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PROPOSAL FOR NAVIGATION IMPROVEMENTS IN THE ST. LAWRENCE RIVER BETWEEN QUEBEC AND MONTREAL

BY

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SUMMARY

Ridges in the channel of the St. Lawrence River, above Quebec, reduce the tide range abruptly. Modification of these restrictions would allow the tidal wave to travel farther upstream, thus reducing the amount of dredging required to maintain the channel because of the increase in bed velocities which assist in scouring the bed material during flood and ebb tide.

There is the added possibility that increasing the range of tide in the upper reaches of the river would have a beneficial effect in reducing the formation of ice and ice packs because of the increased surface velocities. The shipping season at Montreal could likely be extended appreciably.

The proposal outlined in this report is intended to indicate the benefits that could be obtained by improving the river and suggests studies which should be made to investigate the details of the problem.

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PROPOSAL FOR NAVIGATION IMPROVEMENTS IN THE ST. LAWRENCE RIVER BETWEEN QUEBEC AND MONTREAL

1.0 INTRODUCTION

This report outlines a proposal for improving the St. Lawrence River for navigation from Montreal to the Gulf and presents the results of a preliminary study based upon available data. With relatively minor modifications to the channel, it should be possible to reduce channel maintenance and improve ice conditions.

The St. Lawrence Seaway, which has just been opened to ocean-going ships, is the final link in a deep waterway extending to the heart of the continent. The existing navigation channel below Montreal varies in width from 550 to 800 ft. and is maintained by dredging to 35 ft. The cumulative cost to date of maintaining and improving the channel from Montreal to Quebec is understood to be about $100,000,000., and has included removing an extra 51,000,000 cu. yd. of material for deepening from 30 ft. to 35 ft.

The tide range of 3 ft. at the mouth of the river increases to 17 ft. at Gross Island just below Quebec, then decreases abruptly in large increments so that Lake St. Peter is almost non-tidal.

From the Gulf to the Isle of Orleans, the river is wide and deep (Fig. 1). Above Quebec the river channel is narrow and comparatively shallow with shoals and sandbars in several areas.

During the winter months, reaches between Montreal and Lake St. Peter are covered with ice. The action of the tide below the lake breaks up the ice and carries it into the estuary where it tends to accumulate along the south shore owing to the Coriolis effect superimposed on the tidal and river current. An ice-free channel, which has been used for local winter navigation for some years, is usually available along the north shore (Fig. 2). It is probable that, with modern aids to navigation and improved reconnaissance methods, the port of Quebec could be kept open continuously. The remaining barriers to navigation to Montreal then are all located in the river reach above Quebec.

2.0 PROPOSED IMPROVEMENT OF THE LOWER ST. LAWRENCE RIVER

The major difficulties facing navigation are:

(a) sediment in the channel requiring extensive dredging,

(b) swift currents in the narrow sections of the river channel, and

(c) ice formation in the winter months.

These conditions are created by the restrictions in the river channel above Quebec. Rock ridges, such as at Barre à Boulard and Cap à la Roche, and the shoals and sandbars in the river channel above Grondines, constrict the channel and reduce the tide range. Removing these restrictions would reduce the velocity at these points and assist the tidal wave in its progress farther upstream. Consequently both the bed and surface velocities on the flood and ebb, respectively, would be increased in this reach. These should help to scour the bed and prevent the formation of ice packs.

Any improvement should be made in gradual stages with a thorough study on a model of the effect of each proposed change. The size of the river and its importance for international shipping effectively rule out modification by guess work or assumption.

The first steps in the improvement could most advantageously be the modification of the St. Augustin shoal and the ridge at Barre à Boulard. The quantity of excavation required and the design of the improvement (i.e. widening and deepening of the river channel or constructing a separate by-pass channel) cannot be accurately predicted without model studies. However, based on experience with other rivers, an estimated 12,000 sq. ft. increase in flow section would probably be sufficient.

After completing these first stages, careful continous observations should be used to determine the effect of the improvements on the river regime. This would provide useful information for the location and improvement of the next most sensitive points.

These modifications would change the characteristics of the tidal wave, resulting in a reduction of the initial tide range at Quebec, but a partial or total closing of the north channel at Isle of Orleans could, by tidal wave reflection, compensate for the losses and at the same time improve navigation conditions at the downstream end of the island where accretion occurs. Similarly, a restricting channel in Lake St. Peter would increase its tide range by reducing the damping effect of the lake.

The combination of restricting and improving the course of the river channel would enable the tide to be induced farther upstream, with the resulting navigation improvements suggested above.

3.0 TIDE IN THE TIDAL ESTUARY

3.1 General

A tidal wave approaching the coast is a harmonic wave created by lunar and solar influences. In the tidal river its movement is governed mainly by:

(a) the configuration and properties of the original tidal wave entering the estuary from the sea,

(b) the amount of river discharge, and

(c) the morphology of estuary and tidal river bed.

The influence of density difference also should not be overlooked; however, this will be discussed later.

Of these three items, the original wave and river discharge are fixed factors and, under normal conditions, cannot be changed within the tidal river system. The physical properties of the river bed, however, may be modified artificially, subsequently modifying the tide condition.

3.2 Change of the Characteristics of the Tidal Wave in a Tidal Estuary

3.2.1 Increase in Amplitude by Partial Reflection

Progressing upstream from the estuary, cross-section areas controlling the tide fluctuation are continually decreasing and opposing the passage of the tidal wave, which will be partly reflected at each restriction. Beyond each restriction the wave will continue in damped form. Each point of the tidal wave will therefore have superimposed on it a reflection wave travelling downstream from each restriction. Hence, the phase difference between the upward moving wave and reflected wave is small within the range of the tidal river, and therefore two sets of waves will produce a composite wave having a greater magnitude than either of the original waves (Fig. 3).

This reflection process occurs to some extent along the entire tidal length of the river. An indication of the amount of reflection can be found by the location of the null point between flood and ebb current with respect to the tide curve. For a sinusoidal tidal wave with no reflection, the null points are at the elevation of mean water, but these points are moved to positions nearer the high and low water by the superposition of reflection waves until, with total reflection (such as occurs along the coast), they occur at high and low water (Fig. 3).

3.2.2 Decrease in Amplitude Due to Energy Losses

Four components are mainly responsible for the reduction of wave energy:

(a) energy losses caused by eddy, vortex, and cross motion due to irregularities, restrictions, and bends in the river channel,

(b) roughness along the river bed,

(c) rise in the river bed, and

(d) river discharge.

These factors are mainly active in the more upstream section of the river. There, the river is normally restricted and the energy loss created by the irregularity of the bed is the dominant factor in absorbing most of the energy when the flow section is reduced below a certain minimum area.

Roughness plays the same role in a tidal river as in a normal river. Along the boundary of the river bed, separations and the exchange of impulses create energy losses which increase with the increase in roughness and velocity. The relative roughness $\frac{\varepsilon}{R} = \frac{\text{absolute roughness}}{\text{hydraulic radius}}$ is a measure of its effect. For the lower section of a tidal river $\frac{\varepsilon}{R}$ is small and therefore of negligible influence, while farther upstream its effect increases with the decrease of flow section.

In a river channel a further reduction in the tidal energy is produced when the wave loses energy in overcoming the rise in elevation of the river bed. Further difficulties arise when the wave has to progress against the increased hydraulic slope of the river in the smaller upstream channel.

3.3 Tide Characteristics in the St. Lawrence River

The tide range in Cabot Strait at the entrance to the Gulf of St. Lawrence is about 3 ft. It progressively increases up the river, being 6 ft. at Father Point and 16 ft. at Point aux Orignaux. Here a reduction of 0.75 ft. takes place (Fig. 4). The charts show that at this point a ridge at a depth of 10 to 15 fathoms lies across the river bed which is about 40 fathoms deep.

At the ridge the energy losses due to the restriction in the river bed outweigh the reflection effects and reduce the tide range over a short distance. Upstream, however, the reflection again predominates and the range increases to 17 ft. on the average, and 21 ft. at spring tide at Gross Island just below the pronounced restrictions at Isle of Orleans.

Here the wave enters the restricted section of the river and the tide range is reduced substantially through head-losses owing to the restrictions and irregularities in the river channel, the rise in the river bed, and the increased mean water level slope of the river. The prominent restrictions are at St. Augustin shoal, Barre à Boulard, near Lotbinière, at Cap à la Roche and, to a smaller extent, at Three Rivers.

One of the most serious restrictions for the tidal wave, at present, is at Barre à Boulard (Fig. 5). Here, over a distance of about 3000 ft., the river channel is restricted by a ridge to less than 30 percent of the flow area of the river between Quebec and Pointe Platon and 6 percent of the flow area at Gross Island (Fig. 4). The maximum velocity in this section during ebb tide is about 10 ft./sec. As a result the reduction in tide range in this section alone is more than $3\frac{1}{2}$ ft.

Similar reductions are taking place downstream at St. Augustin and upstream at Cap à la Roche because of shoaling. Above these points the river flows over silt, sand and boulders, through which a navigation channel has been dredged. At Lake St. Peter the tide is absorbed and only under favourable conditions, such as spring tide and low river discharge, do small tide fluctuations reach Montreal.

Besides the change in tide range, the form of the tide curve and its subsequent modification during its progress give significant information. At Father Point the tide curve is nearly sinusoidal. Farther upstream the slopes of the tide curve change, the duration of the flood becoming shorter and the ebb longer. At the same time the null points of flow move toward the high and low points of the tide curve. At Quebec the duration of rise is 5 hr. 2 min., and the fall 7 hr. 23 min., and the null points have moved towards high and low tide. This change continues and at Three Rivers, where only 0.5 ft. tide range is left, the ratio is 3 hr. 30 min. to 8 hr. 55 min.

The reason for this change is well explained by the fact that in the equation $C = \sqrt{g \cdot h}$, the wave velocity C depends on the depth h of the water. Because the depths are considerably greater during high tide, the velocity of the wave will therefore be higher.

The ratio between the duration of flood and ebb tide can decrease so much under unfavourable conditions that the flood crest overtakes low water and a bore is created such as occurs in the Petitcodiac River in New Brunswick.

4.0 DENSITY CURRENT

4.1 General

During flood tide, salt water penetrates along the bed into the river system and mixes gradually with the fresh water. During this process, the density difference between the salt and fresh water layers creates currents which are directed upstream on the river bed and downstream on the surface. These movements are superimposed on the tidal and river flow, increasing the bed current during the flood tide and the surface current during ebb tide.

4.2 Density Current in the Saint John River, N.B.

To demonstrate the effect of density difference, hydrographic data collected during a survey made by the National Research Council in the summer of 1958, in the estuary of the Saint John River, are presented (Fig. 7). Just above the harbour the river is restricted by a rocky ridge which forms the well-known Reversing Falls. The water elevation of the large river-lake reservoir above the Falls is, except during the spring flood, 1.5 ft. above mean sea level. Therefore the tide, 21 ft. in mean range, discharges sea water into the river system during half flood to half ebb. During the remainder of the tide cycle, combined sea and river water flows outward through the harbour into the Bay of Fundy. In

Figure 8, the tide curve, the density at the bed and surface, the density difference and the velocities at Point 44 (Fig. 7) are plotted. During low tide the density difference between surface water and bed water is about 0.005. The ebb water flows out strongly over the top three-quarters of the depth, while in the remaining bottom quarter of the depth the denser sea water moves in at 0.8 ft./sec.

On the rising tide the density of the surface water decreases and that of the bottom water increases. Over a time period of three hours a maximum density difference of around 0.015 exists, with its peak at the null point, where the overall movement of the water comes to a standstill before changing from downstream to upstream flow. At this particular moment 90,000 c.f.s. (velocities of 4 ft./sec.) flows outward at the surface and the same amount inward at the bottom (Fig. 9). From here on the salt water rises steeply to the surface and at high tide the density difference is substantially reduced, thereby reducing the superimposed density current. The change-over at the next null point is therefore smooth. At the bottom, however, the salt water wedge very soon starts its inward movement.

From the velocity distributions it can clearly be seen that a density current changes entirely the conventional flow picture of a non-tidal river.

In Figure 10, velocities are plotted which would exist when:

(a) no tide or density difference were present, i.e. the river discharge only would flow through the harbour;

(b) river and tide were present, but no density difference; and

(c) river, tide and density difference were present, as occurred naturally.

The river discharge alone would cause currents not exceeding 1.33 ft./sec., while with the tide they increase to 2 ft./sec. With the density current included, bed and surface velocities change entirely. While the velocity which would occur with tides but with no density difference is close to zero, surface velocities of 4 ft./sec. are directed downstream and bottom velocities of 2 ft./sec. upstream. The outward flow occurs continuously at the surface. Only a short time after high tide, its strength is reduced to nearly zero with almost no change in direction. The bed velocity changes direction for two hours, but its maximum velocity downstream is only 0.6 ft./sec. A density current therefore increases the surface velocities downstream and the bottom velocities upstream by a considerable amount. This fact is of the utmost importance.

4.3 Density Current in the St. Lawrence River

The density currents in the St. Lawrence River are not as violent as in the Saint John River because the density exchange takes place over a greater distance. The principle, however, is the same and the velocities of flood current at the bottom and the velocities of ebb current at the surface are increased. The velocity picture will be similar to that shown on Figure 10.

The navigation charts show that the maximum velocities at Quebec Bridge and at Barre à Boulard are approximately the same, i.e. 6 knots or about 10 ft./sec., during ebb tide. Both sections are straight channels with no exceptional restrictions. The flow section at Quebec Bridge is 180,000 sq. ft. and at Barre à Boulard, 60,000 sq. ft. This indicates that at Quebec a powerful salt water wedge must restrict a substantial part of the deeper river bed.

5.0 SEDIMENT IN THE RIVER

In a river, tidal or non-tidal, the current transports the sediment and forms the river bed.

In a non-tidal river the velocity distribution along a vertical line from the bed to the surface is approximately parabolic. For each discharge a fixed relationship exists between bed and mean velocity which depends on depth, configuration of channel, and roughness.

In a tidal river, however, there is no fixed ratio between the bed and mean velocities. The velocities change with the tide in strength and direction and are substantially increased on the bed during flood and at the surface during ebb by a current created by the density difference. For sediment transport only the bed velocity is of importance. In the equations established by Lervi, Goutscharow and Niebuhr (Ref. 1) the amount of material transported depends approximately on the cube of the bed velocity.

To demonstrate the effect of the third power, the bed velocities and the corresponding third power velocities are plotted for the assumed velocity picture of the St. Lawrence River (see Fig. 11). The higher flood velocities have a dominating effect and carry sediment far upstream into the river. In the St. Lawrence it is carried upstream of Grondines and may possibly reach Lake St. Peter. The upstream limit is where the bed velocities of the ebb tide or the non-tidal river flow out-weigh the flood and density velocities. This zone changes with the tide range and the river discharge.

As may readily be seen, a change in the tide by increasing its range and density current would increase the bed velocities and shift the sediment zone farther upstream, leaving behind a self-maintaining deep river bed.

6.0 EXAMPLES OF OTHER TIDAL RIVERS

6.1 General

In Europe, a number of tidal rivers have been regulated for navigation, e.g. in France, the River Seine between Le Havre and Rouen and, in Germany, the River Weser between Bremerhaven and Bremen. The latter is described in Reference 1.

6.2 Regulation of the River Weser

In the middle of the 19th century, the Weser below Bremen could hardly be considered a waterway because the depth available was less than 6 ft.

From 1850 to 1880, the city of Bremen tried to improve conditions but without great success. Finally, in 1880, Professor Franzius drew up a plan for regulating the tidal stream of the river enabling ships with 15-ft. draught to sail up to Bremen. His basic idea was to use the transporting forces of an increased tidal wave to help clear and maintain a navigation channel.

To achieve a tidal wave which would progress farther upstream, he proposed:

(a) increasing the current in the main channel by enlarging it and blocking off minor diversions,

(b) enlarging the flow section in restricted areas,

(c) straightening sharp river bends,

(d) dredging a channel through sandbars,

(e) closing off side arms at their upstream ends, and

(f) increasing flow section downstream gradually to take care of the increase in tidal discharge.

The finished work was successful. Soundings made in 1889 proved that, while dredging up to this time amounted to 6 million cu. yd., the water had flushed out a further 8 million cu. yd. The regulation has since been extended and at present there is a navigation channel 27 ft. deep.

6.2.1 Modification of the Tidal Wave

In Figure 12 the curves for high and low tide, before and after regulation, are plotted. As is normal, the tide range increases from 7 ft. at Heligoland Island to 10.7 ft. at Bremerhaven as a result of reflection. From here to Brake, the tide range remains constant for both conditions, indicating that head loss and gain in range through reflection are balanced. Above Brake the range was reduced under the conditions existing before 1880, but under present conditions the range is maintained up to Bremen, as can be seen on the graph, by lowering the low tide and partially raising high tide water levels.

6.3 Discussion

The curves for high and low water of the River Weser before regulation (Fig. 12) and the St. Lawrence (Fig. 13) are similar. In both rivers high tide elevations diminish over a short distance; however, the decrease in tide range is mainly caused by the steep rise in the low water.

The regulation in the River Weser straightened the high water curve and lowered the low water by 10 ft., increasing the tide range at Bremen from less than 1 ft. to 11 ft. This is exceptional and is due to the small river discharge compared with the tide volume.

In the St. Lawrence River an increase in the tide range of 2 to 3 ft. at Lake St. Peter may be sufficient.

7.0 PROTOTYPE OBSERVATIONS AND MODEL STUDIES

7.1 Survey of the St. Lawrence River

Available data were sufficient for a preliminary analysis of the problem and an outline of a general proposal. For a detailed study, additional data are required to give a clearer picture of the complicated hydraulic structure of the lower St. Lawrence River.

Information is required at a number of cross-sections of the river, particularly in the restricted areas between Quebec and Montreal. Water elevations, velocities, directions of flow and densities from bed to surface, bed load movements and ice observations are required. These observations must be taken over several seasons and must be related to the river discharge. In addition, a geological survey of bed material and rock structures should be conducted.

7.2 Model Studies

The size of the St. Lawrence River rules out any modification to it without a thorough study on a model. Tide studies, which include density currents and, to some extent, bed movement, are complicated. However, they have been conducted on other estuaries, and have given valuable advance information which could not be obtained by any other means.

With the limited data available at present, it is difficult to outline a study in detail, but the section to cover is that between Quebec and Cap à la Roche. A study of the sediment problem below Isle of Orleans could be incorporated.

Besides these studies on a river model, basic flume studies on tidal waves, density currents and bed load movements will be required.

8.0 POSSIBLE IMPROVEMENTS IN ICE CONDITIONS

8.1 Existing Ice Conditions

On the St. Lawrence two different types of ice are found - sheet ice and frazil. The sheet ice is formed in still water and low velocity sections, the frazil in rapids and swift sections. While the ice is moving along the river it reaches sections where velocities and turbulence are moderate and there

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From the viewpoint of pack ice formation the river can be divided into three sections:

(a) below Quebec, where it forms along the south shore leaving an open channel along the north shore,

(b) the clear section between Quebec and the lower end of Lake St. Peter, and

(c) the section covered with ice packs above the lower end of Lake St. Peter.

In the section below Quebec the ice is subjected to a 10- to 17-ft. rise and fall during a tide cycle, to a movement caused by the Coriolis effect, and to strong velocities in general created by the tide and density current. Immediately above Quebec the tide, with its flushing effect, is still strong, and farther upstream where the tide diminishes, restrictions and sandbars in the bed create a swift current which prevents the formation of ice bridges.

8.2 Possible Improvements

At present there is little tide in Lake St. Peter and ice packs form from there to Montreal. If a tide could be introduced there is a possibility that pack ice would not form and a clear channel would result.

To illustrate this effect of tide and density upon the normal river current, the Saint John River data (Fig. 10) show that the normal river current is increased from 0.33 ft./sec to 4 ft./sec. at the surface. This great modification of the velocity distribution is exceptional. Unfortunately, there is no indication of the relationship existing between height of the tide, density and river discharge on the one hand, and velocity modification on the other. One fact is certain: the introduction of a tide would modify the velocities as already described, but the amount is unknown.

In Appendix E of Reference 2, about "Ice Formation on the St. Lawrence and Other Rivers", it is stated under Item 26:

An examination of data accumulated (during ice survey) shows that with velocities between 2.7 and 3.3 ft./sec., ice covers, if formed, will go and come with changes of weather but, with velocities in excess of about 3.3 ft./sec., surfaces will generally remain open under all winter conditions on the St. Lawrence.

The present surface velocities above Lake St. Peter are of the order of about 2.7 ft./sec. An increase of only 25 percent would be sufficient to fulfil the above requirement for keeping the river free of ice cover. It should be possible to establish this by introducing a relatively small tide in this section. In addition, the rise and fall of the water surface would break off the ice from the shores and islands.

9.0 REFERENCES

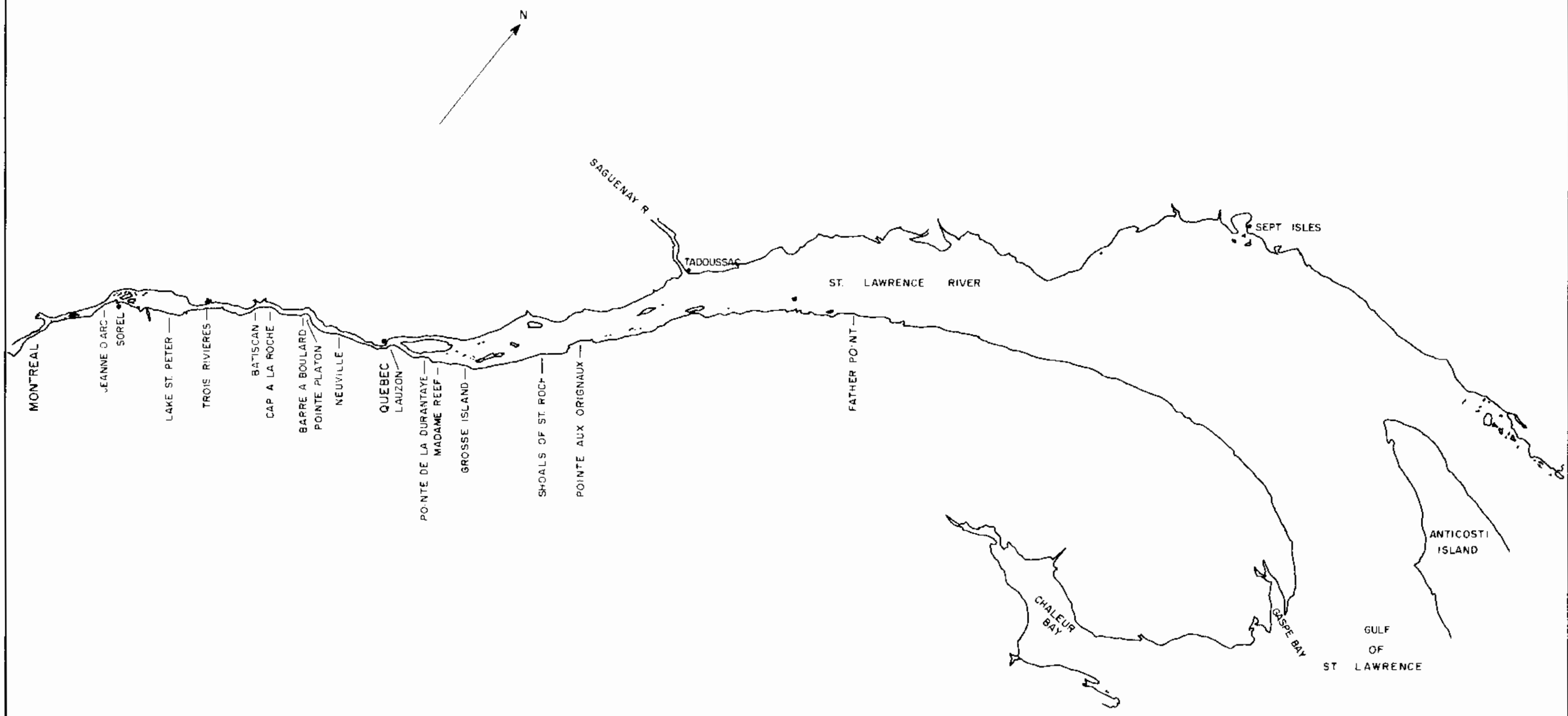
1. Tideänderungen durch Einbauten in Tideflüssen (Modification of the Tide Wave by Changes of the Configuration of the Tidal River), by Hansgeorg Wittmer. Published in "Mitteilungen der Hannoverschen Versuchsanstalt für Grundbau und Wasserbau", Franzius-Institut der Technischen Hochschule, Hannover, Vol. 13.

2. Report of Joint Board of Engineers, St. Lawrence Waterway Project, November 1926.

10.0 ACKNOWLEDGEMENT

The reference by Hansgeorg Wittmer provided valuable assistance in instituting this proposal.

/AM



TIDAL SECTION OF THE ST. LAWRENCE RIVER

FIG. 1
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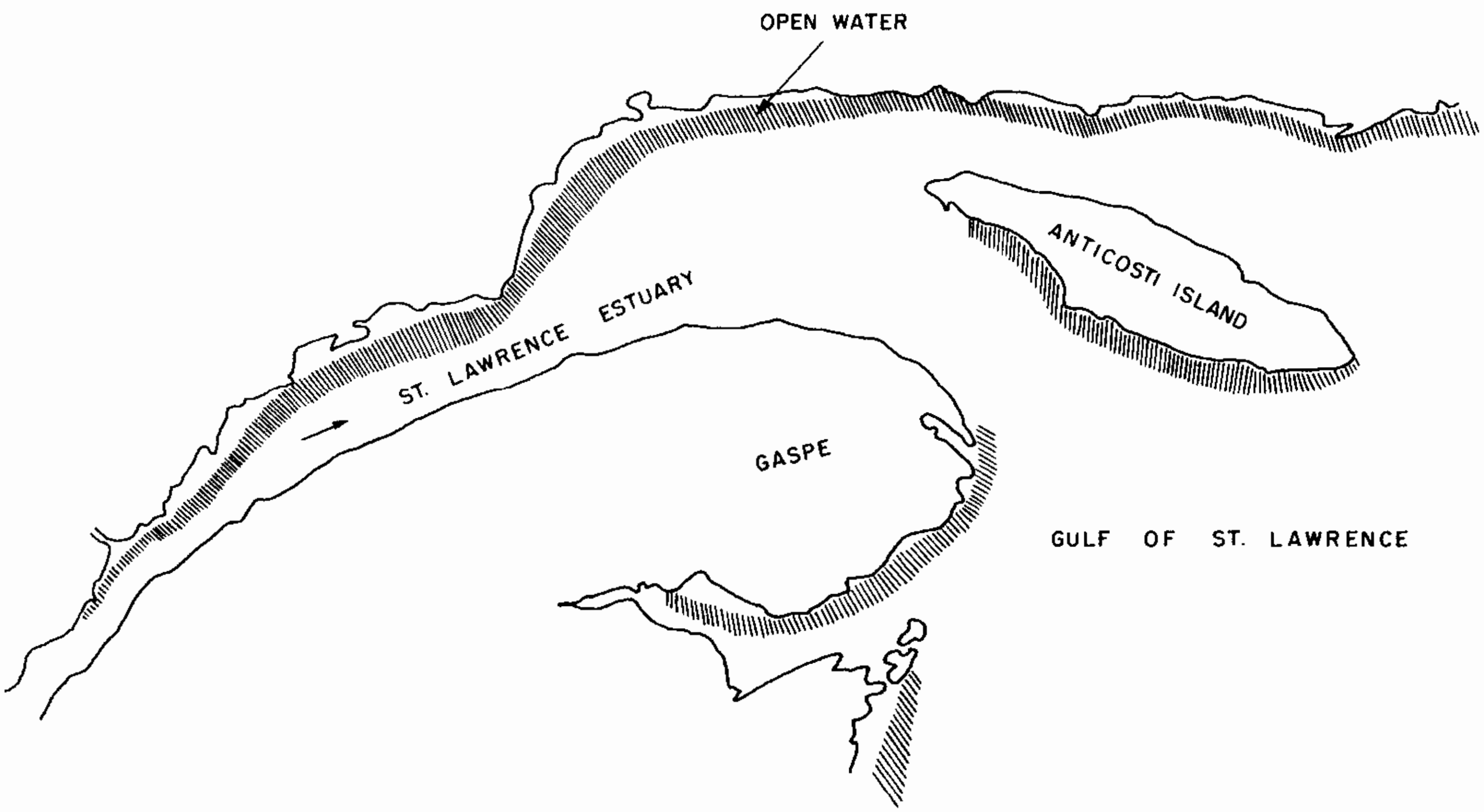
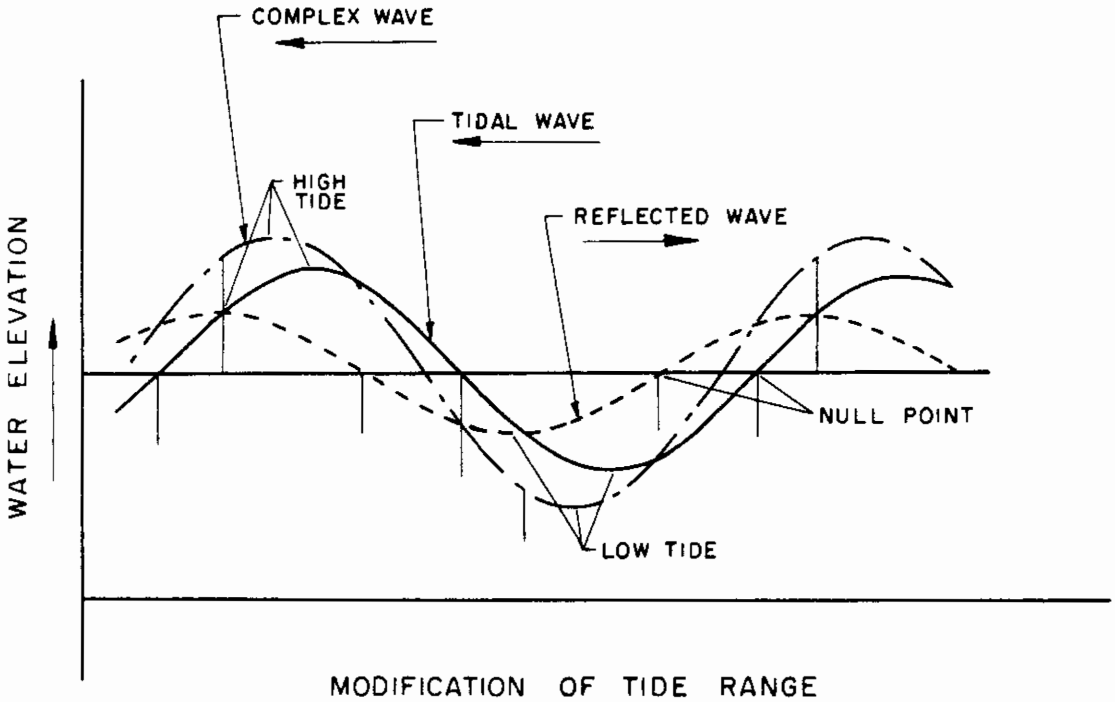
FIG. 2
MH-85



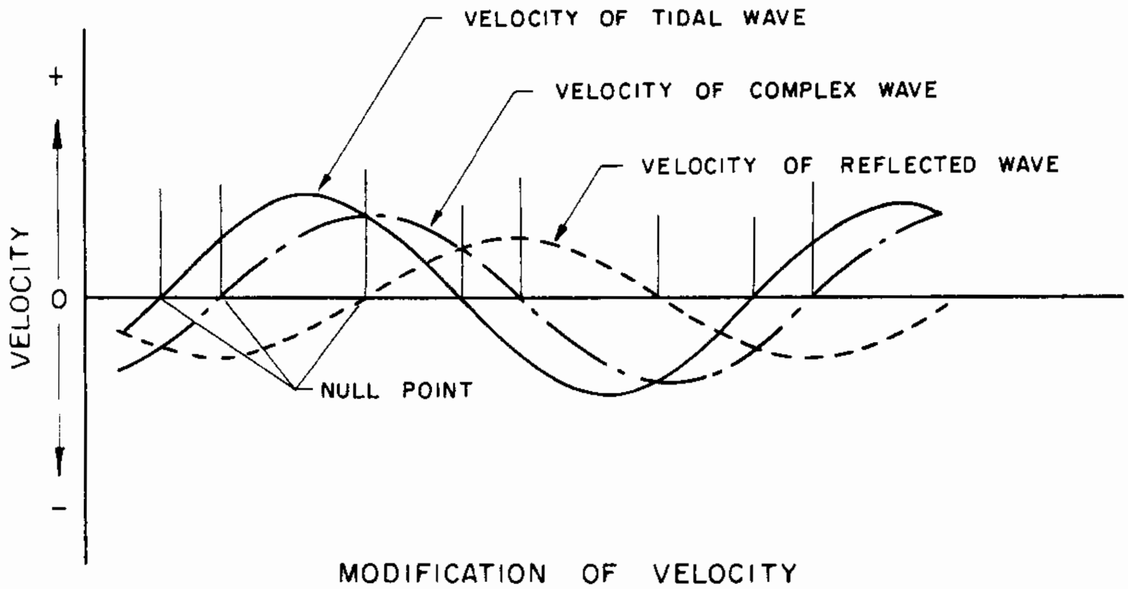
GENERAL AREAS OF OPEN WATER DURING WINTER 1957

EXTRACT FROM GEOGRAPHICAL PAPER No. 14, DEPARTMENT OF MINES AND TECHNICAL SURVEYS, OTTAWA

FIG. 3
MH-85

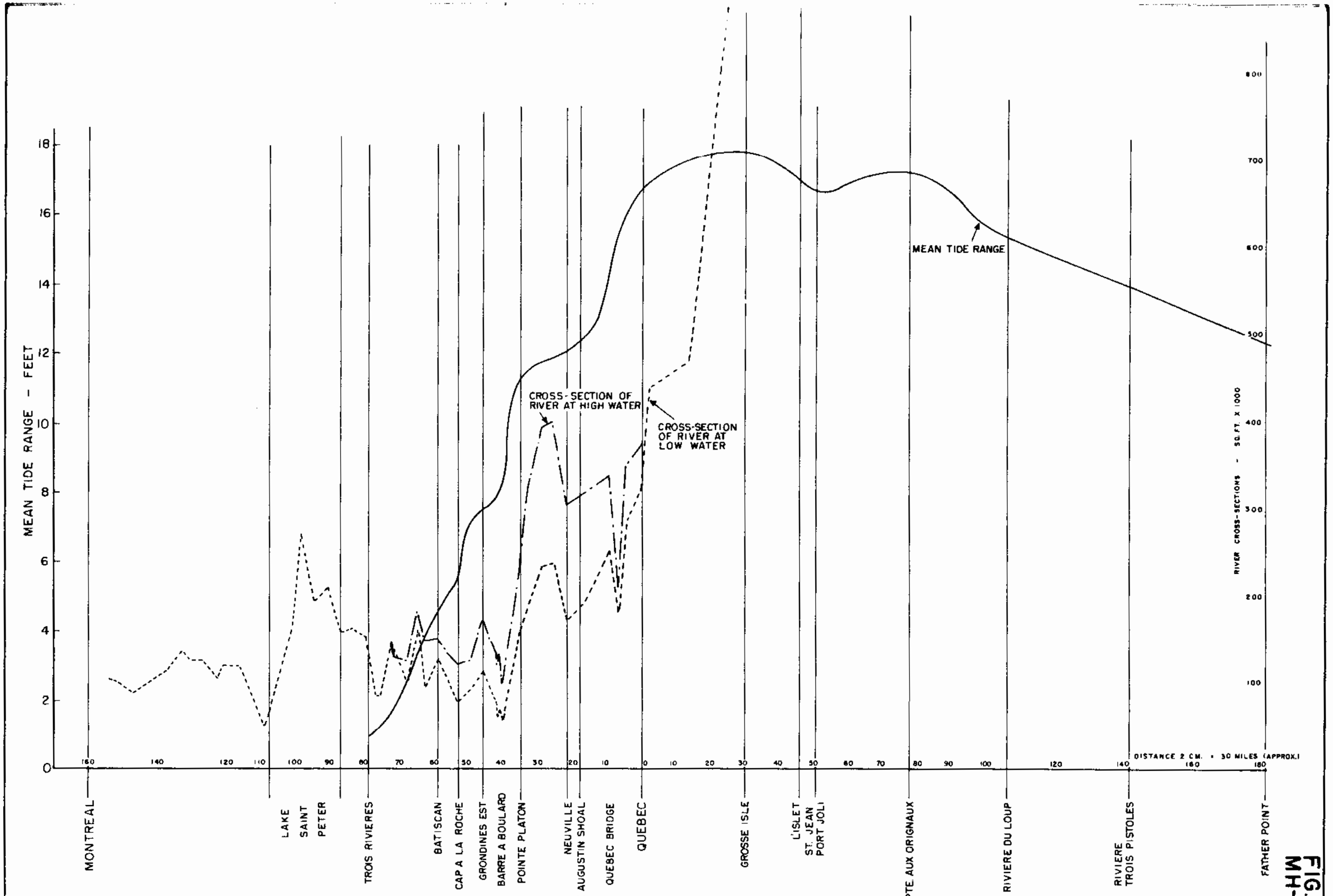


MODIFICATION OF TIDE RANGE



MODIFICATION OF VELOCITY

SUPERPOSITION OF REFLECTED WAVE ON TIDAL WAVE
(SCHEMATICALLY)



TIDE RANGES IN THE ST. LAWRENCE RIVER AND CROSS-SECTIONAL FLOW AREAS

FIG. 4
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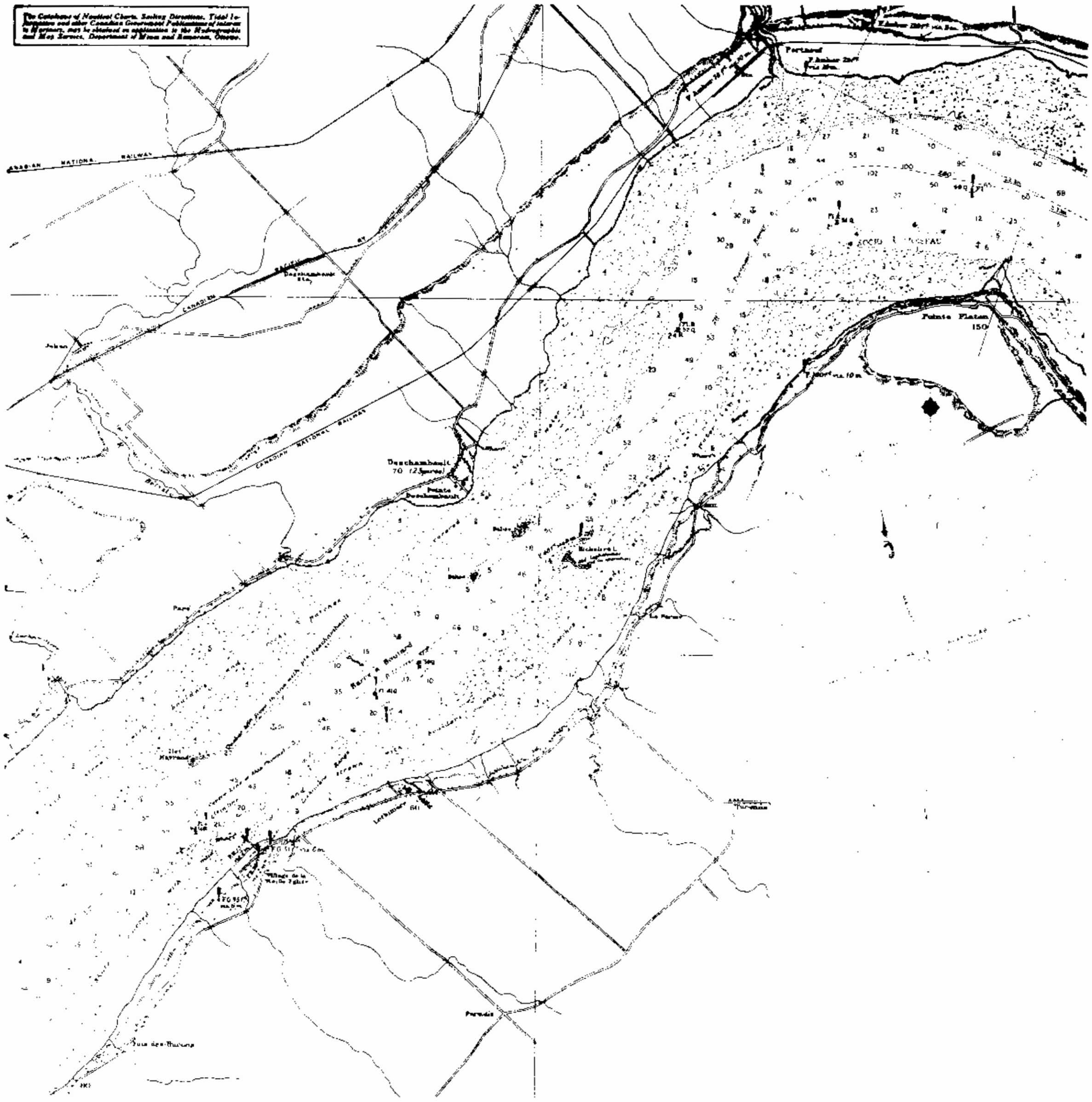
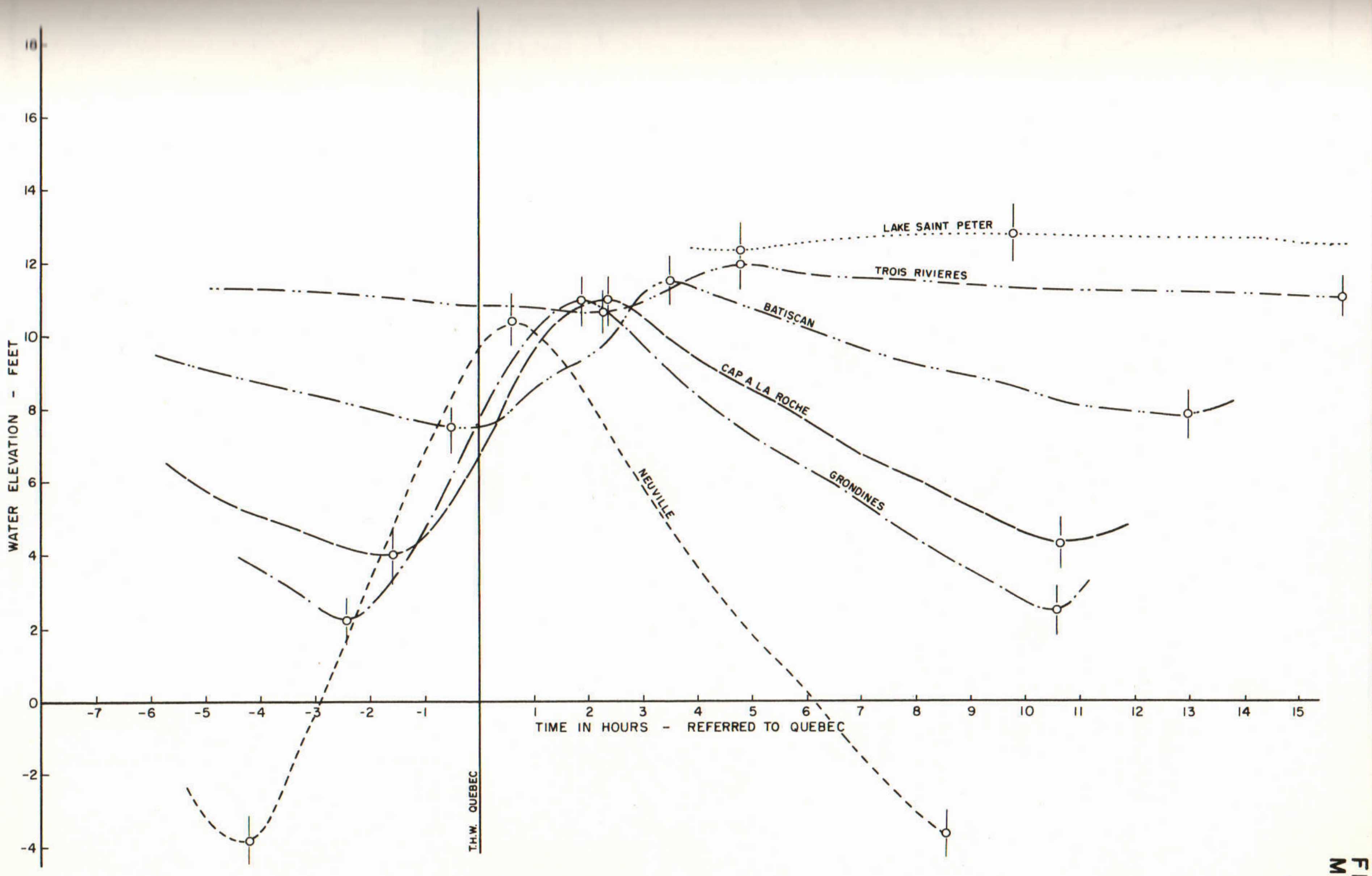
FIG. 5
MH-85

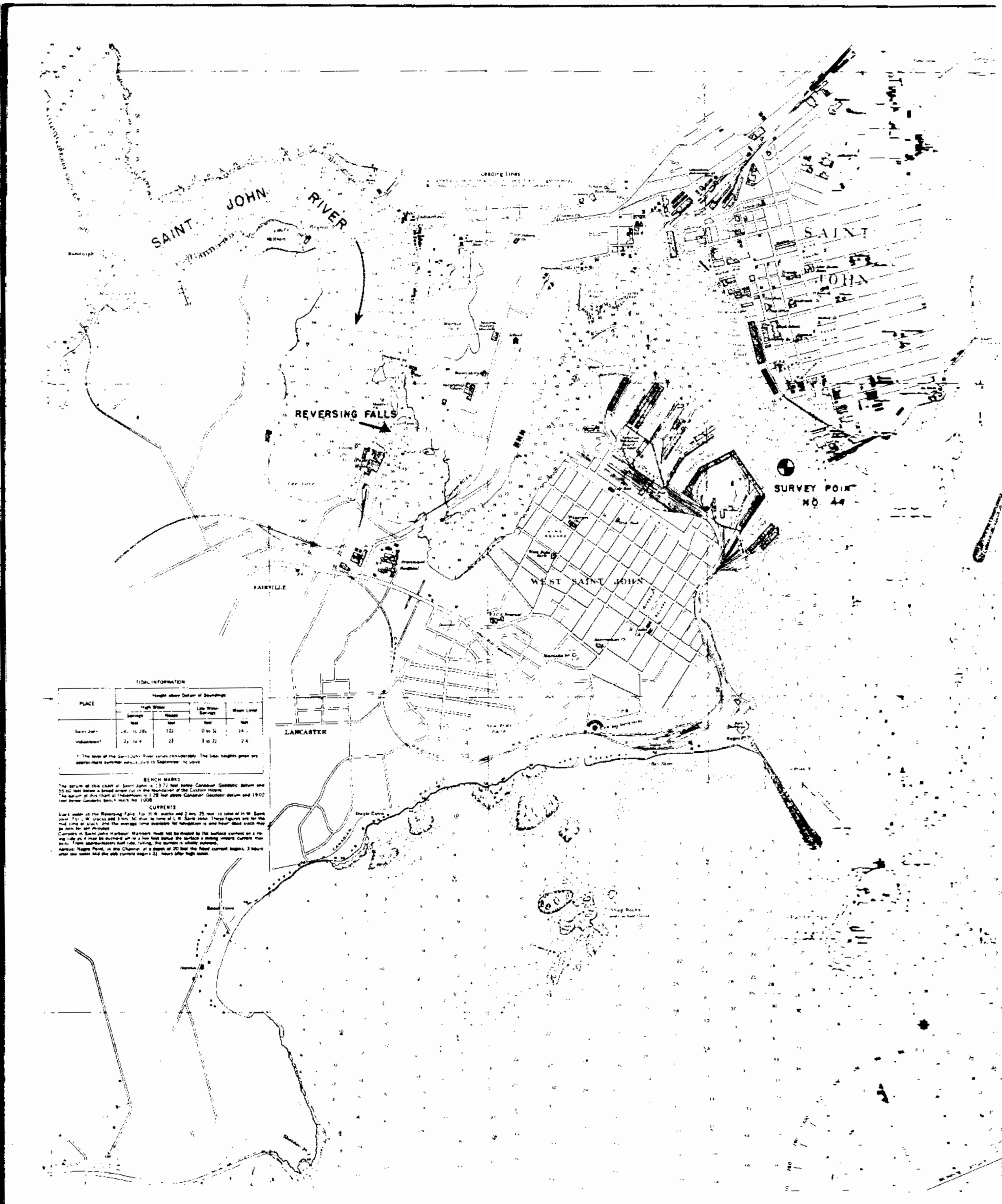


PLAN OF THE REACH AT LOTBINIERE
(BARRE A BOULARD)



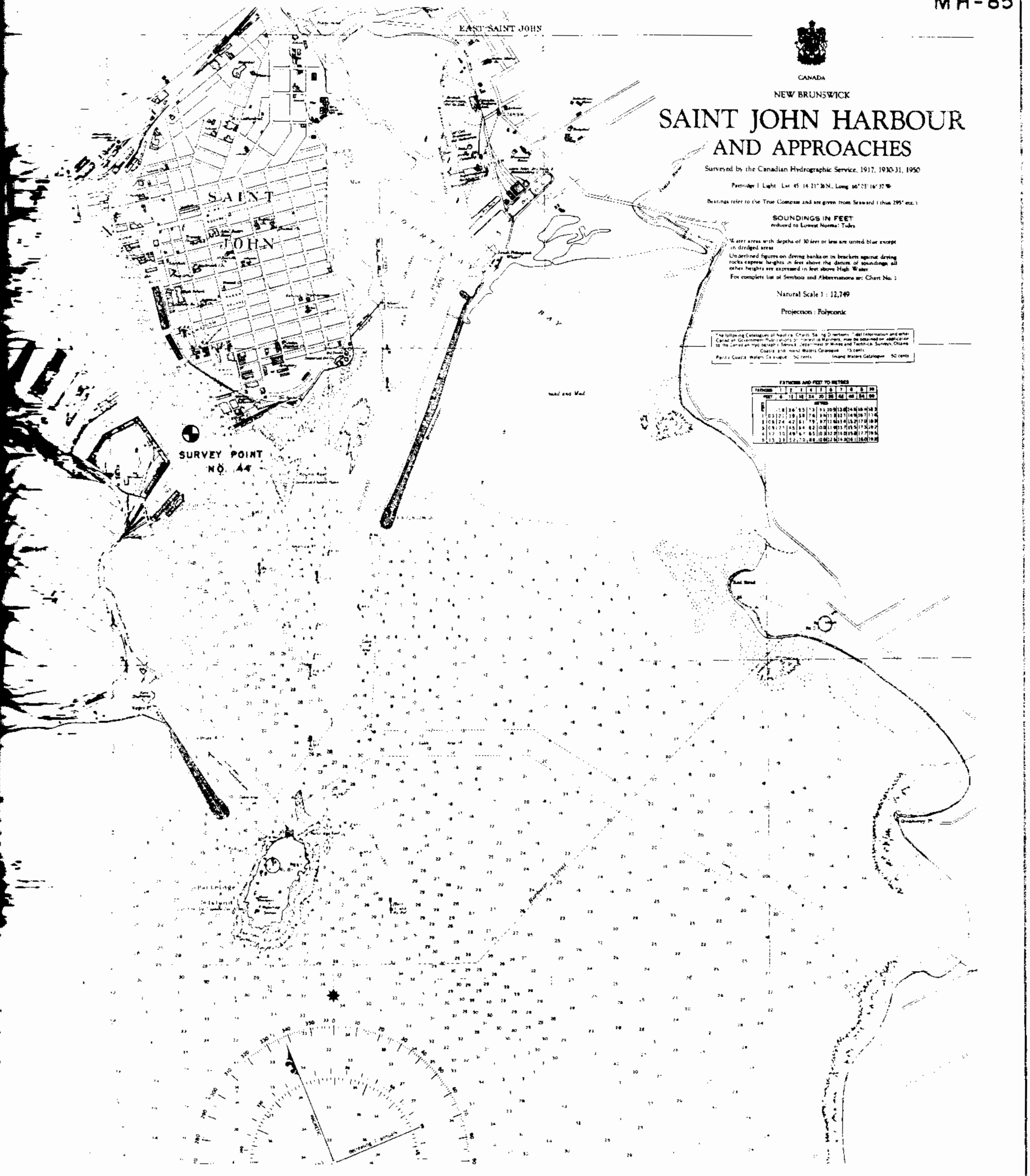
TIDAL WAVE IN THE ST. LAWRENCE RIVER ABOVE QUEBEC

FIG. 6
MH-85

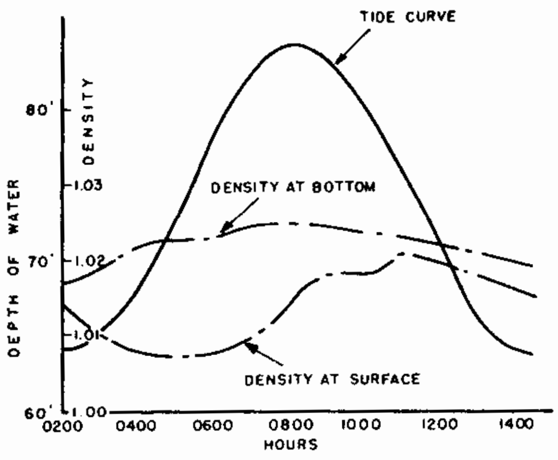


PLAN OF SAINT JOHN HARBOUR,

FIG. 7
MH-85



OF SAINT JOHN HARBOUR, N. B.



TIDE CURVE AND DENSITY AT POINT 44

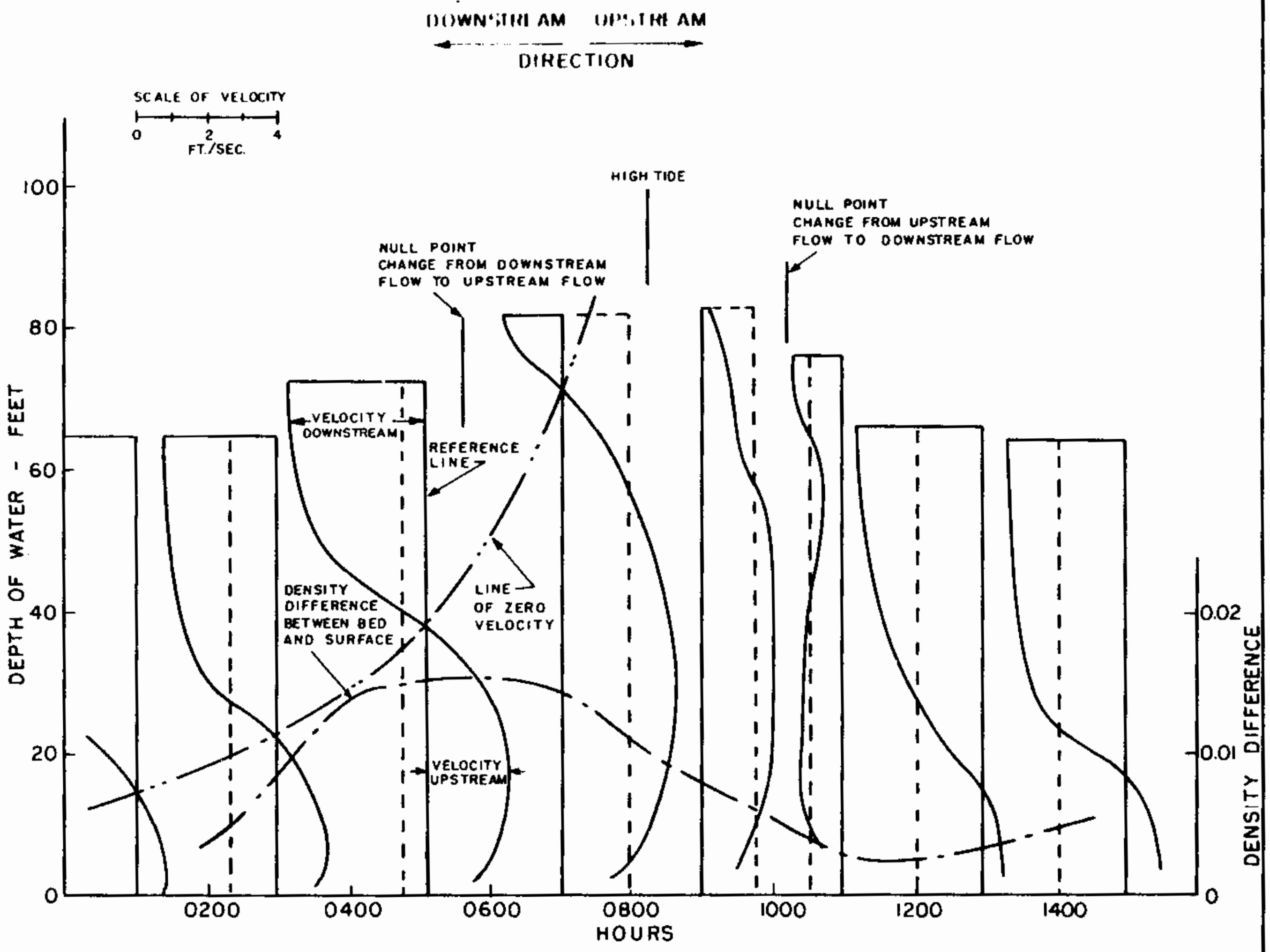


FIG. 8
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DENSITY DIFFERENCES AND VELOCITIES OF SURVEY POSITION NO. 44, SAINT JOHN HARBOUR, N.B.
AUG. 22, 1958

FIG. 9
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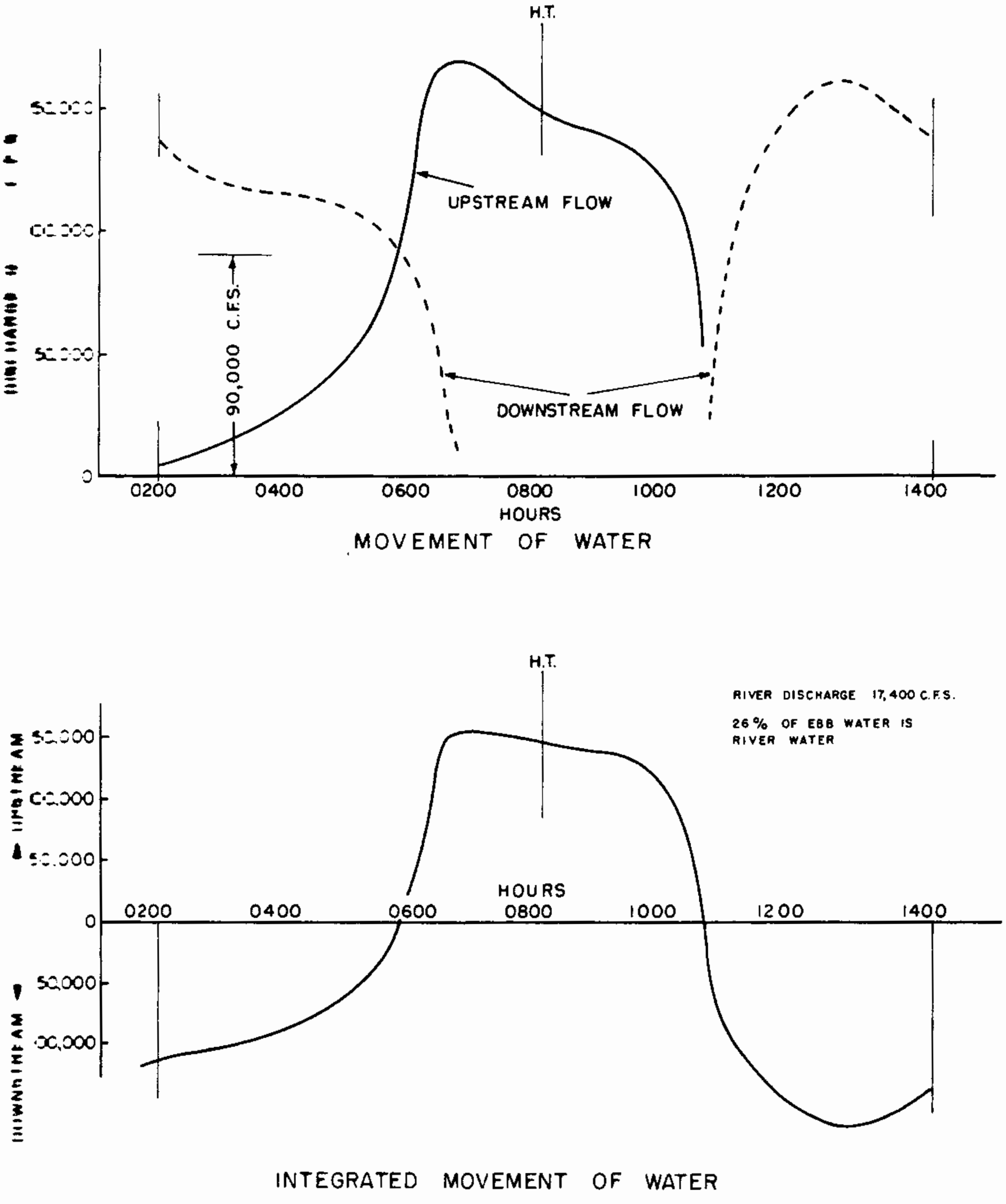
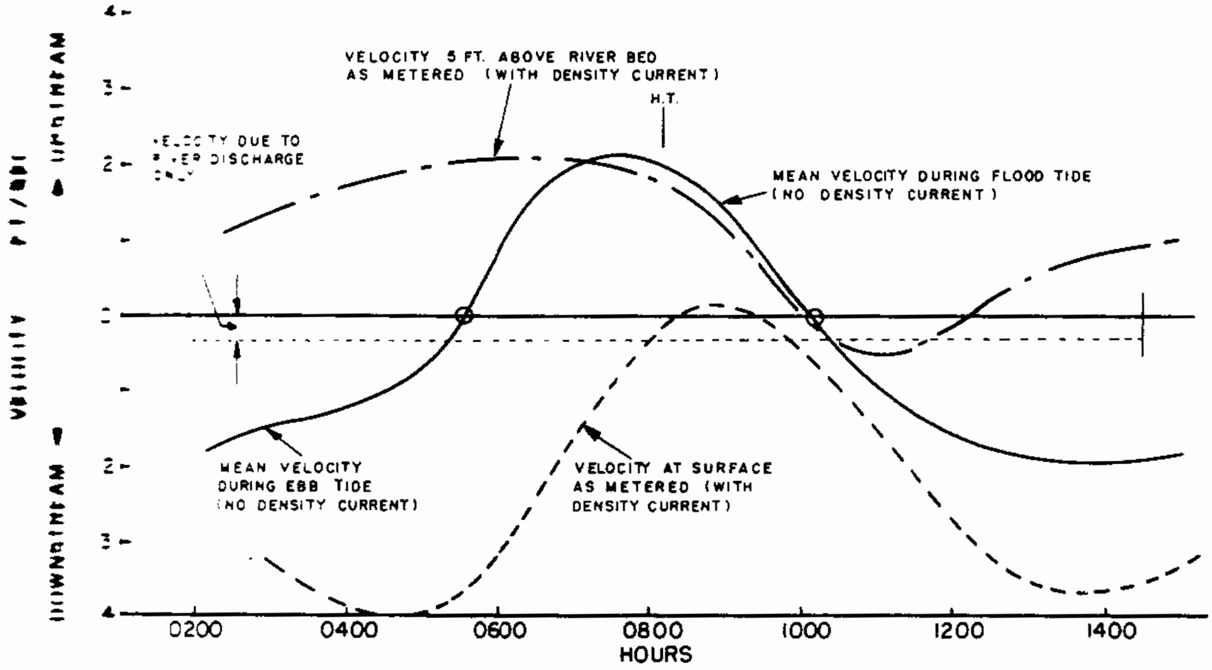
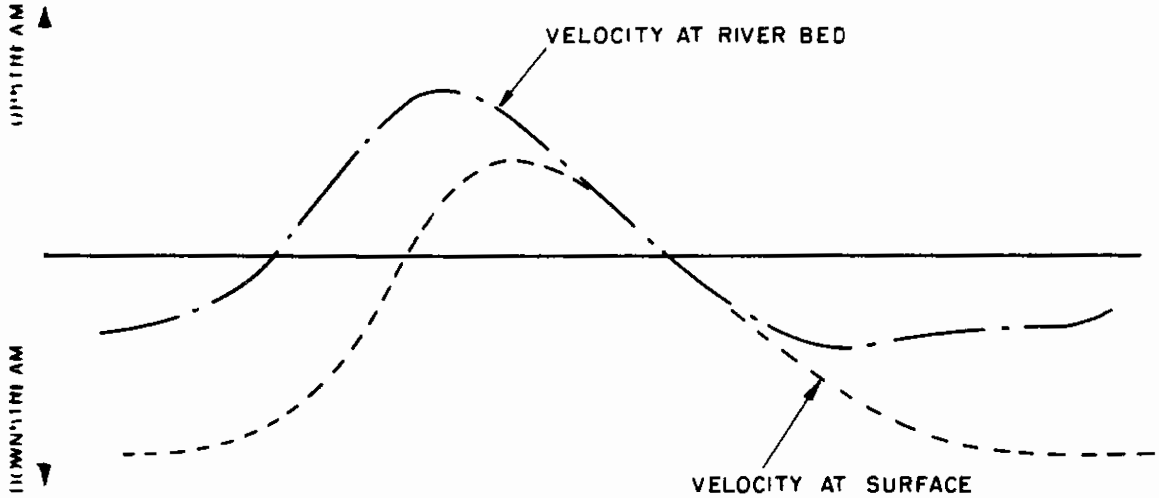


DISCHARGE ANALYSIS ACROSS THE CHANNEL AT SURVEY POSITION NO. 44
SAINT JOHN HARBOUR, N.B.
AUG. 22, 1958

FIG. 10
MH-85

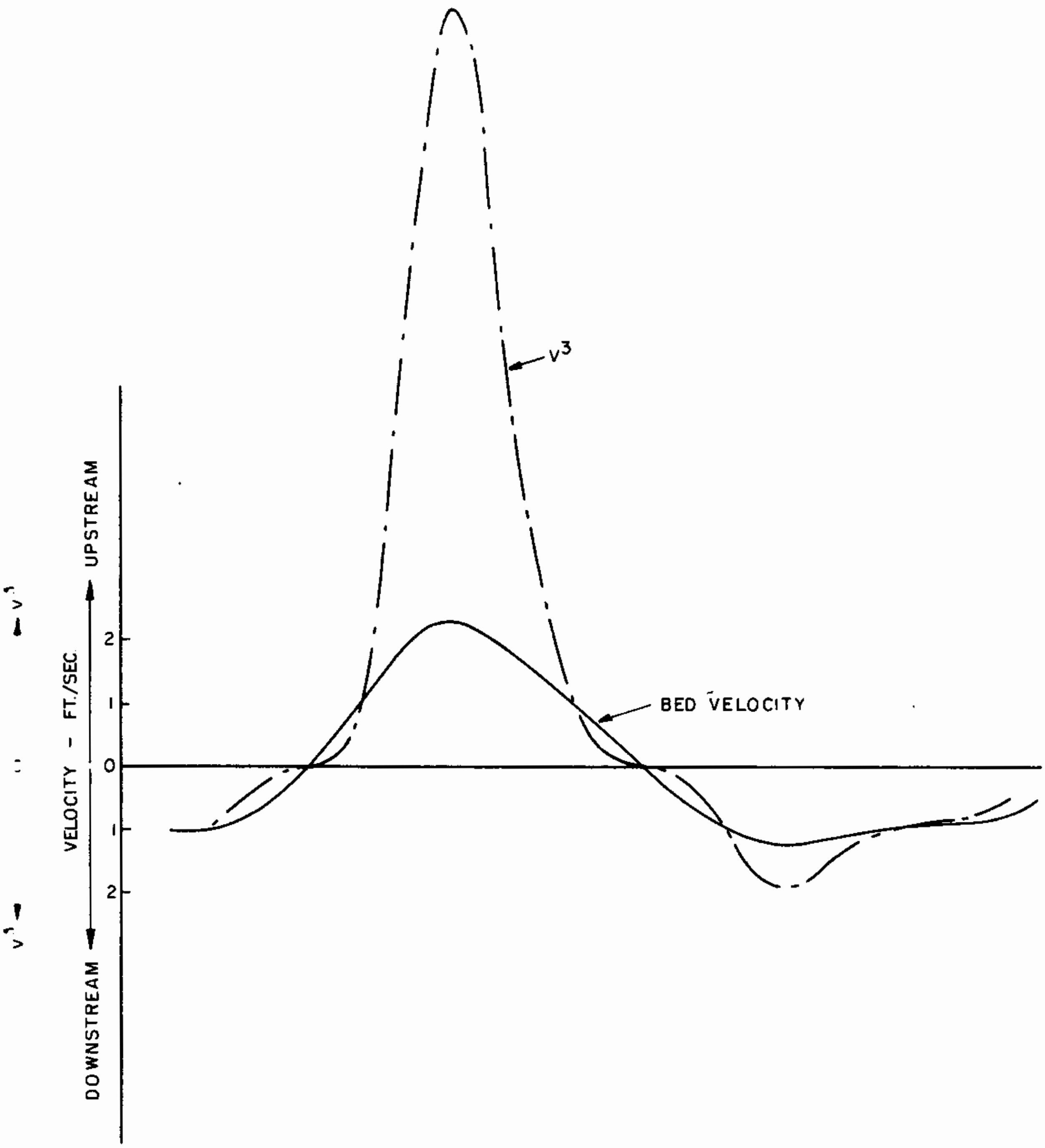


RIVER, TIDAL, AND DENSITY CURRENT
POSITION 44, SAINT JOHN HARBOUR



ASSUMED SURFACE AND BED VELOCITIES
IN THE ST. LAWRENCE RIVER

FIG. 11
MH-85



ASSUMED BED VELOCITIES OF THE ST. LAWRENCE RIVER AND THE CUBE OF THESE VELOCITIES

FIG. 12,13
MH-85

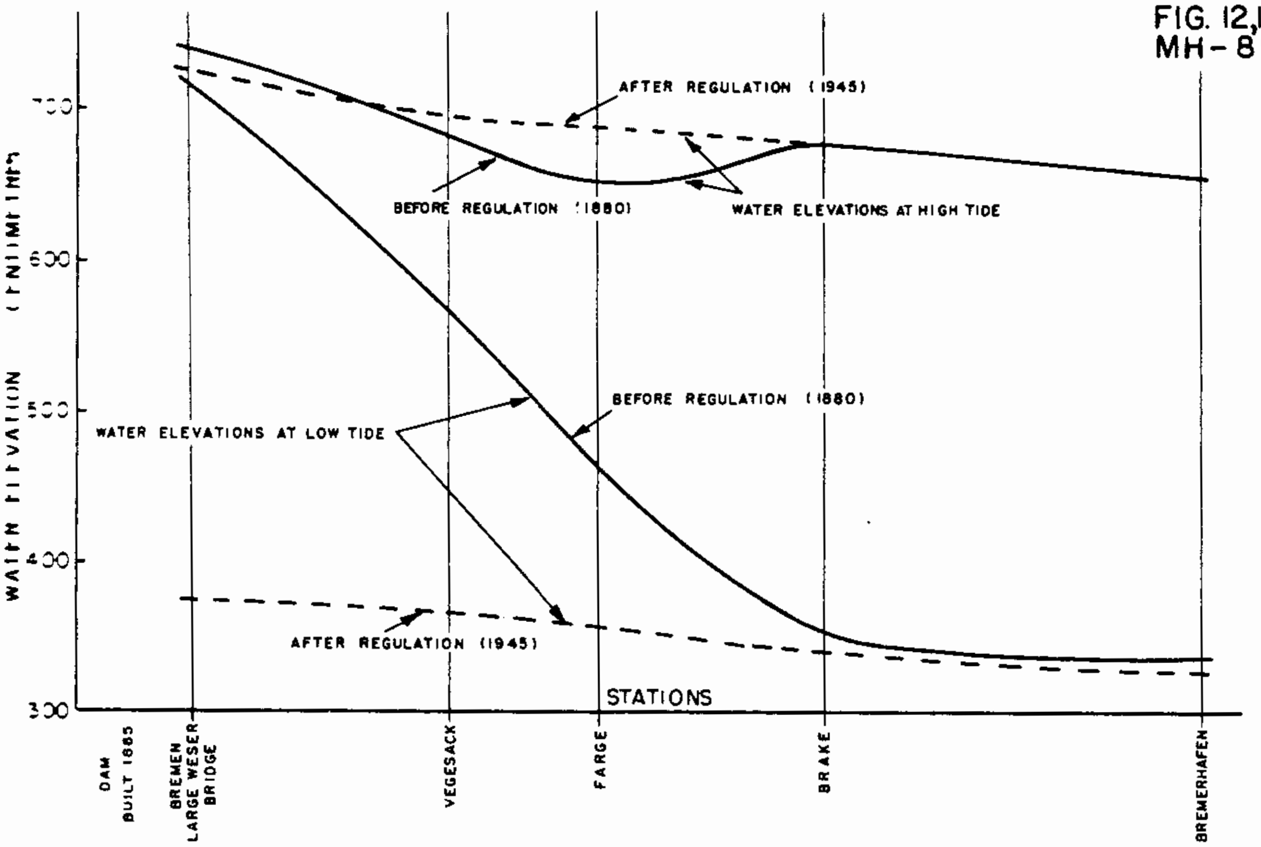


FIG 12 TIDE RANGE AND TIDE MODIFICATION IN THE RIVER WESER, REF. I

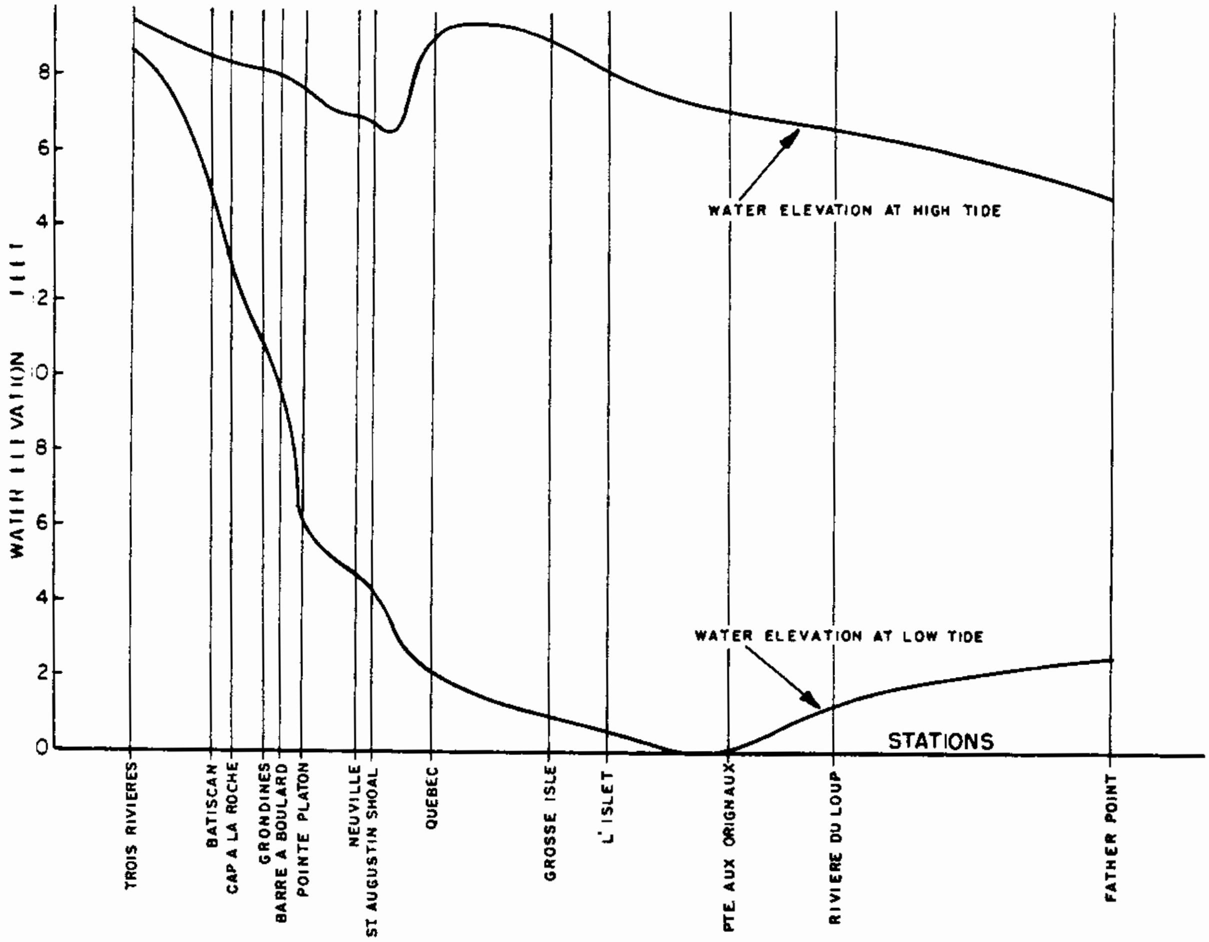


FIG 13 TIDE RANGE IN THE ST. LAWRENCE RIVER