

As is usual for this type of inlet, the currents are inward during rising-tide and outward during falling-tide. They are weak,

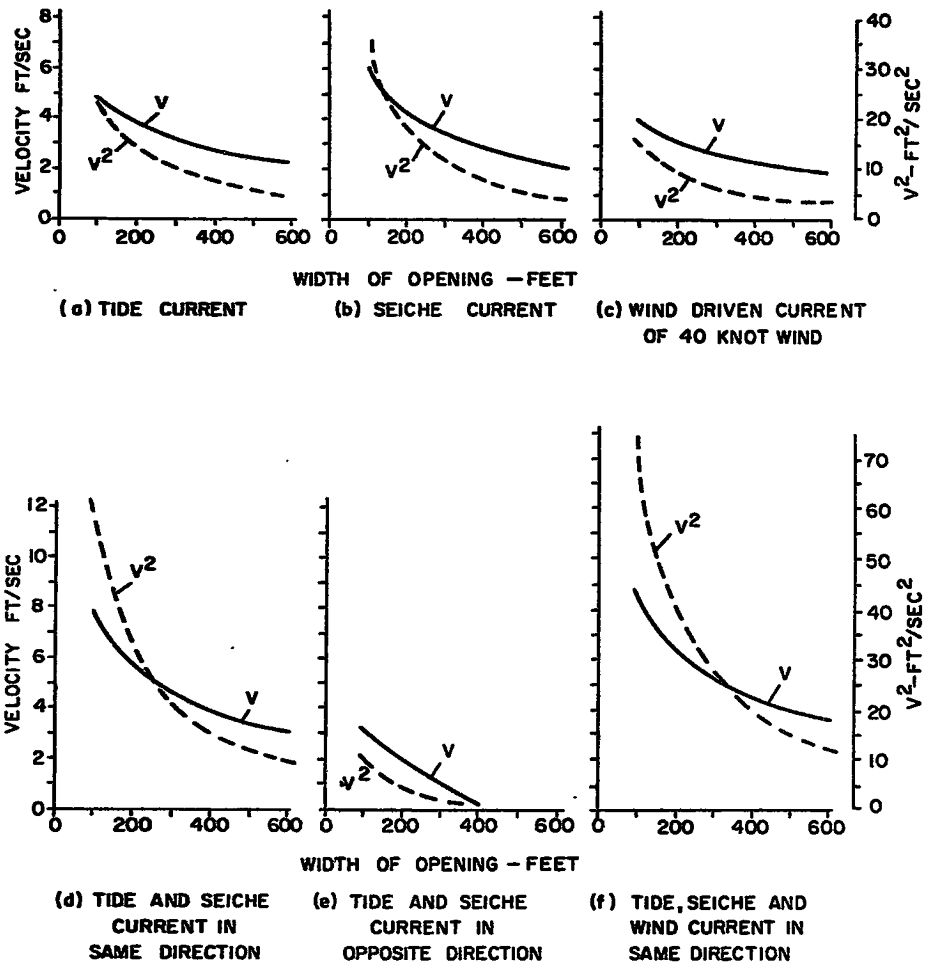


Fig. 27. Current Combinations Versus Channel Widths of Lennox Dam Opening

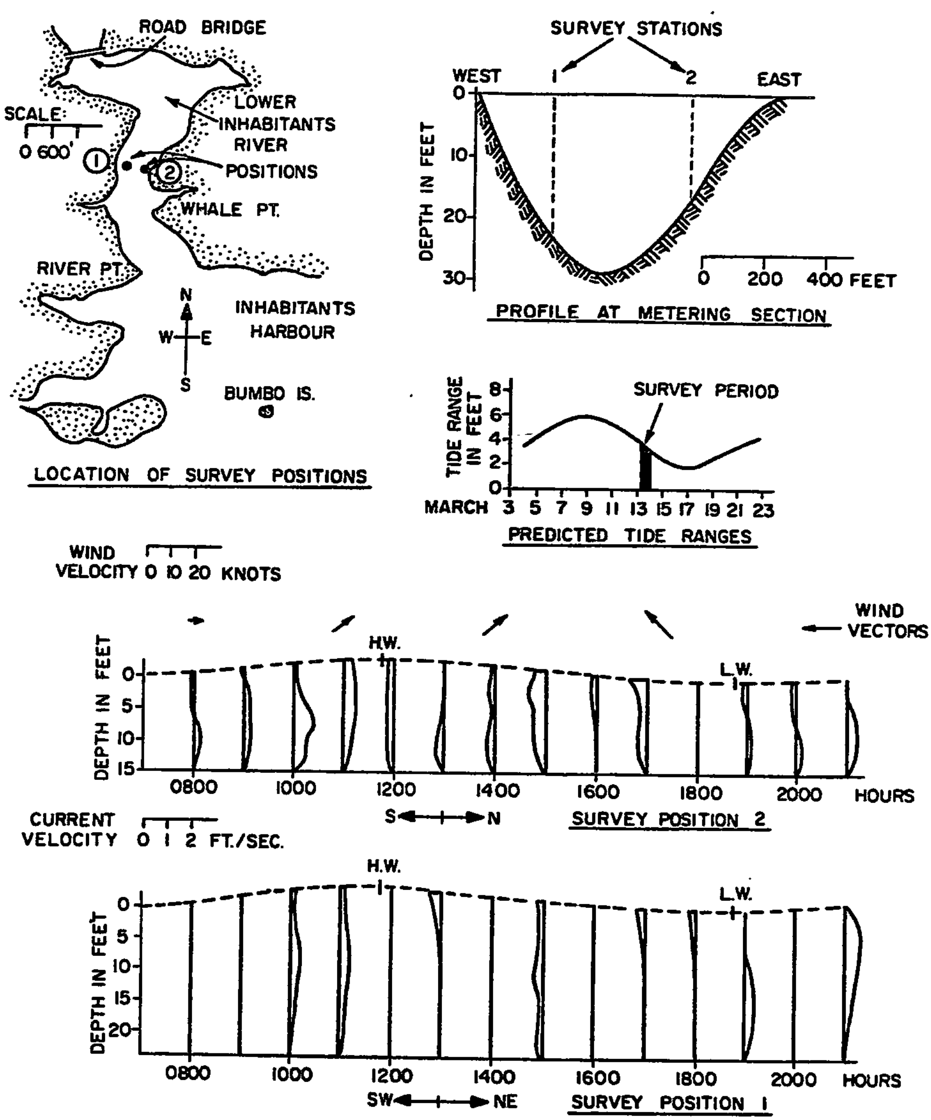


Fig. 28. Current Survey of River Inhabitants; 13 March, 1970

though stronger on the east side of the channel than on the west side; the maximum being 0.6 ft/s and 0.3 ft/s respectively.

These currents were related to a predicted tide range of 3.75 ft. At higher tide ranges the currents would have been greater--probably in the order of more than 30%. There was a density difference between the surface layer and the deeper layer of the channel; the vertical salinity gradient sometimes being greater than four parts per thousand. During freshet, starting in April, a strong density current developed, which, together with the tidal currents, presumably created current velocities several times larger than those observed.

5.3 Guysborough River

The area near Guysborough Inlet was relatively unaffected by oil pollution. However, to be prepared for any eventuality, a brush-boom was installed at the inlet to the system. Current measurements were requested for this task.

Two types of surveys were performed, one from an anchored ship with shipborne current meters and salinity-temperature measuring devices, and a second with moored self-recording current meters placed 9 feet below Low-Water. The first was done on 18 March, 1970, and lasted for 14 hours or more than a complete tide cycle, and the second, also started on 18 March, was in operation for 9½ days. The first survey was made to obtain information about the vertical distribution of currents and water properties while the second was to provide data regarding the change in currents with respect to increasing and decreasing tide ranges and changing wind direction. The locations of the survey positions and the survey data are plotted on Figure 29.

On the east side of the channel at station 1, the northwesterly or inward flow during rising-tide was, in spite of a strong wind in

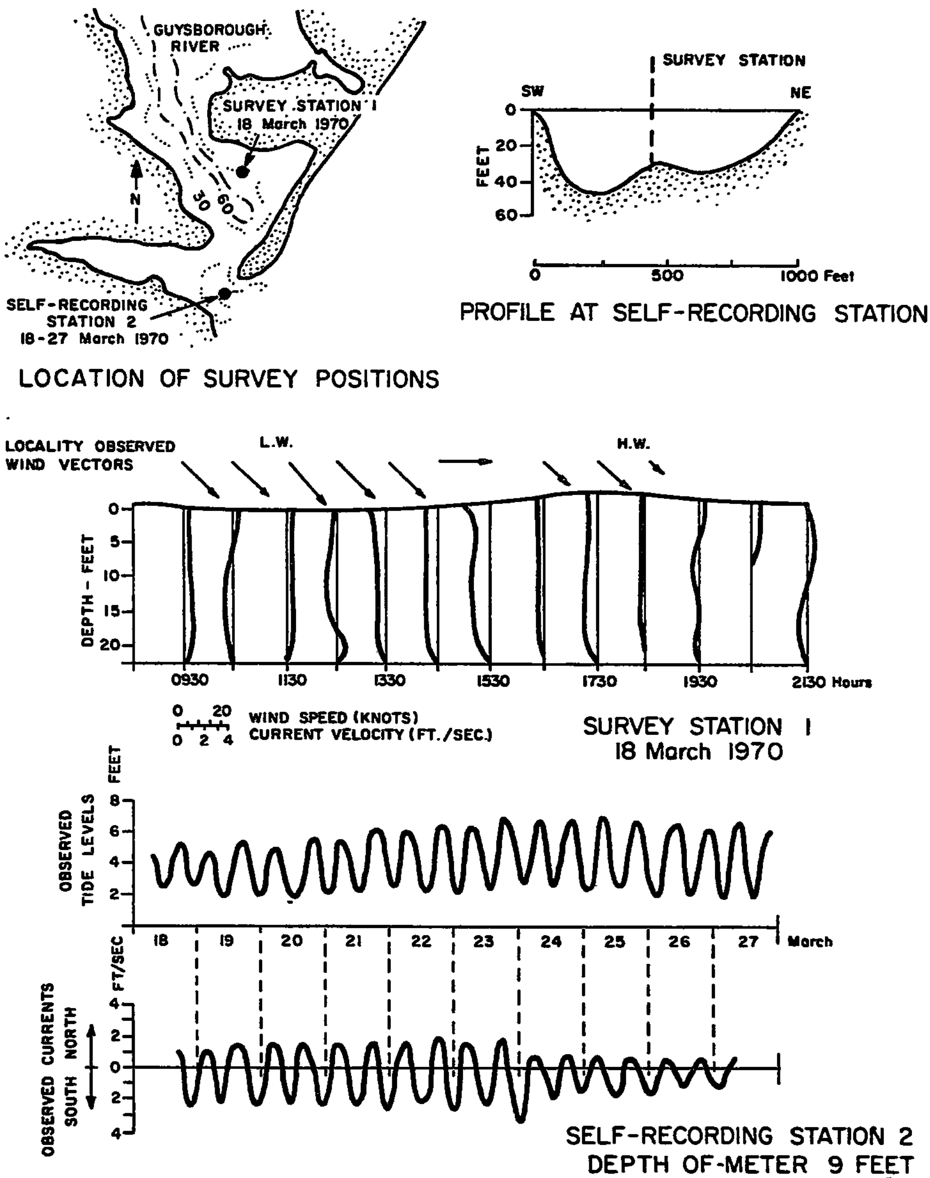


Fig. 29. Current Survey of Guysborough River; 18 March; 18 to 27 March, 1970

the opposite direction, up to 2 feet per second and prevailed through the entire depth. The outward currents during falling-tide were weak, but a non-directional current meter, installed during the same period on the west side of the channel, indicated that there was, at least on the surface, a continuous outflow throughout the entire tide cycle. Thus, it appears that during northwesterly winds the water flows inward more on the easterly side and outward more on the westerly side of the inlet.

The 9-day observations at Station 2 in the centre of the inlet indicate that on 18 March, the maximum current was 2.4 feet per second with a tide range of 2.5 feet. In the following days, from 18 March to 24 March, the tide range more than doubled; the increase in High-water being .reater than the decrease in Low-Water. This large rise in level indicated the presence of a meteorological disturbance which caused the water level in the Bay to rise by about 1.3 feet. Little increase in the maximum current velocities could be observed during the increasing tide ranges. However, on 24 March, after a steady wind from the east, which had pushed the water up the river system for three hours, suddenly ceased, the returning flow super-imposed on the outgoing tide created an ebb-flow of more than 4 feet per second (2.4 knots). This current surge moved the current meter into deeper water, making it impossible to compare the subsequent data with those of previous observations.

It is therefore possible that when a large tide range occurs with a certain combination of meteorological conditions, the currents in the mouth of the inlet to Guysborough River can be well over 4 feet per second.

Log and brush-booms up to 1000 feet long have been able to with-stand currents of 2 feet per second. The drag-force on objects in the water increases with the square of the current velocity, therefore, a current of 4 feet per second would produce a force on a boom four times larger than that due to a current of 2 feet per second current. A boom of the conventional design may not be able to withstand such forces. Anchors may also be a problem.

5.4. Petit-de-Grat Inlet

Petit-de-Grat Inlet separates Petit-de-Grat Island from Isle Madame and houses a fishing harbour with two fish processing plants. Small fishing vessels can enter the Inlet from the Bay of Rocks.

Because the approaches of Petit-de-Grat Harbour were heavily polluted with oil at an early stage and again later, it was important that more information be obtained on the character of the currents and the forces which generated them. Two surveys were conducted towards the end of March,--one with a self-recording current meter at the northern end of the Inlet and the second with three current meters from Petit-de-Grat bridge.

The self-recording unit did not function properly and upon recovery, it was found that a piece of wood had jammed the propeller.

The survey from the bridge was performed on 25 March, 1970, over a period of one tide cycle. Since the results from the three meters are very similar, the data from only one are plotted on Figure 30.

As may be readily seen, the currents flowed continuously towards the Bay of Rocks with only one exception at 1230 hours. The current strengths fluctuated from about 0.3 feet per second to more than 2 feet per second; the highest currents being near Low and High-Water. Whether these currents were generated primarily by winds or by a combination of winds and tides, cannot be determined by observations over one day.

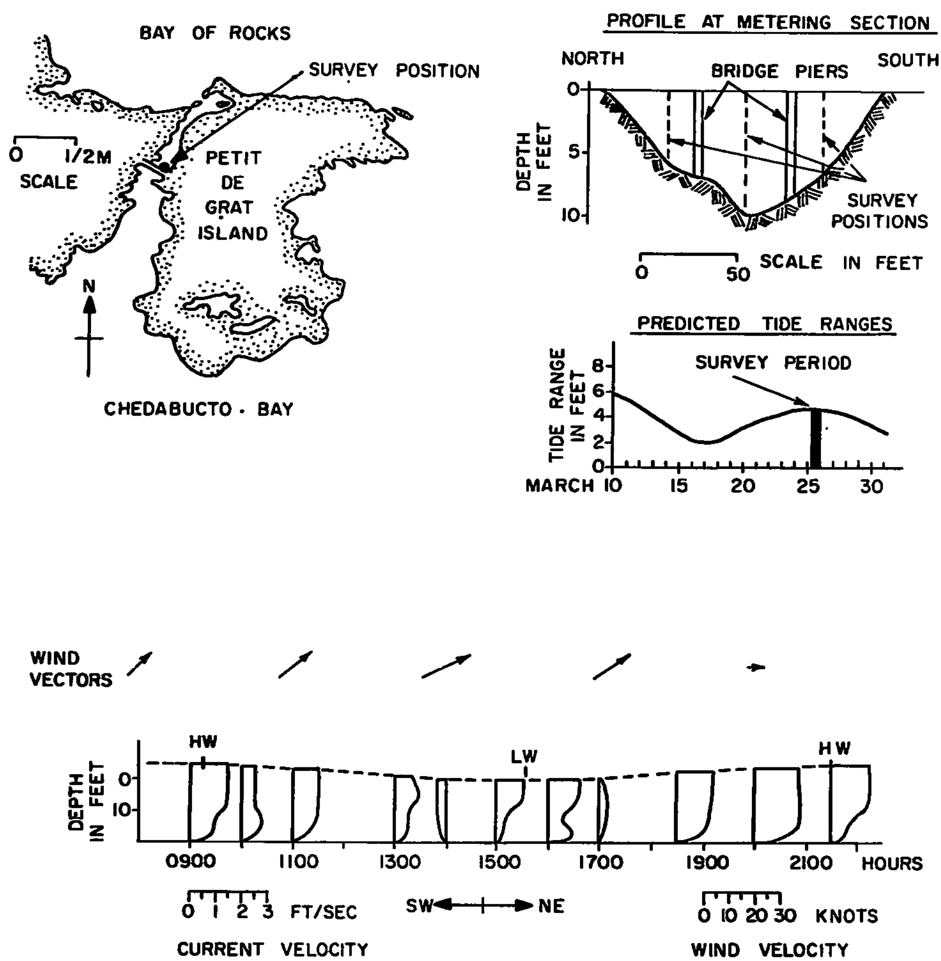


Fig. 30. Current Survey of Petit-de-Grat Inlet; 25 March, 1970.

5.5. Forecast of Oil Movement

On 25 March at 1600 hours an oil spill occurred at the wreck and it was requested that its movement be predicted during the coming 10 hours. During the remaining daylight hours the movement of the oil slick was followed by ships.

It was obvious that the oil was moving under the combined effects of tide and wind. For a predicted tide range of 4 feet, the current amplitudes were assumed on the basis of the 1968 current survey to be 0.8 feet per second at an angle of 285^0 at rising tide and 1.1 foot per second at an angle of 140^0 at falling tide. The direction of the wind was reported to be from 260^0. Problems arose in estimating the strength of the wind over the oil slick; Jersyman Island lighthouse reporting this to be 5 knots. Combining the force of this wind with that of the tide in a force diagram, indicated that the oil would move towards Janvrin Island rather than toward Jersyman Island.

The other source of wind information was the gradient wind which indicated an average wind of 15 to 20 knots from a direction of 250^0. Assuming this to be correct, the observed course and speed of oil slick could be verified using an oil slick speed to wind speed ratio of 0.020.

Using these data and hoping that the wind would not change direction during the night, the course of the oil was charted by vector addition. The resultant vector, and thus the point where the oil would probably be the next morning, is shown in Figure 31.

Reconnaissance flights the following day verified the forecast.

5.6 Circulation Study of Chedabucto Bay

The surveys conducted during the earlier field operation were

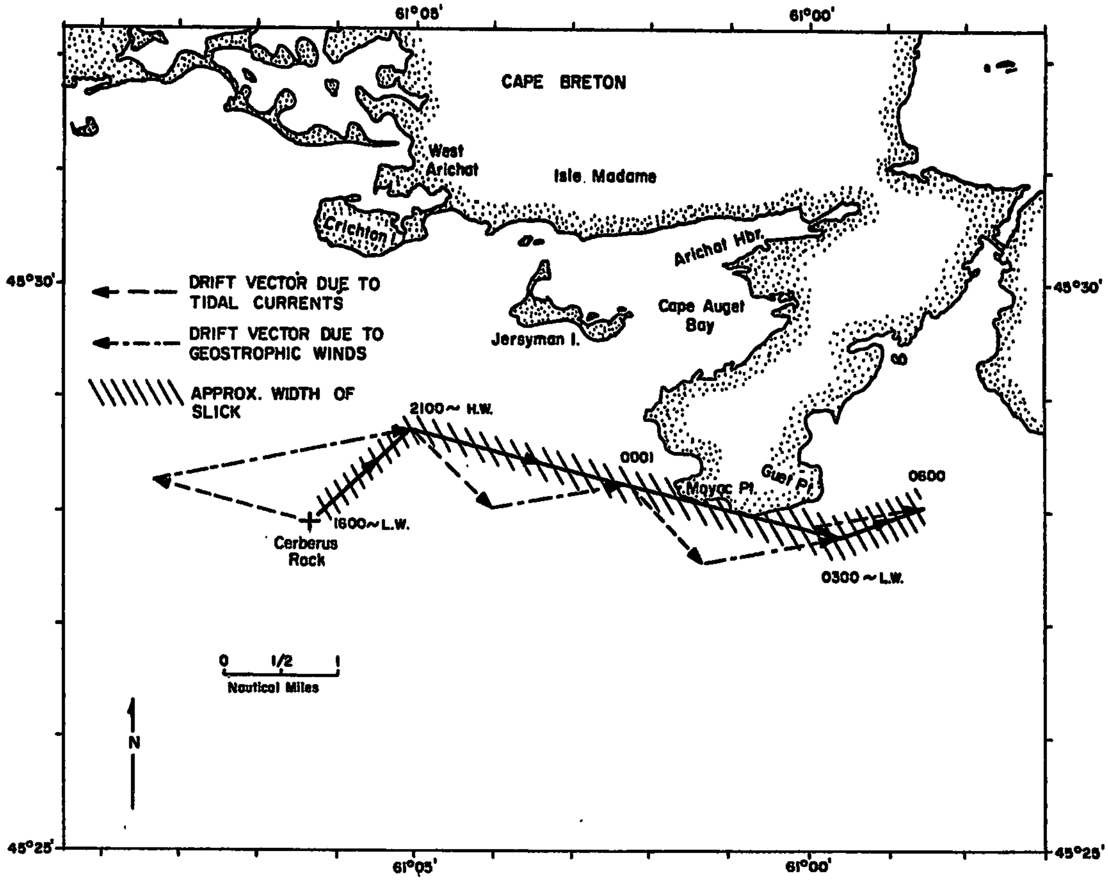


Fig. 31. Calculated Track of Movement of Oil Spill; 25-26 March, 1970

dictated by the need for information required during the salvage operation. These surveys were conducted in adjoining inlets and channels which had been or might be affected by oil pollution.

Little or nothing, however, was known either of the hydrodynamics of Chedabucto Bay itself or of their effect on the oil disaster. It was imperative to have information on the flushing rate and circulation pattern of both the wind driven surface layer and the deeper layers. Because of the possibility that these deeper layers were involved in the transport of oil droplets into or out of the Bay, it was necessary to study their movement in order to have a better understanding of the disaster and its consequences.

For this purpose, 18 self-recording current meters were placed in two transverse sections across the Bay; the first being located at the entrance to the Bay and the second at the centre. The installation across the entrance section consisted of two moorings with three self-recording current meters arranged vertically and the one at the centre of the Bay consisted of three moorings each with four current meters arranged vertically. Shipborne meters were used near the shore at each survey cross section. These ship stations were located on the north side at Heath Head, on the south side at George Island, and in the outer survey section, and on the north and south side at Crichton Island and Black Point respectively, in the inner survey section. The locations of the moorings and ship stations are shown on Figure 32. The self-recording stations were in operation from 6 April to 23 April, 1970, and the ship stations were occupied on 16 and 22 April at Heath Head, on 16, 17 and 22 April at George Island, on 11, 15 and 21 April at Crichton Island, and on 11, 15 and 21 April at Black Point. Salinity and temperature observations were made at all stations of the survey system on 8, 10, 12, 13, 14, 15 and 16 April, 1970.

The data of the shipborne shore stations have been analyzed and

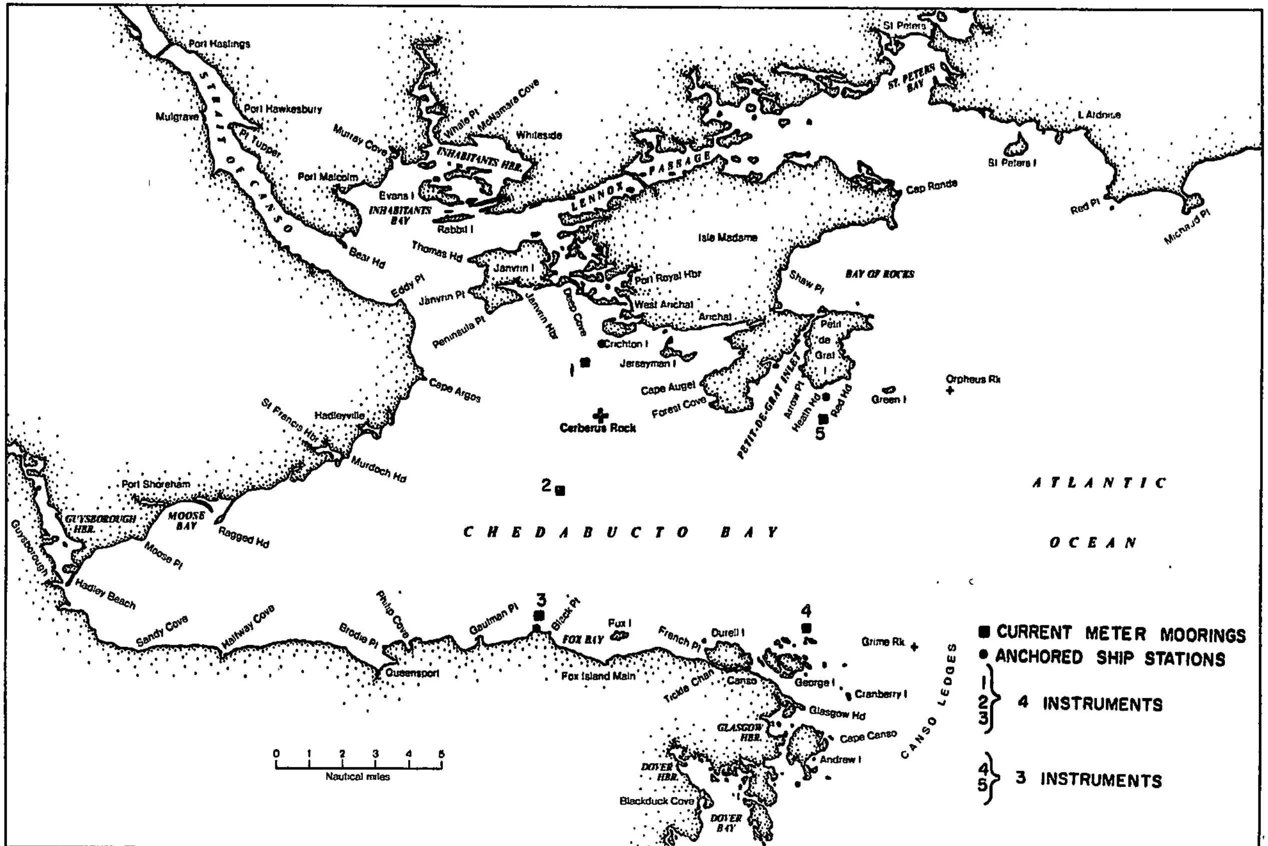


Fig. 32. Location of Current Meter Stations for Circulation Study of Chedabucto Bay.

plotted, however, there has been insufficient time to analyze the data from the 18 self-recording current meters of the moored stations.

Some interesting features have emerged from the data of the shore stations. The results obtained at Crichton Island and Black Point are plotted on Figure 33, and at Heath Head and George Island on Figure 34. The first pair were surveyed on 21 April with a wind of about 10 knots from the NW, and the latter on 22 April with a wind of similar strength from the ESE.

At Black Point, on the south side of the Bay, the current through the entire depth was stable and in good agreement with the tide. During falling tide, the water generally moved outward with currents in the order of 0.4 to 0.6 ft/sec., but during rising tide, the water was divided into two layers, an upper layer which flowed outward and a lower layer which flowed inward. The thickness of the upper layer increased with time. Because the wind acting upon the small strip of water along the coast could not have caused such large currents, they must have been due to the accumulative effect of the wind driven surface layer over a large area of the Bay which gathered along the south shore and from there flowed out into the ocean. Furthermore, the salinity and temperature distributions indicated that there was also a density current which contributed to the strong outward surface flow. Hence, not only tides, but also winds and density differences appear to be important factors in the circulation processes of this part of the Bay.

At Crichton Island, on the north side of the Bay, conditions were quite different. There seemed to be no order in the current structure, nor could any correlation be found with tide, wind or mass field. For no apparent reasons, the current changed direction in one or two hours period or formed short-lived well defined two-layer flow systems. This behaviour may be related to the seiche phenomenon observed in Lennox Passage, but whether these surging currents were caused or

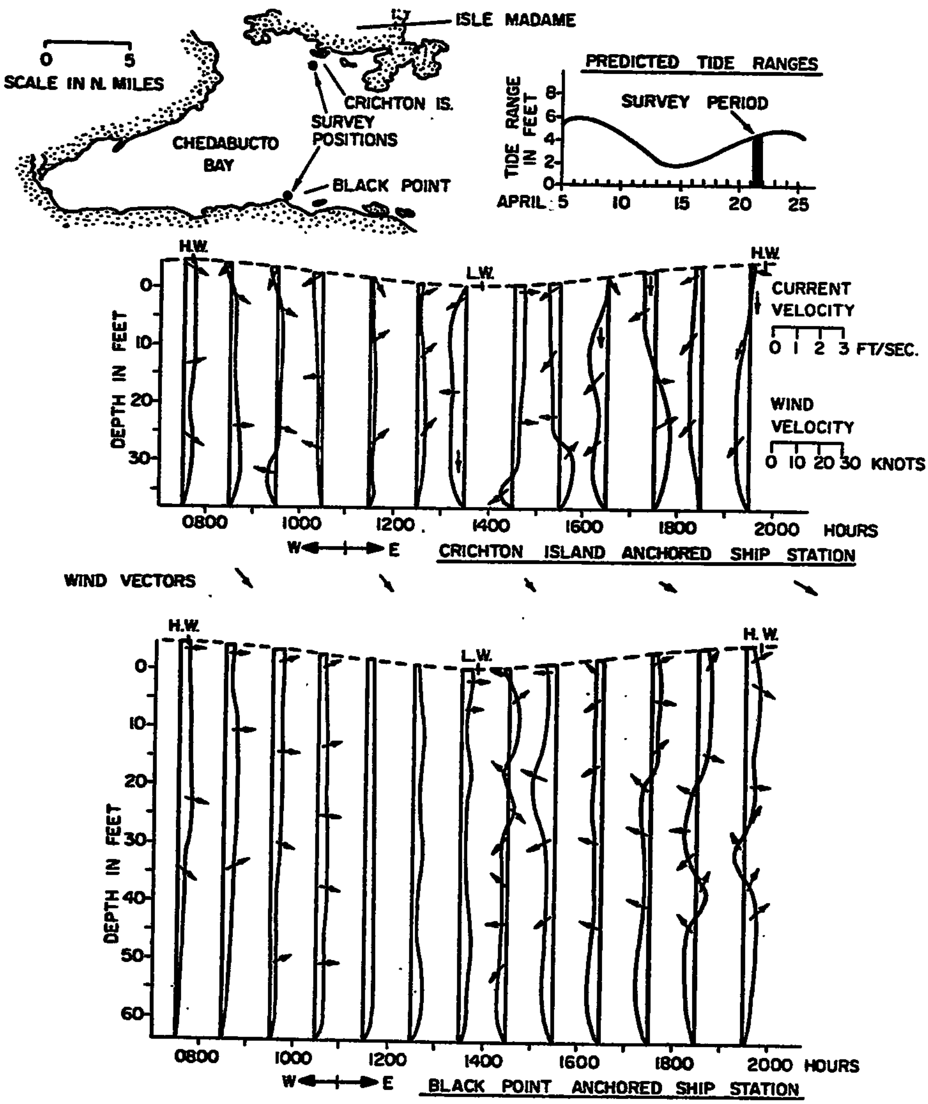


Fig. 33. Current Survey at Crichton Island and Black Point Stations; 21 April, 1970

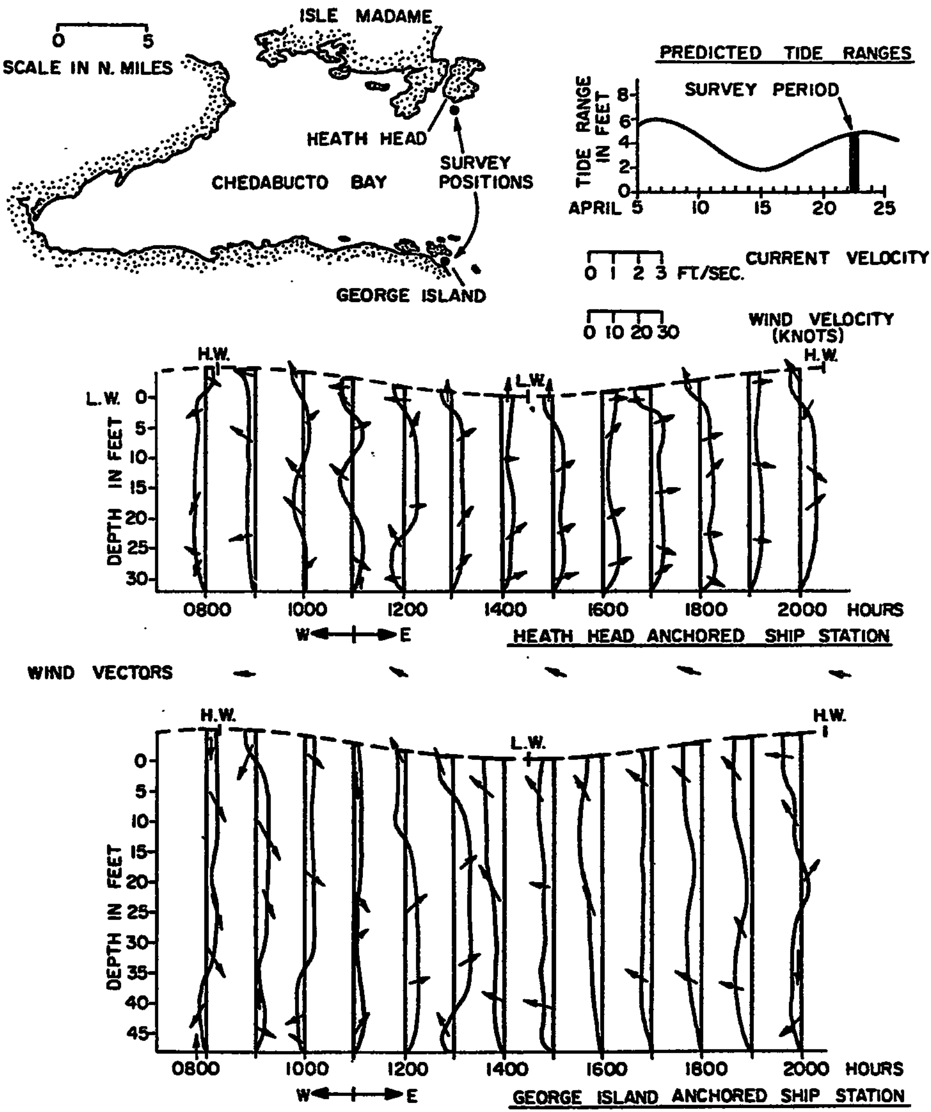


Fig. 34. Current Survey at Heath Head and George Island Stations; 22 April, 1970

influenced in any way by closing off Lennox Passage cannot be stated.

The two outer stations, i.e. on the north side at Heath Head and on the south side at George Island in Canso Harbour Channel were surveyed on 22 April with a prevailing wind of 5 to 10 knots from ESE. As shown in Figure 34, the current structure at both stations was well defined; the currents, however, are more outward on the north side of the Bay and more inward on the south side. At present, no explanation can be given for this behaviour. In spite of the predominantly outward flow, the surface layer nearly always flowed inward. In these instances there was practically no density effect involved and the currents were probably primarily wind driven but here again, the currents were too large to have been generated only by wind shear stressed on the narrow band of water along the shore. The currents must therefore have been due to the accumulative effect of the wind over a wider body of water.

From this brief review, it appears that the currents on both sides of the entrance to the Bay are influenced primarily by tides and winds, while in the Bay they are affected by density currents along the south side and almost completely controlled by seiche-like surges along the north side.

6. ACKNOWLEDGEMENT

The writer gratefully acknowledges the support of a number of persons who were involved in the operation. In the field they included Messrs. D. Dobson, R. Cassivi, F. Ewing, R. Lively, C. Peterson, M. De la Ronde, T. Berkely, B. Hartling, M. Scotney, R. David and J.G. Dessureault.

Special mention is made of Mr. S. MacPhee for his untiring effort in installing and maintaining the wave measuring equipment and Mr. G. Seibert for applying a computer program in the analysis of wave refraction and wave hindcast.

I would also like to thank the Water Survey, Inland Waters Branch, for installing and maintaining three tide gauges; the Atlantic Weather Central and the Meteorological Branch of the Department of Transport for collecting and processing the wind data; the Fisheries Research Board and the Department of Fisheries for providing the survey ship "NAVICULA" and permitting the use of fisheries patrol boats and Mr. E. S. Turner of the National Research Council for having reviewed the report.