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The Physical Oceanography and Sedimentation of Rivière au Tonnerre

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BEDFORD INSTITUTE OF OCEANOGRAPHY

Dartmouth, Nova Scotia
Canada

THE PHYSICAL OCEANOGRAPHY AND SEDIMENTATION OF RIVIERE AU TONNERRE

by

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Department of Fisheries and the Environment

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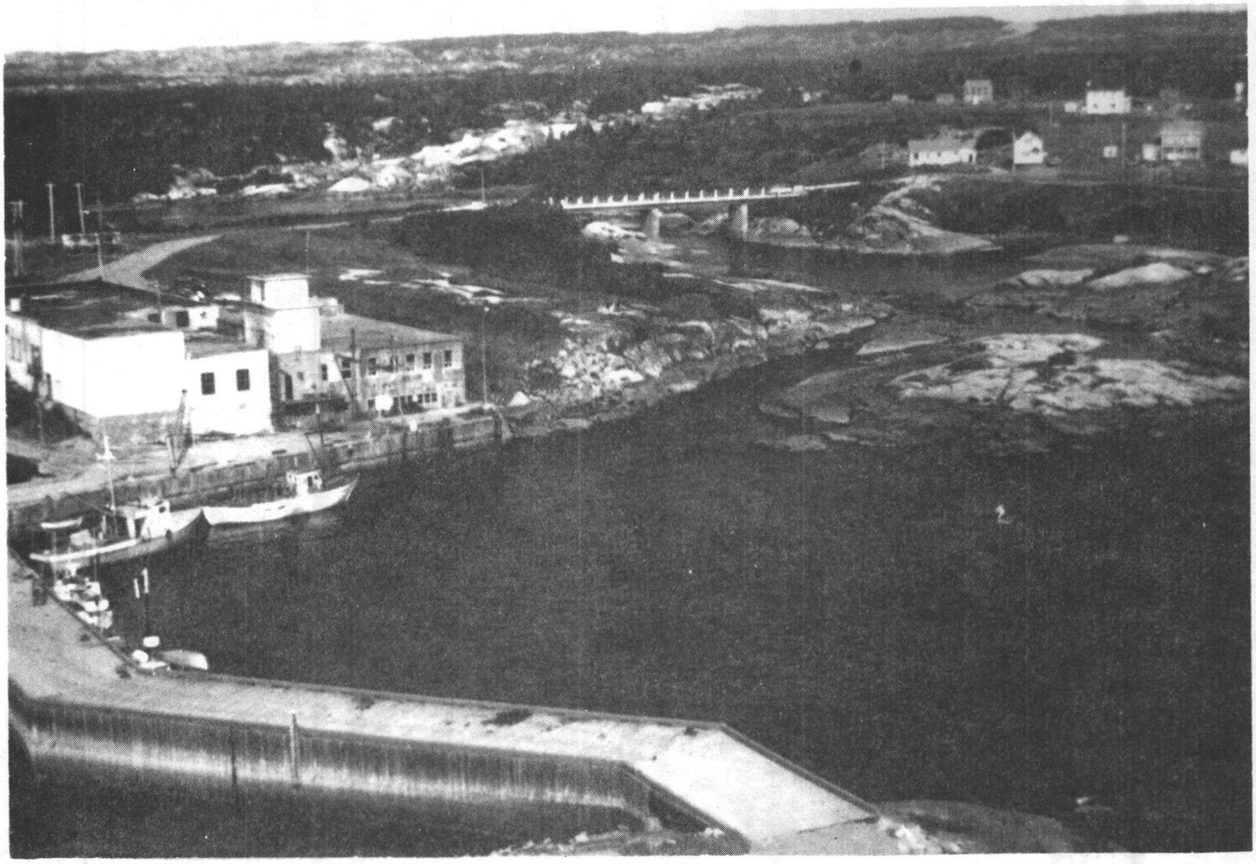

Aerial Views of Rivière au Tonnerre and Harbour

SYNOPSIS

Based on surveys conducted in September 1976 and June 1977, the environmental forces and processes that cause sedimentation in Rivière au Tonnerre, Quebec, are studied and evaluated. It is demonstrated that the salt water layer of the haline circulation acts as a sand trap, preventing the river from carrying its sediment load seaward and, in conjunction with littoral drift, assists in the transport of sand from the nearshore zone into the mouth of the river system. This process is kept in balance by the larger river discharges, which flush the salt water from the outlet and with it the sand deposits. The solution to the problem is to generate a current field at the bottom of the navigation channel similar to that for the higher river discharges. For the outer shoal, a dyke system is suggested to achieve this, and for the inner shoal, a change in the distribution of the discharge through the overflow channels of the rock ledge above the basin should provide the required depth. It is recommended that the proposals be studied in detail in a physical model.

SOMMAIRE

En se basant sur une enquête préliminaire effectuée en septembre 1976 et juin 1977, on étudie et évalue les processus et les forces environnementales qui causent la sédimentation dans la Rivière au Tonnerre (Qué.). On démontre que la couche d'eau salée de la circulation "haline" agit comme une trappe de sable qui empêche la rivière d'entraîner son fardeau de sédiments en direction de la mer. Avec la poussée littorale elle contribue au transport près du rivage du sable jusqu'à l'embouchure du système de la rivière. La rivière pendant les époques de débits volumineux chasse l'eau salée et les dépôts de sable de l'embouchure et ainsi maintient la sédimentation en équilibre. La solution au problème consiste à provoquer, au fond du chenal de navigation, des courants semblables à ceux qui se produisent au moment où le débit de la rivière est le plus volumineux. Pour ce qui est du haut-fond extérieur, on suggère la mise en place d'un réseau de digues pour atteindre ce but; pour ce qui est du haut-fond intérieur, on estime qu'une modification de la distribution du débit à l'aide des chenaux déversoirs du banc de récifs situé en amont du bassin devrait permettre d'obtenir la profondeur requise. On recommande que les propositions soient étudiées en détail à l'aide d'une maquette.

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1.0 INTRODUCTION

At the request of the Small Craft Harbours Branch of the Federal Department of the Environment, a combined oceanographic and hydrographic survey was carried out during the period 16-20 September 1976, for information on the mechanics of the siltation processes in the harbour area of Rivière au Tonnerre, Quebec (Fig. 1). An additional survey was made during the following June, to acquire more data relating to higher river discharges.

The harbour and town - the latter with a population less than 1000 - lie on the north shore of the Gulf of St. Lawrence, 120 km east of Sept Iles and 60 km west of Mingan, the two nearest safe harbours on this coast. Rivière au Tonnerre harbour (Figs. 2 & 3) can accommodate small vessels of up to one metre draft at low water (LW) or about three metres draft at high water (HW) - a limitation imposed by two sandbars, one lying just outside the entrance to the harbour and another in the navigation approach to the fish plant. This plant is located on the western side of the harbour and, at the time of the initial survey, was being used by three small draggers, each about 15 m long.

The sandbar at the outlet usually forms during the first southerly storm after the spring freshet of the river. Even when dredged out, the sandbar returns with the next storm.

The aim of this study is to provide data and conclusions which can be used to secure a more stable navigation channel for the harbour.

2.0 PHYSIOGRAPHY

2.1 Description of Coastal Region and River System

In general, the north shore of the Gulf of St. Lawrence is characterized by masses of rugged bedrock rising out of the water, interspersed with sandy coves and gravel beaches. The bedrock continues inland in a series of terraces, to an elevation of 300 m in a distance of 25 km and to 800 m after an additional 50 km. Along the coast, bare bedrock is visible in all areas; the meagre topsoil is composed mostly of sand. Seaward, all observations, either visual or by sampling, indicate a sandy bed in the offshore locations.

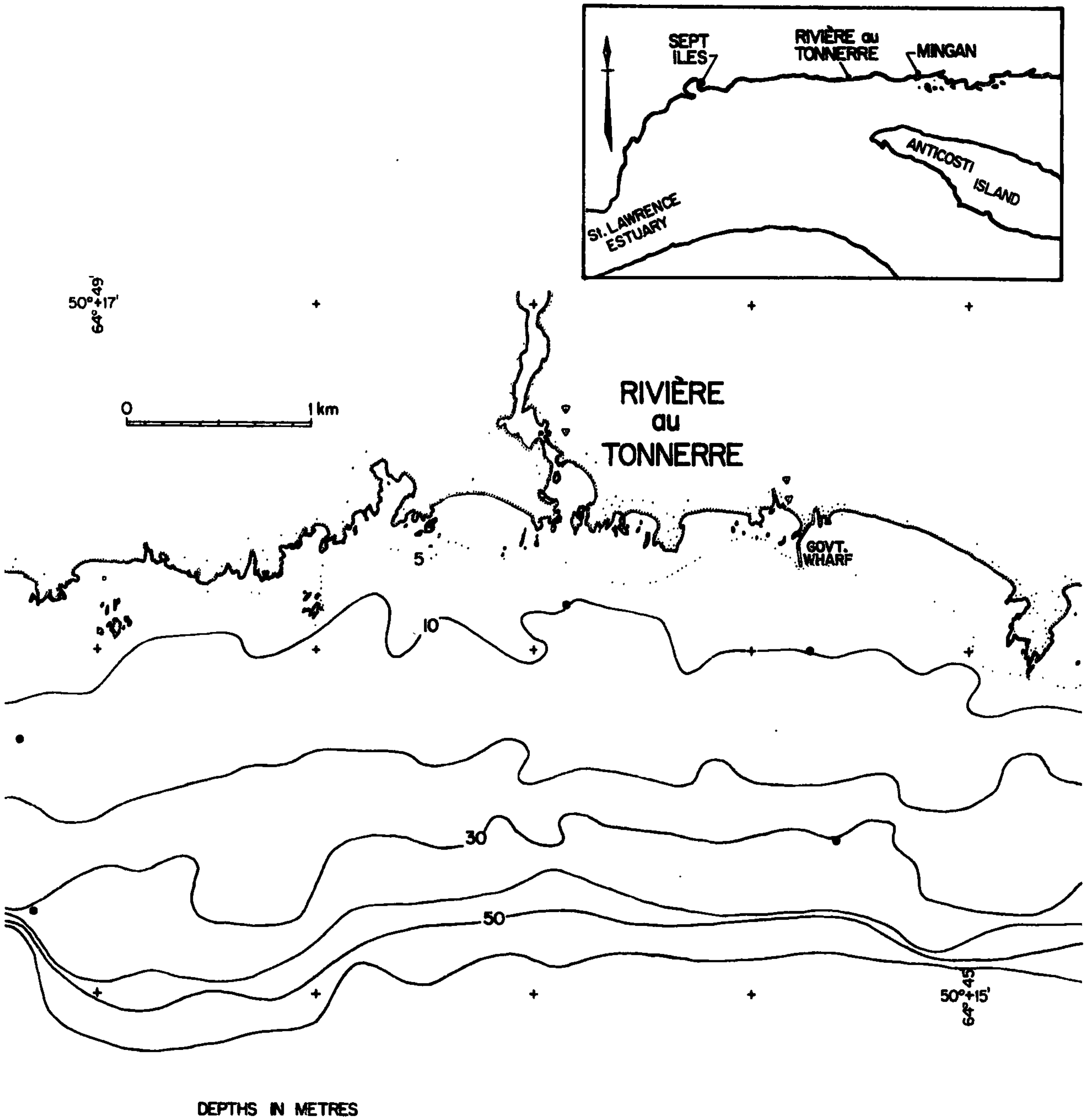

Fig. 1 Rivière au Tonnerre - Location and Offshore Bathymetry.

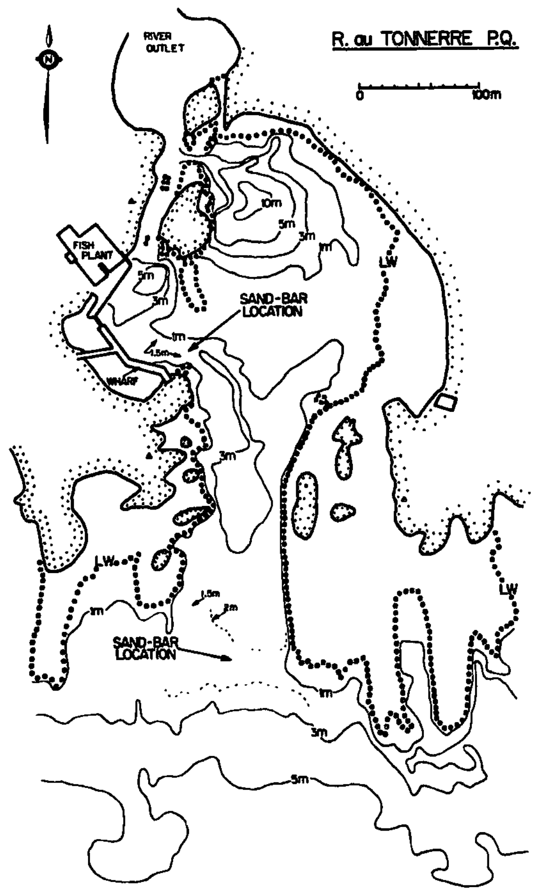

Fig. 2 - The Outlet System of Rivière au Tonnerre Sept. 1976.

Fig. 3 - The Outlet System of Rivière au Tonnerre June 1977.

Many of the rivers in this area entering the Gulf of St. Lawrence have sand barriers across their mouths with just a small opening remaining for the river discharge. The outlets through the sandbars are not consistently located in any particular position. Rivière au Tonnerre differs from this pattern by having practically no exposed sandbars; the mouth of the harbour, the basin and the river channel above being carved out of rock, presumably during the ice age.

In the system, there is very little natural storage to regulate the run-off. The river water discharges wildly through rock fissures and over numerous rapids.

The river enters the harbour basin from the northwest where its discharge is divided into two branches by a large outcrop of bedrock. One branch of the flow is directed southwest past the fish plant and public wharf, and the other to the southeast across the main body of the basin. The shape of the harbour is roughly circular with an east to west dimension of less than 300 m. This basin is basically a large sand trap. Seismic soundings show a sand layer 25 m thick rising to 0.5 m below LW. In the outlet channel the greatest water depth was 4.5 m in September 1976, and the sand layer approximately 3 m thick. At the eastern end of the public wharf a shoal forms during the low discharge season, reducing depths to less than 1.1 m. This interferes with navigation.

At LW the 200 m long outlet from the harbour basin to the Gulf narrows from about 130 m to 57 m halfway along the channel, then widens to about 110 m as it reaches the open water. A number of cross-sections and a longitudinal section were chosen (Fig. 4) to demonstrate the relationship between widths, depths, and cross-sectional areas. As shown in Figure 5 and given numerically in Table 1, the depths are greatest where the channel is narrowest, and shallowest where the channel is widest at its two ends. This applies particularly to the seaward side where, in line with the LW coastline, and close to the breaker zone, a shoal with a water depth of 1.3 m, was located in September 1976, forming a major hazard to navigation.

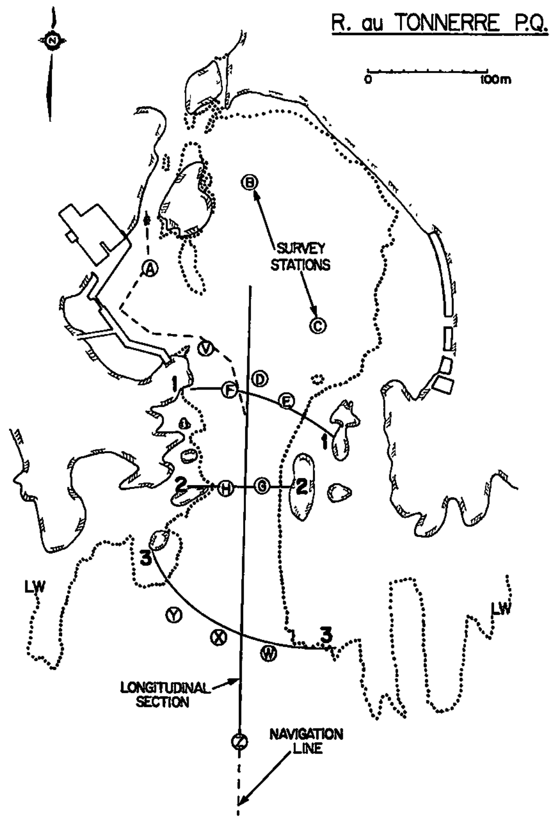

Fig. 4 - Location of Stations and Selected Cross-Sections

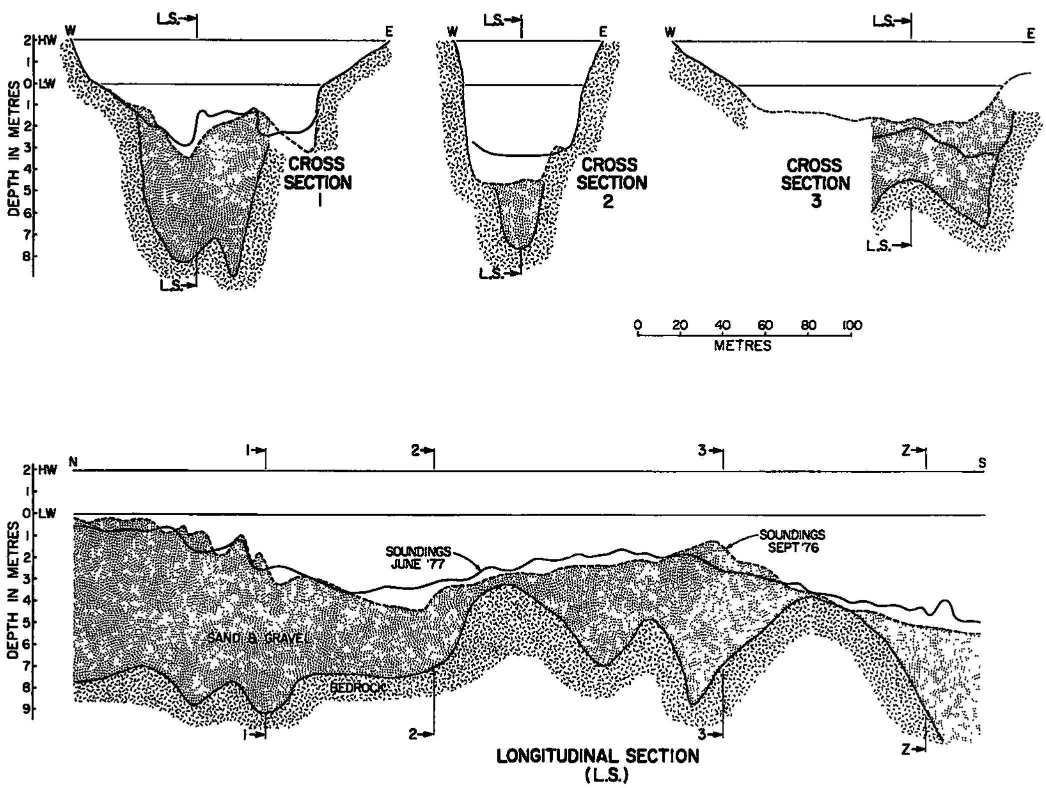

Fig. 5 - Cross Sections & Longitudinal Section of Harbour Outlet

Table 1

Cross-sectional Areas, Widths and Depths of the Outlet Channel

Section	Area below LW(A) m^2	Average Width (W) m	Average Depth (A/W) m
1	197	104	1.9
2	216	57	3.8
3	168	129	1.3

From here on seaward the bed drops off quickly. It should therefore be noted that within the outlet the width of the channel plays an important role in maintaining the depth of water.

Also shown in Figure 5 is the thickness of the underlying sand and gravel layer. It varies from 3 to 6 m with the greater values at the seaward shoal. During freshets, part of this sand is transported seaward (i.e. from section 3 towards station Z), leaving a temporary increase in water depths. This sand, however, is quickly replenished by the next southerly storm.

2.2 River Discharge and Tide

Rivière au Tonnerre is a snow-fed river with few lakes in the system to provide storage and thus equalize the flow. The run-off responds immediately to melting snow and rainy periods. The hydrograph in Figure 6 exhibits this feature in the steeply rising discharges and narrow peaks during spring, and smaller but equally steep peaks in the fall. The 22-year average daily discharge for the spring freshet is 115 m^3/s which is about six times the summer flow and 30 times the winter discharge. The largest mean daily discharge on record was 782 m^3/s.

The run-off varies greatly from day to day as shown in the preliminary river gauge data in Figure 7. During the survey in 1976 the discharge was 40 to 50 m^3/s during the first phase of the survey on 16 and 17 September but dropped to 21 m^3/s during the second phase on 20 September. In June 1977 the discharges were predictably higher but surprisingly uniform varying only from 55 to 68 m^3/s during the survey. The river had already passed its peak of 128 m^3/s on 25 May.

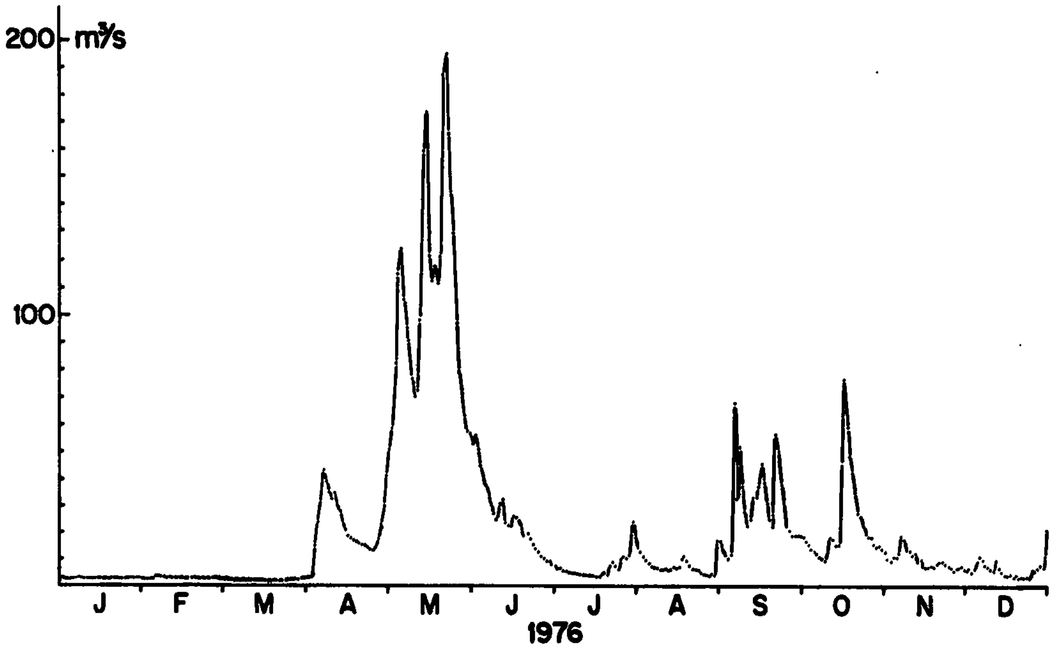

Fig. 6 - Daily Hydrograph of Rivière au Tonnerre for 1976

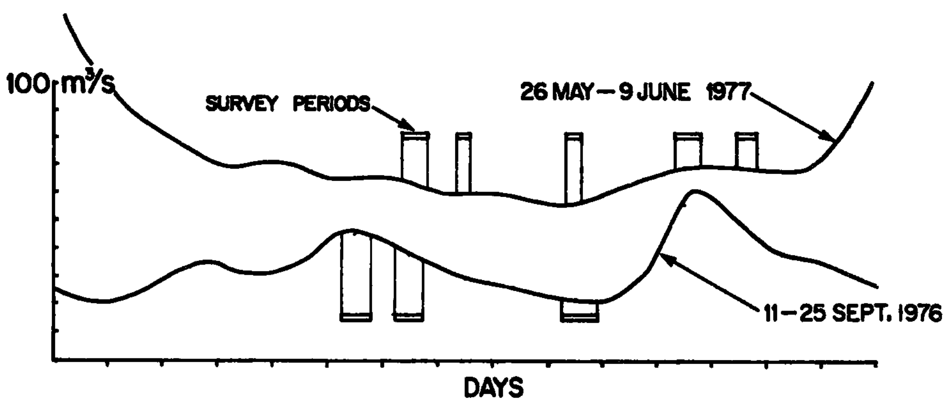

Fig. 7 - Daily River Discharges During 1976 and 1977 Surveys

The tide is predominantly semidiurnal with two HWs and two LWs daily and with a range varying from less than 0.75 m to more than 3.0 m (Figs. 8 and 9). With an average tidal range of 2 m and a mean surface area of the basin of 55 000 m^2, the tidal volume is 110 000 m^3. Thus the inward and outward flowing water due to tidal volume only would vary from 0 to 10 m^3/s, which at its peak would be about half of the summer river discharge.

During the September 1976 survey, small and medium tide ranges occurred. The June 1977 survey was carried out in medium to large tide ranges.

2.3 Winds and Waves

Wind records at Sept Iles over the period 1955 to 1972 show that the predominant direction during the winter was from the north and northwest, that is offshore winds, while during the summer the wind was more from the east with southwest being the next most frequent direction. Some maximum values observed were gusts up to 160 km/hr, an hourly speed of 100 km/hr from south-southwest and 30 km/hr from the east for the mean monthly velocity in December and January. With the exception of the water levels and the circulation in the offshore region, these winds have little or no direct influence on the dynamics of the river system and its outlet.

The waves which are generated by these winds, however, are particularly important to the mouth of the inlet where they break on the shoal, frequently making navigation into the harbour difficult. The largest waves probably come from east and southeast over a fetch length of 500 km and from southwest with a fetch of 120 km. Waves in excess of 4 to 5 m in height can occur.

Figure 10 shows refraction diagrams of 6 and 10 second waves approaching from SW, S and SE. As can be seen, waves with periods in excess of 6 seconds are redirected by the underwater topography of the near-shore zone in such a way that their crests are parallel or nearly parallel to the coastline when they reach the mouth of the inlet, and then break on the sandbar lying in the approaches to the harbour. The breaking waves also play an important role in the formation of the sand bar.

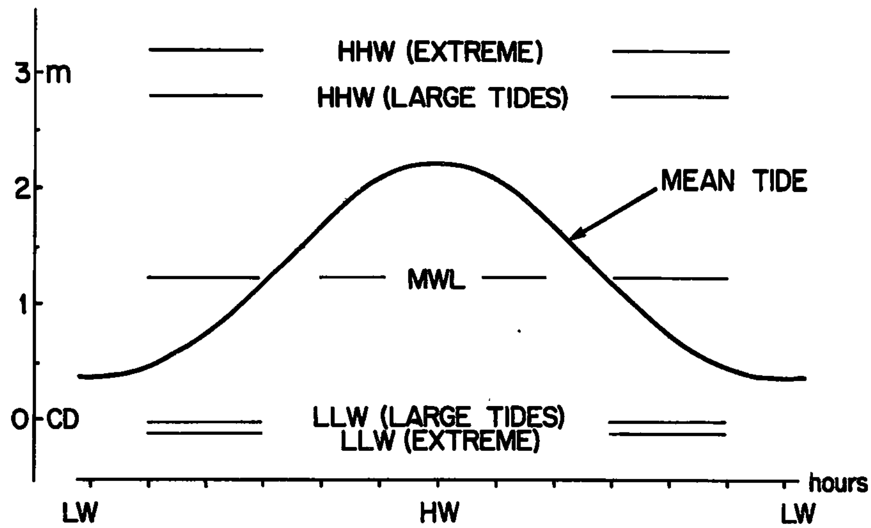

Fig. 8 - Tide Ranges at Rivière au Tonnerre

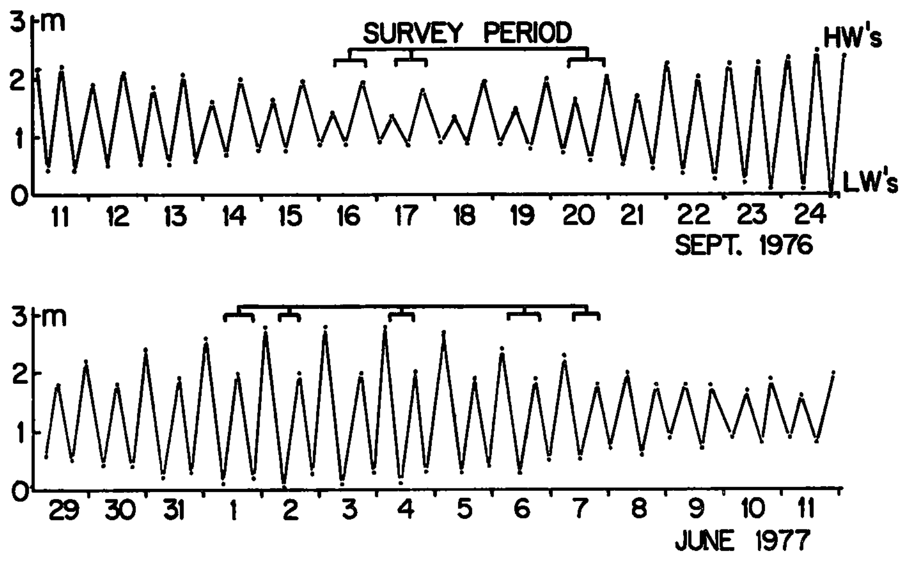

Fig. 9 - Predicted Tides During Surveys

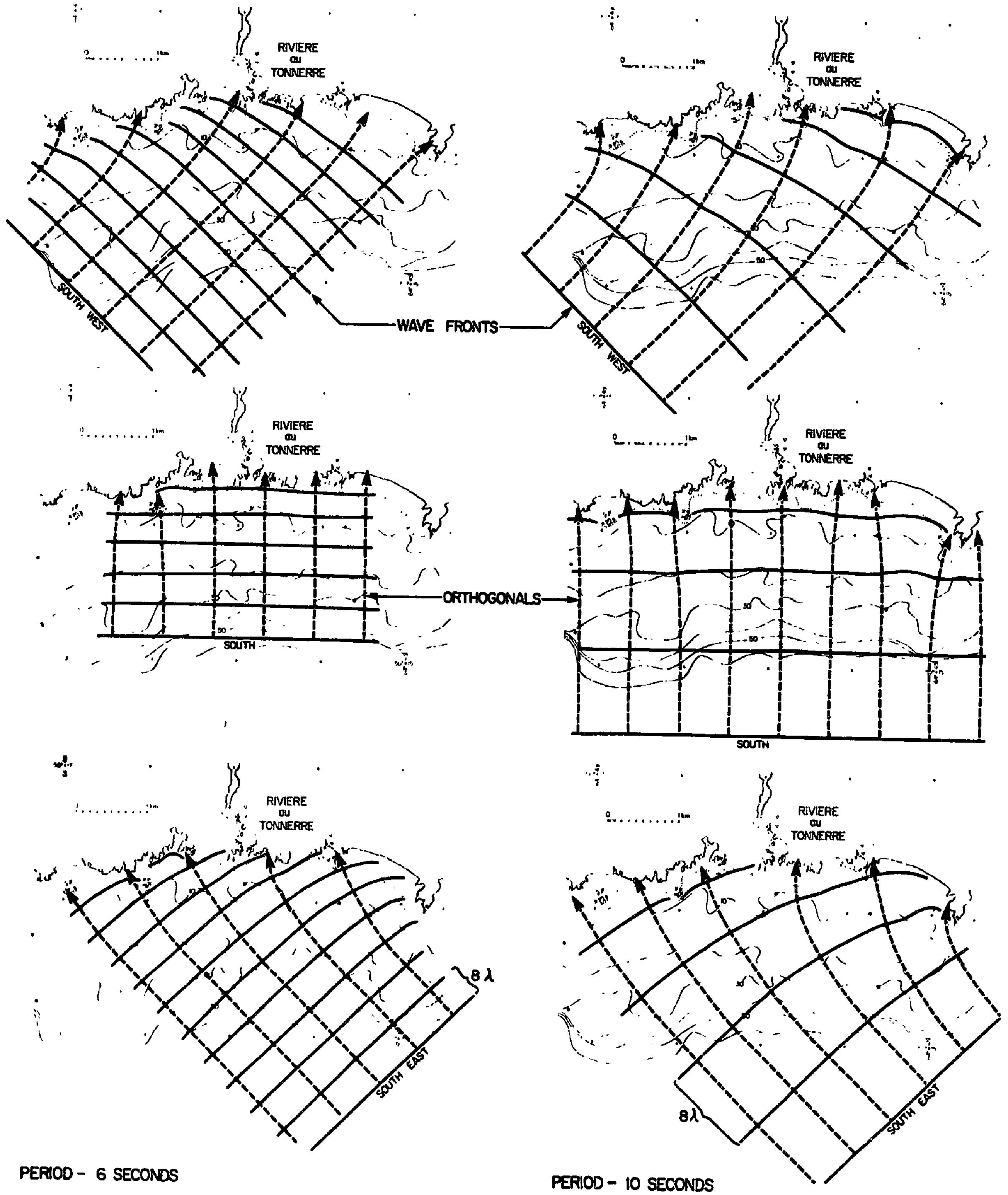

Fig. 10 - Wave Refraction Diagrams of 6 and 10 second Waves Approaching from SW, S and SE directions

An example of the severity of wave action in this region is shown by the condition of the government wharf lying 1.2 km along the coast to the east of the harbour entrance. One hundred and thirty metres long and extending out to the 5 m depth contour its inner 50 m has been heavily damaged on the western side by wave action. This damage started soon after the wharf was completed.

2.4 Sand

Sand is supplied to the harbour basin and the outlet channel from two sources, the river and the offshore region. The sand from the river is provided primarily by freshets. During this period, the currents are so strong that the sand cannot settle and is carried out to the offshore region, where it is deposited in deeper waters. This is typical of the many other rivers along the coast. The offshore sand is brought into motion by wave action and,as waves approach the coastline at an angle to the underwater contour lines, a longshore transport - referred to as littoral drift - is initiated whereby large quantities of sand are moved past the outlet. From there the sand is carried into the outlet by the inward-directed bottom flow of the salt water wedge as well as by wave action. From the two sources, the off-shore region and the river, there is always enough sand available to compensate for any excavation in the outlet system. Hence, it is impractical to maintain greater navigation depths by dredging. Even at discharges lower then the freshet, some sand can still be carried by the river. This sand will be able to fall out of suspension when reaching the lower velocity areas of the harbour, and be deposited in the harbour basin by the inward moving salt water underneath.

3.0 SURVEYS

Before any recommendation could be made for improving the navigation conditions, oceanographic measurements had to be carried out to obtain a better understanding of the nature and magnitude of the forces which cause the shoaling in the system. In 1976 ten days were spent at the site of which only three days, between September 16 and 20, could be used for the survey. In 1977, eight days were needed for two full cycles of data. In addition, an aerial reconnaissance was made to compare the site with neighbouring systems.

For the first survey an eight metre launch was used from CSS *Maxwell* of the Canadian Hydrographic Service, which was stationed in the area to carry out a bathymetric survey of the region. In June 1977 a small five metre outboard runabout was transported to the area for the work. A network of stations was established as shown in Figure 4 where temperatures, salinities, and current velocities were measured. Until the June, 1977 survey, no stations were placed over the shoal areas due to ignorance of their location. Rough weather and breaking waves frequently interrupted both surveys and forced the mothership CSS *Maxwell* to Mingan harbour for protection. It was therefore difficult to obtain continuous records over complete tidal periods. When possible, four stations were occupied in rotation during a tide cycle, thus supplying data every three-quarters of an hour in the basin and outlet, and every hour and a half in the offshore area.

Temperatures and salinities were measured with a Beckman RS5 portable salinometer, and, in 1976, the current velocities with a BENDIX savonius rotor, directional current meter (1977 measurements were made with an ENDECO current meter). The salinometer and the current meter were coupled together for deployment at the same time.

Because of the rough and turbulent conditions which prevailed during the survey, the high sensitivity of the BENDIX direction sensor produced data with variations which had to be smoothed by the application of time series interpretation over a tide cycle. This enabled qualitative trends to be picked out, from which consistent quantitative results were obtained. The design of the ENDECO current meter produced much more stable measurements in the turbulent flow conditions, and the field data could be plotted directly without time series processing. The differences between the two records can be seen in Fig. 22 where the smoothed BENDIX lines contrast markedly with the ENDECO data.

4.0 SURVEY RESULTS AND THEIR ANALYSIS

The data have been processed and analyzed and the results are presented graphically. The important velocity (Figs. 11-14) and salinity (Figs. 15-18) data are given in vertical profiles at quarterly tide stages;

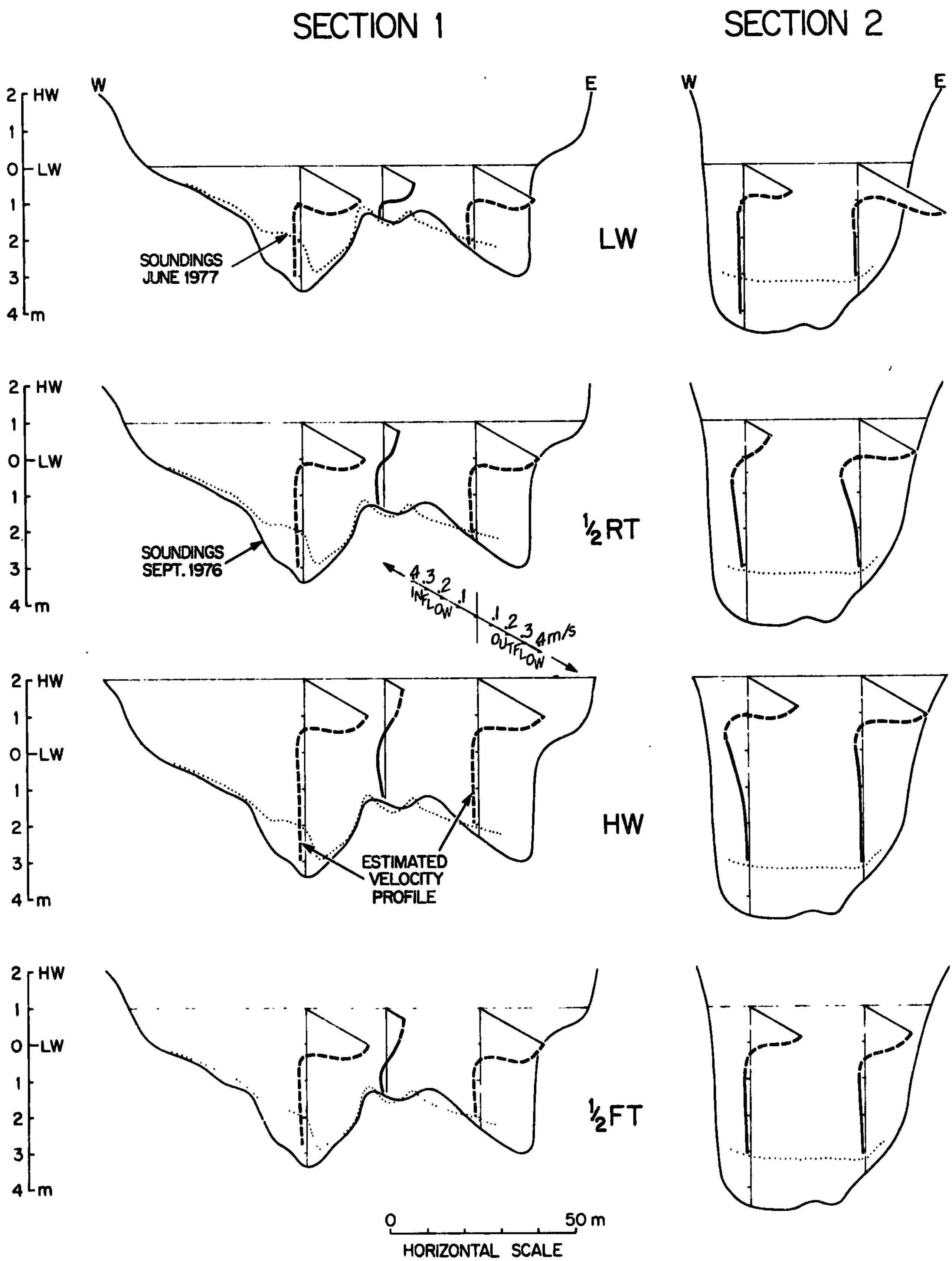

Fig. 11 - Current Velocities in Sections 1 and 2 of the Outlet Channel for $Q = 21\ m^3/s$

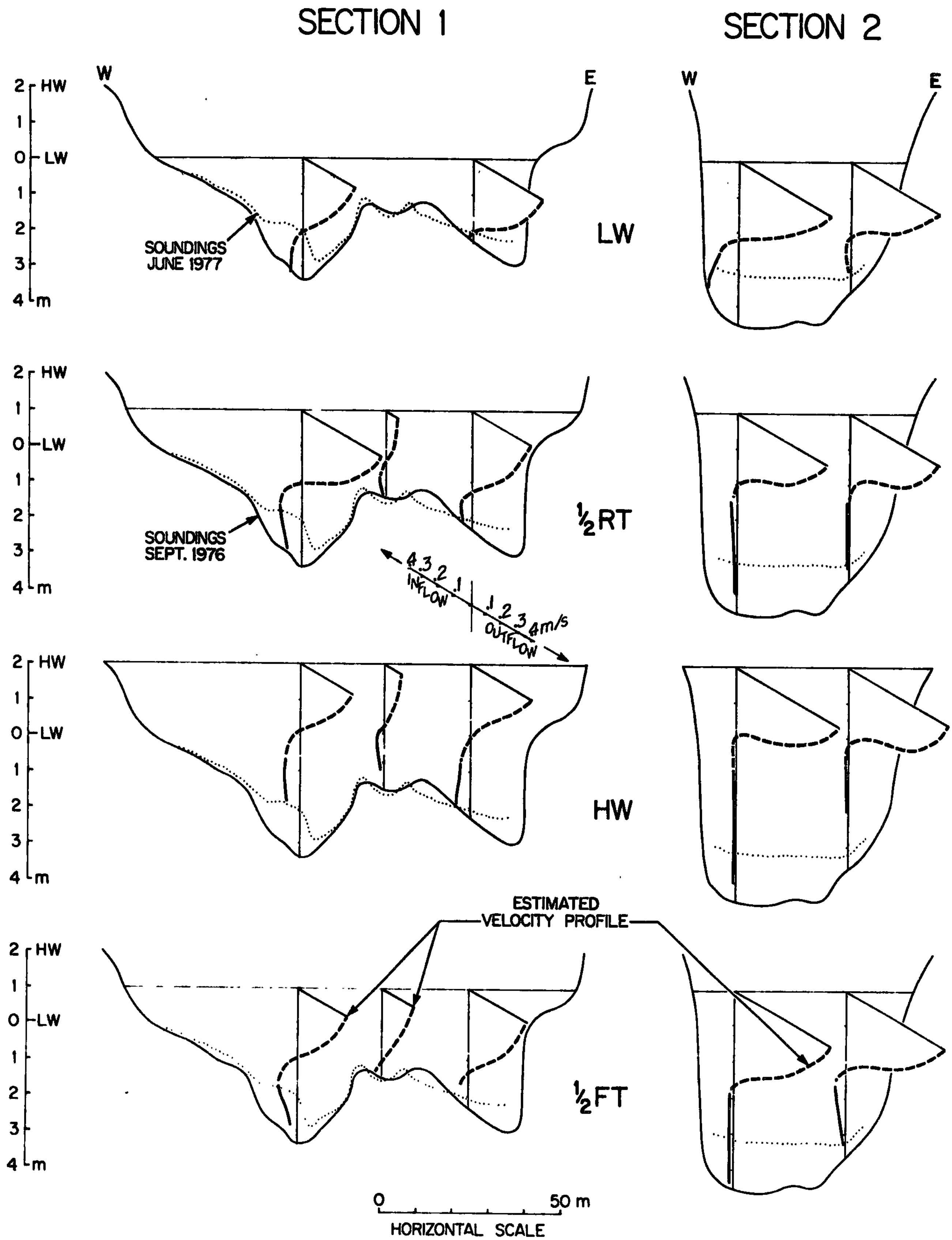

Fig. 12 - Current Velocities in Sections 1 and 2 of the Outlet Channel for Q = 38 m^3/s

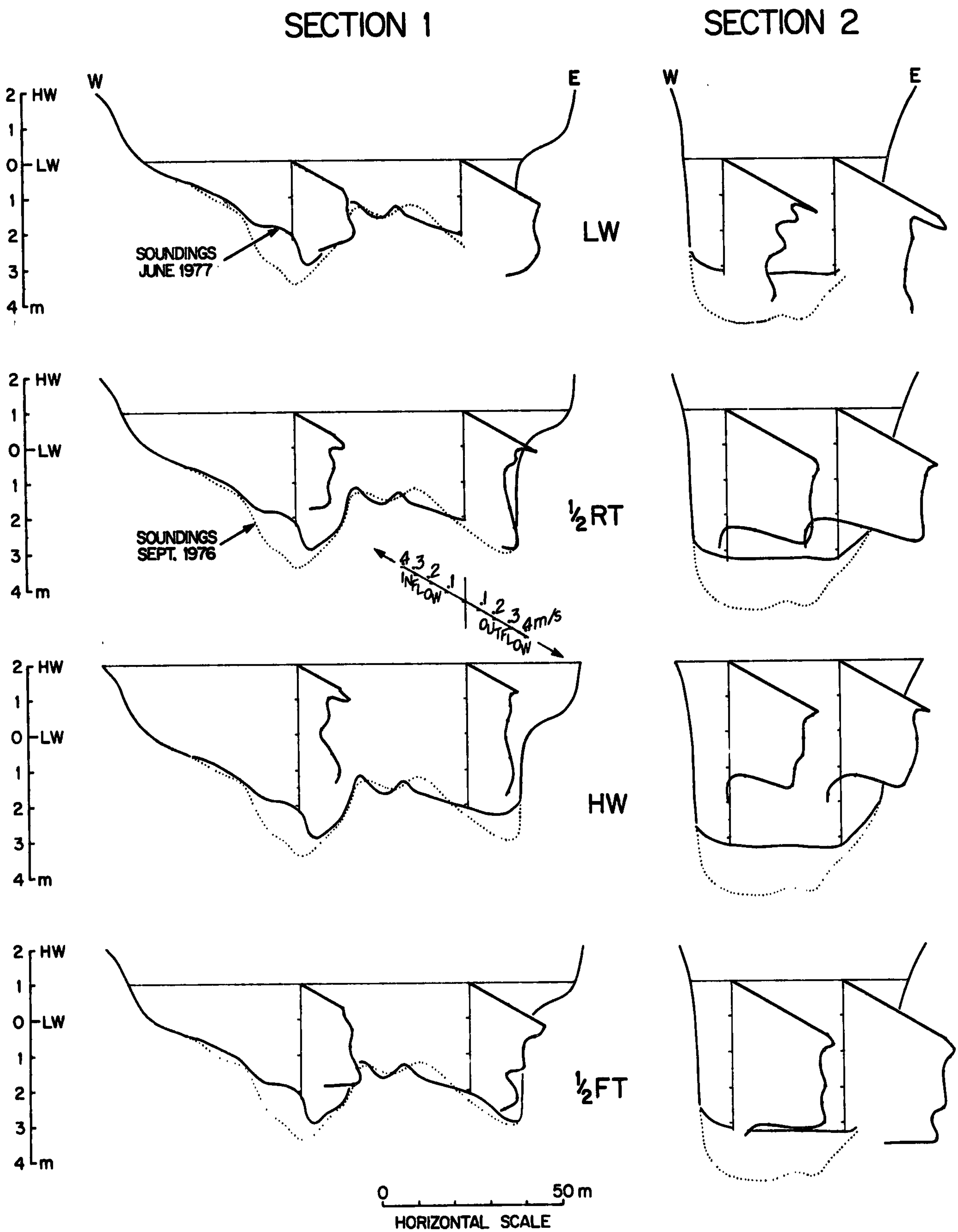

Fig. 13 - Current Velocities in Sections 1 and 2 of the Outlet Channel for $Q = 68\ m^3/s$

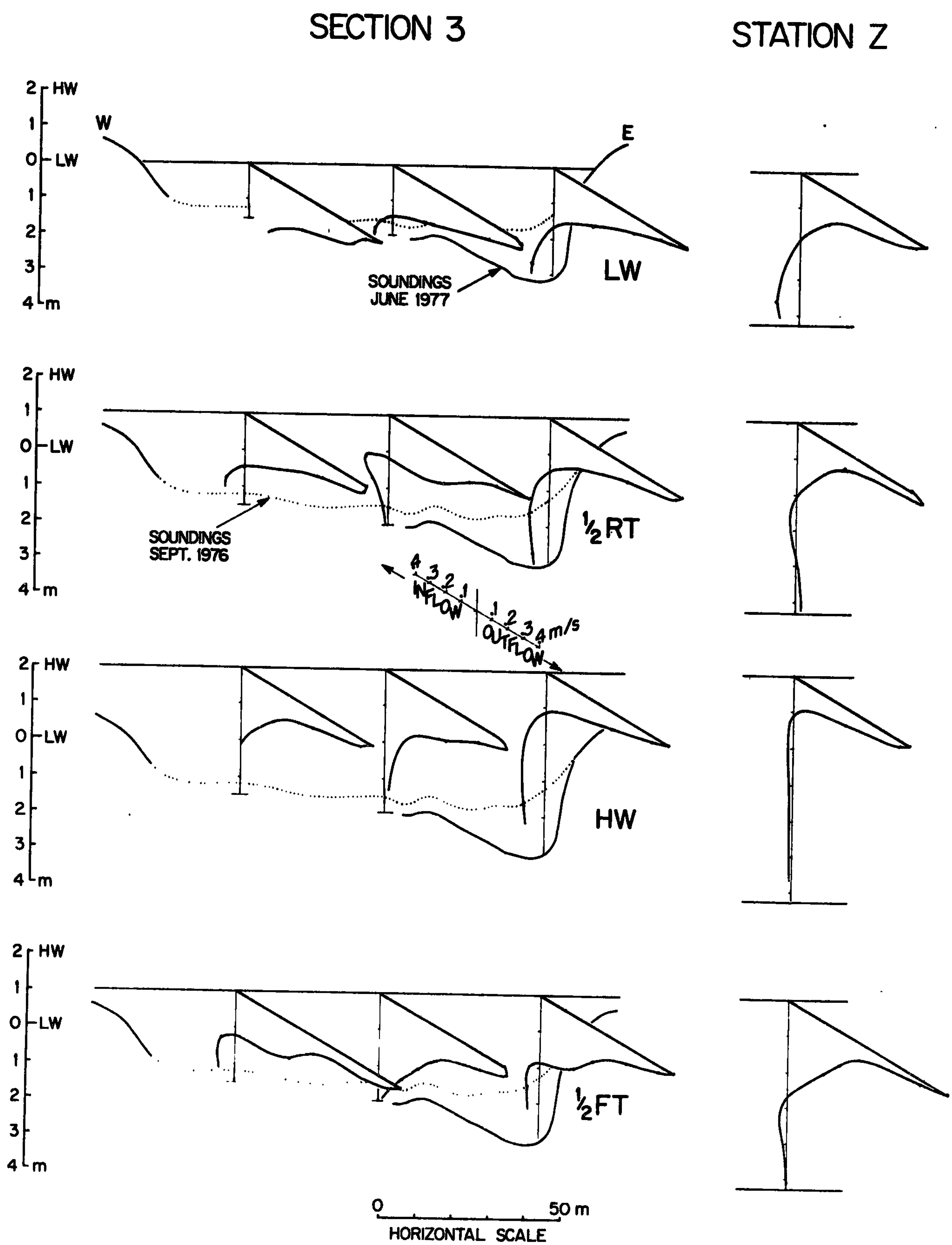

Fig. 14 - Current Velocities in Section 3 of the Outlet Channel and Station Z for Q = 68 m^3/s

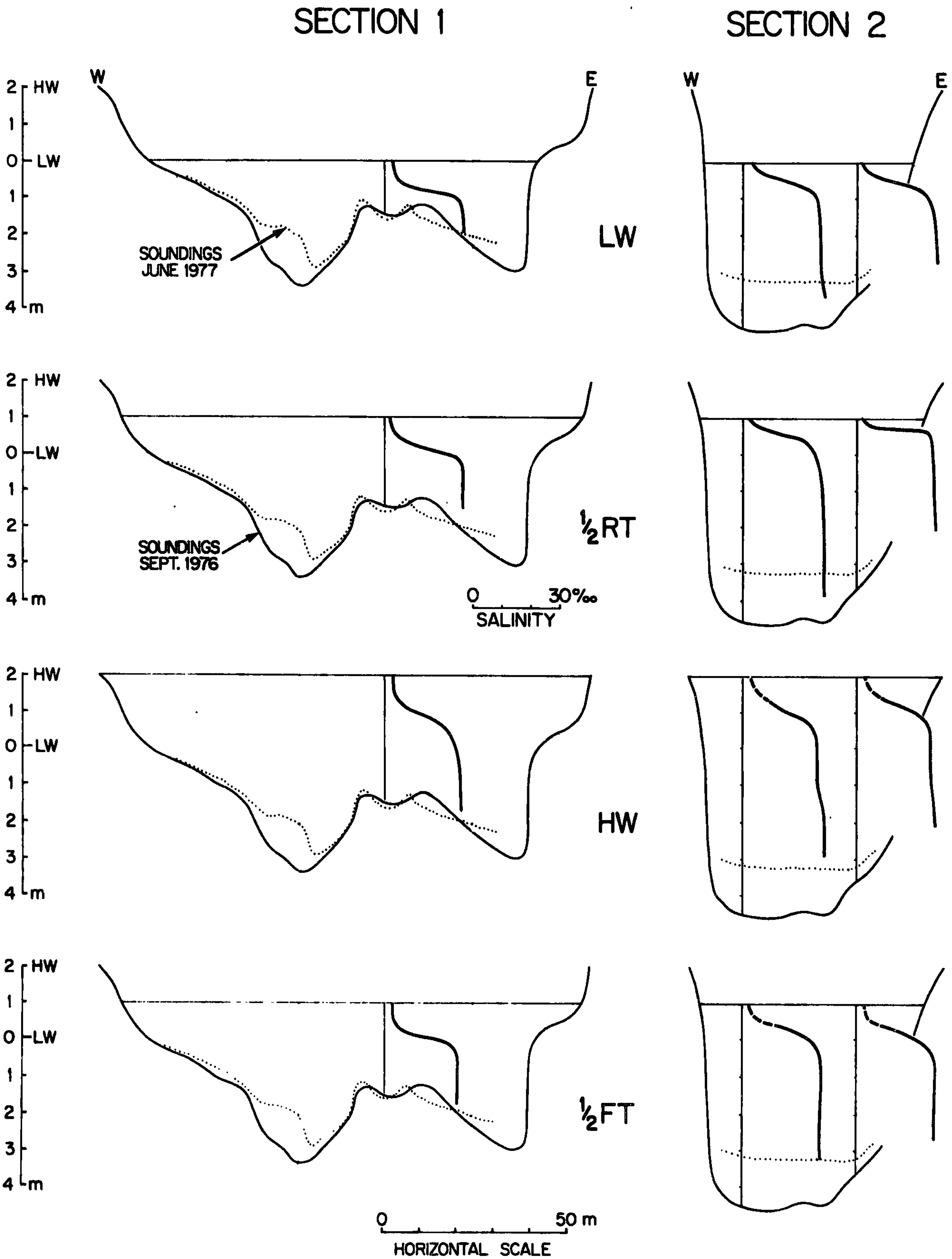

Fig. 15 - Salinity Profiles in Sections 1 and 2 of the Outlet Channel for Q = 21 m^3/s

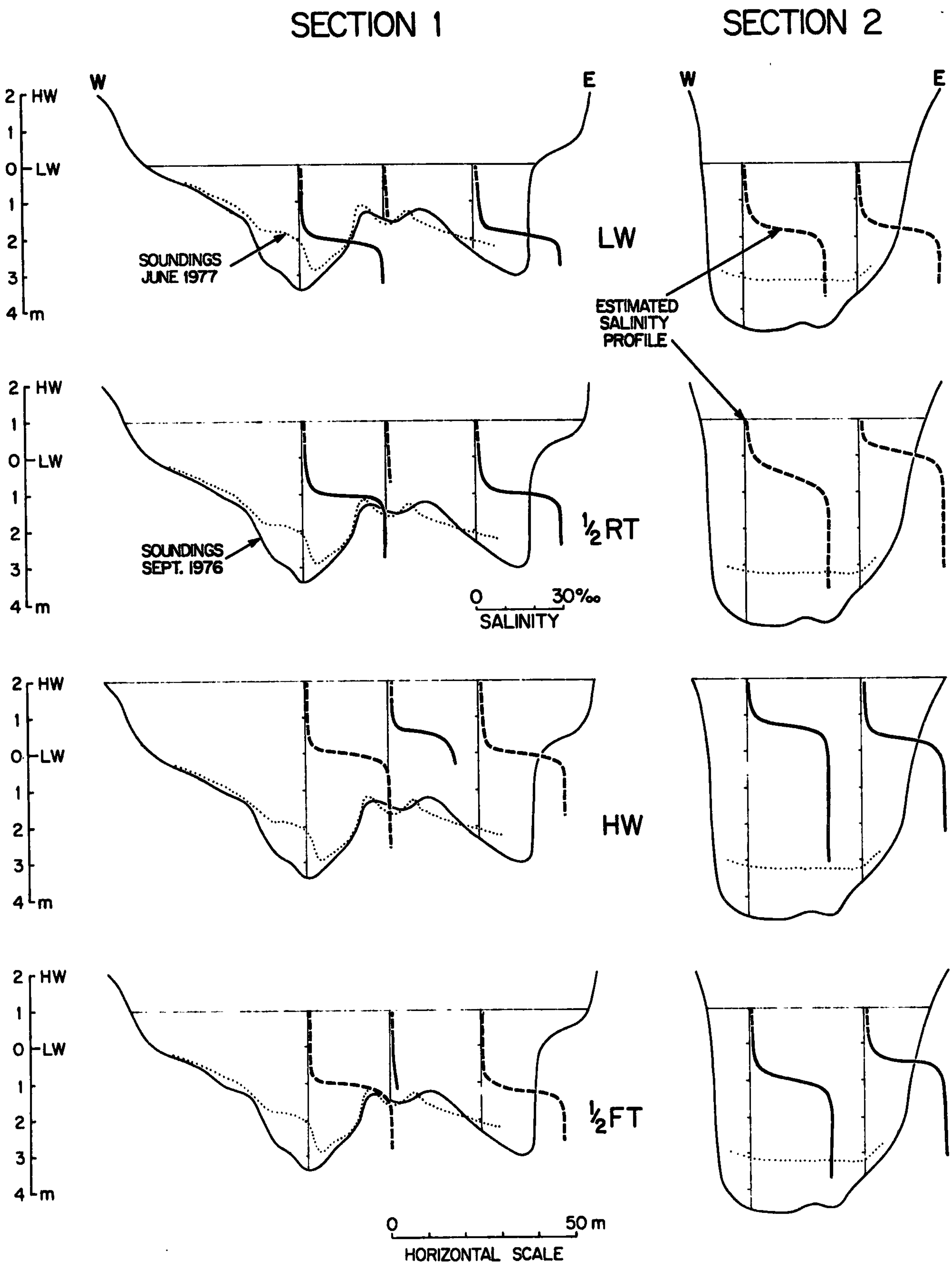

Fig. 16 - Salinity Profiles in Sections 1 and 2 of the Outlet Channel for Q = 38 m^3/s

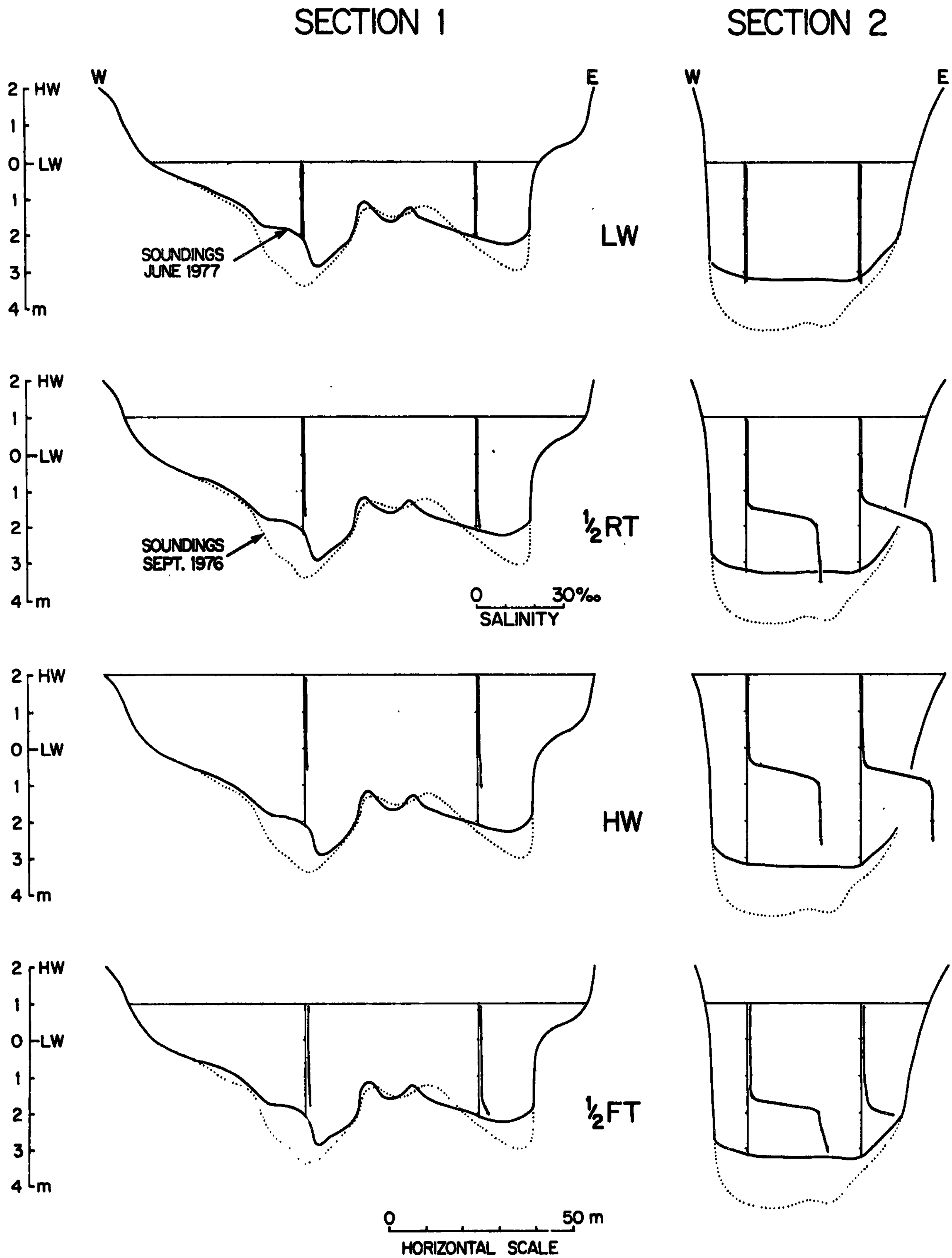

Fig. 17 - Salinity Profiles in Sections 1 and 2 of the Outlet Channel for $Q = 68\ m^3/s$

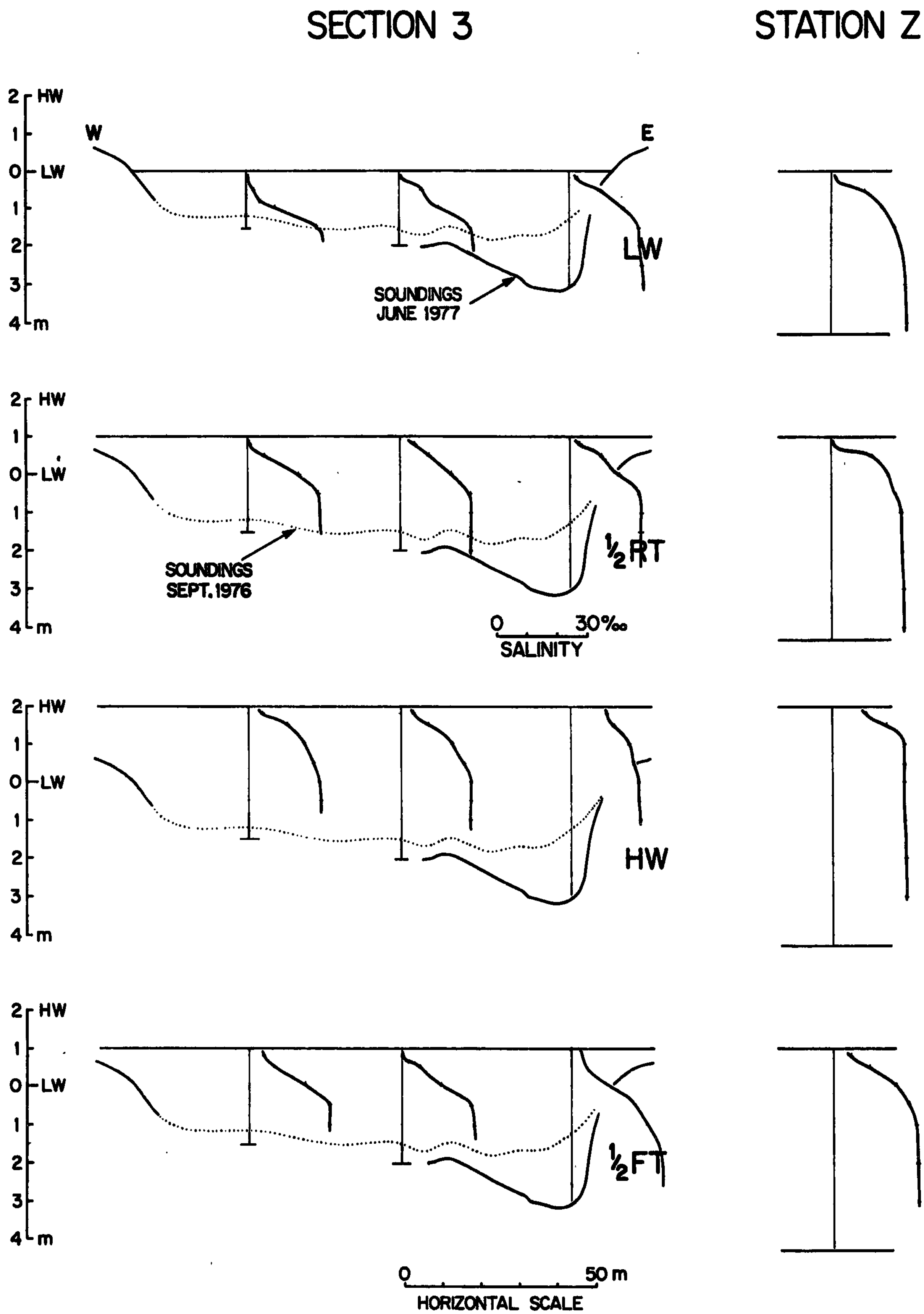

Fig. 18 - Salinity Profiles in Section 3 of the Outlet Channel and Station Z for Q = 68 m^3/s

i.e. at Low Water (LW), ½ Rising Tide (½RT), High Water (HW), and ½ Falling Tide (½FT). As mentioned before, insufficient information on the location of the shoals is to blame for not surveying these areas in September 1976. Further complications arose when the river discharge data were received which indicated that on September 17, when Section 1 was surveyed, the river flow was 38 m^3s, nearly twice that of September 20, (21 m^3/s) when Section 2 was surveyed. This difference in the river flow has a significant impact on the velocity and salinity distribution of the system. By using overlapping data, missing points and profiles were reconstructed in order to be able to compare the differences of the two discharges. Actual surveyed data are plotted in solid lines while estimates are presented in dashed lines.

A general inspection of velocity and salinity profiles of Sections 1, 2 and 3 and station Z in Figures 11 to 14 and of Figures 15 to 18 respectively, indicate that during the entire tide cycle, there was a well defined two-layer flow system, in which the surface layer was always outward and the deeper layer always inward directed. The surface layer consisted of fresh or near-fresh water while the deep layer was undiluted salt water. Between the two layers was an intermediate layer or transition zone, up to 1.5 m thick, in which the salinity varied from 0 at the upper interface to 25‰ at the lower. The currents in this transition layer were highly turbulent and always outward directed with the surface layer.

The thickness of the surface layer changed with distance from the open water and with river discharge, while the size of the intermediate layer remained quite constant. The changes with distance from the mouth of the channel are shown in Fig. 19 where the vertical velocity and salinity profiles along the channel are plotted for the discharge of 68 m^3/s. The three layers are indicated by shading. As can be seen, the freshwater layer decreased quickly seaward from the full depth of the channel to virtually zero depth at Section 3, while the saltwater layer decreased in thickness in the opposite direction. The thickness of the freshwater layer remained quite constant in depth for each station during a tide cycle, and the saltwater layer increased and decreased with the tide stages. This variation in depth is a function of the intrusion of the saltwater wedge.

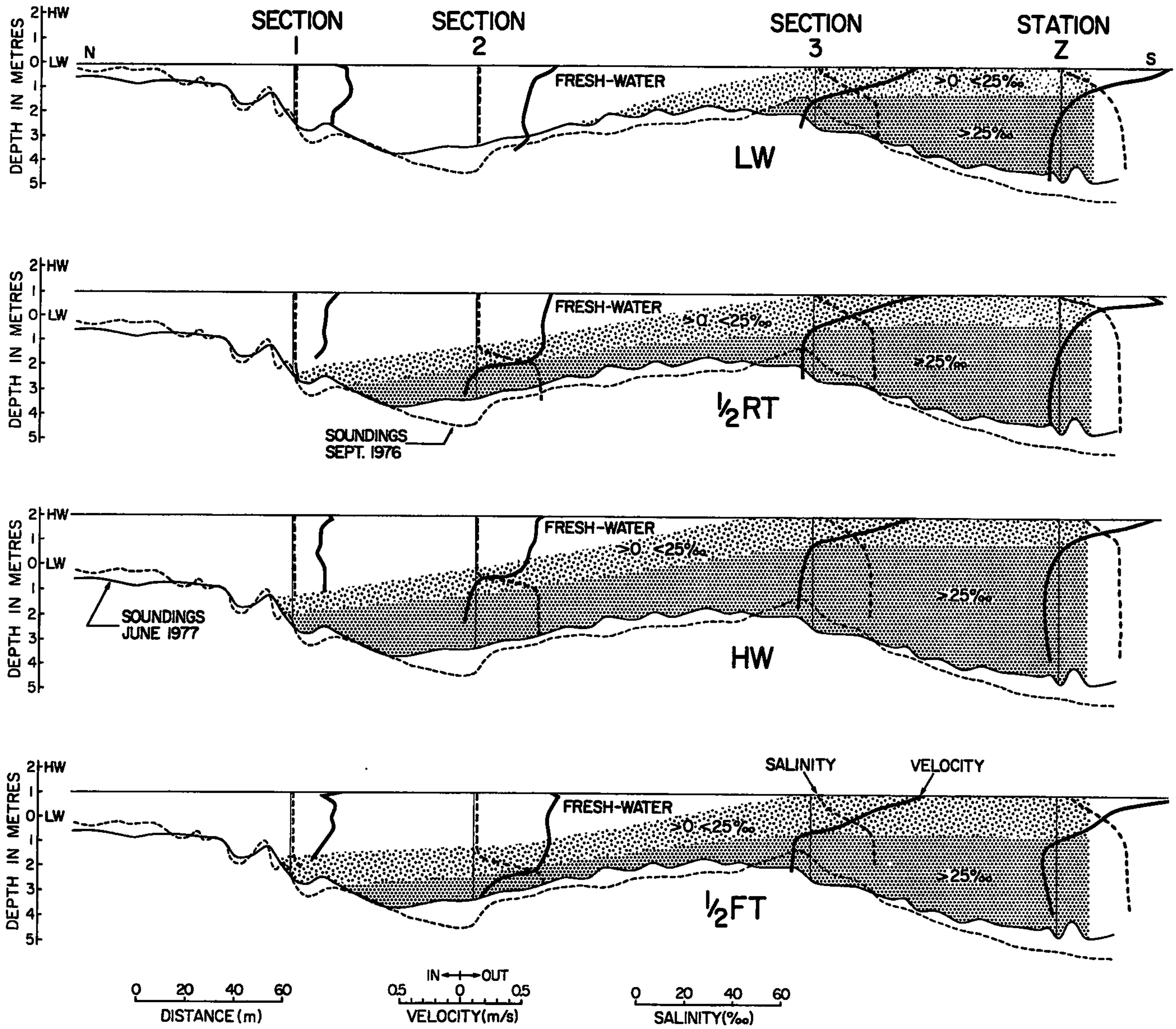

Fig. 19 - Current and Salinity Variation Along the Outlet Channel for $Q = 68\ m^3/s$

At LW the intrusion was shortest and even the tip of the mixed layer was pushed back to Section 2. At HW more than half of the depth of the channel was filled with saltwater.

An intermediate or mixing zone must exist as long as these two major water bodies meet. For a given point in the channel and a given discharge its thickness remained constant throughout the tide cycle. Seaward, its thickness gradually increased to reach a fairly constant value off-shore from Section 3. Like the freshwater layer, the intermediate layer was always outward directed.

While the thickness of the surface layers remained constant for a given point in the channel during a tide cycle, it varied with river discharge as demonstrated in Fig. 20. For an increase in discharge from 21 m^3/s to 68 m^3/s, its thickness at Section 2 grew from 1.2 m to 4.4 m. The mixing layer remained quite constant, but the salinity layer decreased in relationship to the increase of the freshwater layer (Fig. 21). It should be noted that increases in discharge from 21 m^3/s to 68 m^3/s do not change the velocity structure and its strength at the bed of the channel. Only after the saltwater and part of the intermediate layer is removed from the channel, can a change in current field occur which will erode the channel and carry the sand seaward.

Thus, the saltwater profiles as well as the velocity distribution and therefore the depth of water in the channel are primarily controlled by the river discharge. As long as saltwater is in the system, depths will not increase. At Section 2, this critical point is at about 60 m^3/s (Fig. 20). Discharge in excess of this value will deepen the channel. For lower discharges, the tidal volume of the system and the saltwater for mixing into the intermediate layer are provided mainly by the inward directed deeper layer. The amount required for mixing is more than six times the tidal volume. In spite of this large demand for saltwater, its velocity is frequently too small to be measured.

As shown in Fig. 20, with increasing river flow, the thickness of the combined layer increased thus blocking the salt water from entering the system. Clearly, this blocking action is most effective at LW when the

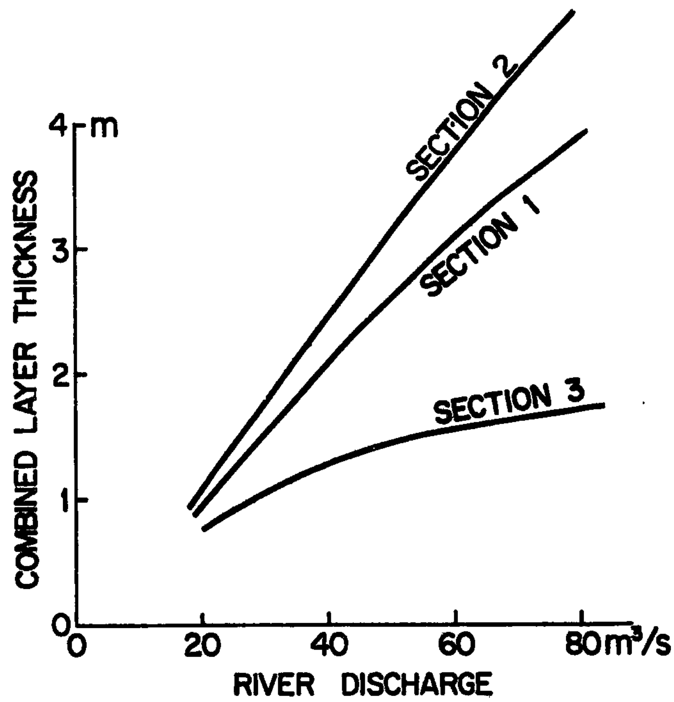

Fig. 20 - Thickness of Surface plus Intermediate Layers Verses River Discharge

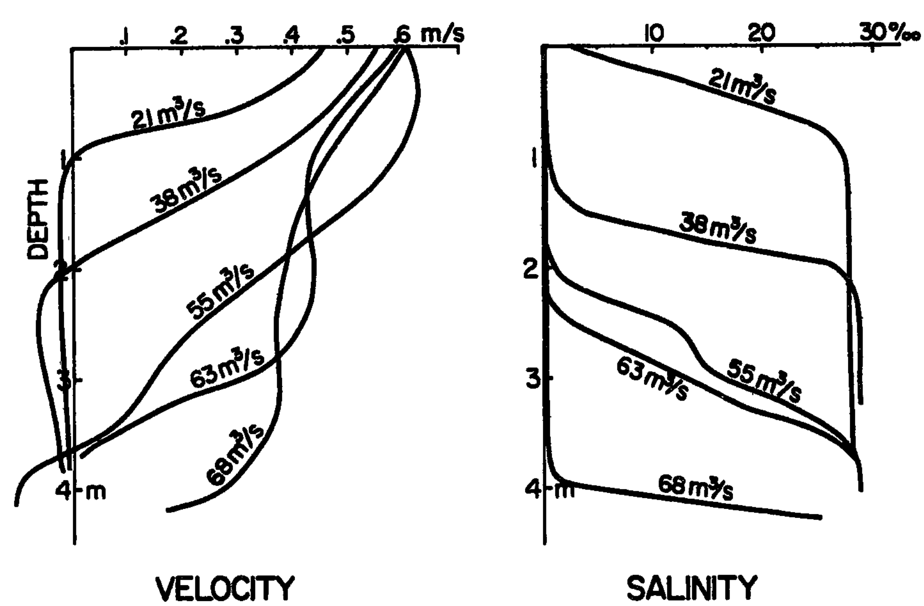

Fig. 21 - Velocity and Salinity Profiles at Section 2 for Various River Discharges

depth of water is at a minimum. At this stage the intermediate layer may come in contact with the bed of the channel where its turbulent motion will, for a short period, erode the sand, and produce greater depths.

Also in Fig. 20, Section 2, by virtue of its narrow cross-section, is in terms of combined layer thickness the most efficient cross-section, maintaining depths always greater than the other two sections. At Section 3, the thickness of the combined layer of about 1.3 m at LW is in agreement with the water depth over the shoal at a discharge of about 40 m^3/s. The curve indicates that a river flow exceeding 90 m^3/s would be required to achieve a water depth approaching 2 m over the shoal.

At Station A near the fish plant, the profiles of the currents and salinities over a tidal cycle during discharges of 38 and 68 m^3/s are shown in Figure 22. As mentioned earlier, these two sets of profiles differ in quality due to the use of two different current meters. The station is under the influence of the outflow from the southern channel which carries about one-third of the river flow and controls the water depths along the wharf. During September 1976, the surface and intermediate layers were appreciably deeper than those of the outlet channel, the upper layer varying from 2 to 4 m at HW and LW respectively and the intermediate layer thickness being nearly twice that at the outlet. Obviously, this type of flow structure is necessary in order to maintain the depth of 6 m below LW at A.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The two major regions of shoaling in the navigation lane, are at the two ends of the outlet channel (Figs. 2 and 3). Concerning the outer sandbar (on Section 3), it can be assumed from Figure 7 that the depth of 1.3 m below LW over the shoal was related to a river discharge of between 30 and 45 m^3/s. During smaller and larger discharges, the depths will change only marginally as indicated in Figure 20.

The variation of the river flow in 1976 is shown in Figure 6. For most of the year, the discharge was below 20 m^3/s. During the winter months, when the harbour is icebound, the depths are at their smallest, probably below 0.5 m, while in May and June, they approach 2 m. During

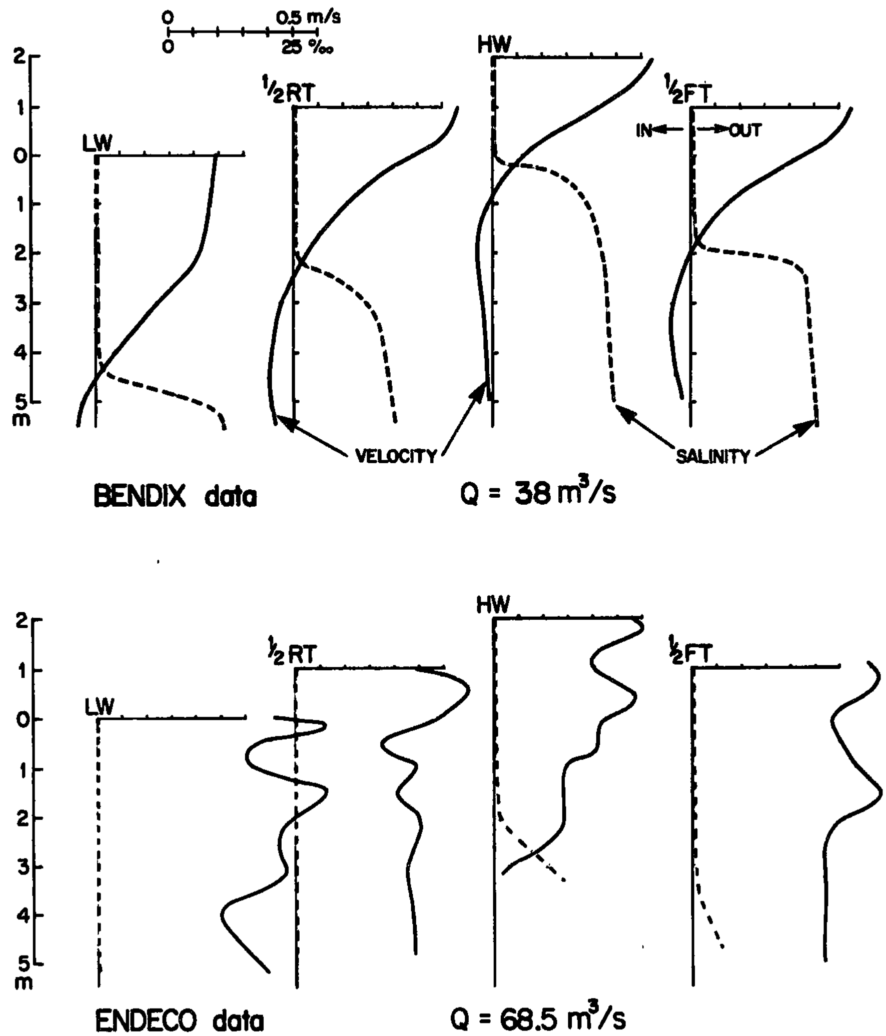

Fig. 22 - Velocity and Salinity Profiles at Station A for
Q = 38 and 68 m^3/s

summer and autumn, the flow varied on the average between 10 and 30 m^3/s with some peaks to 50 m^3/s and once to 75 m^3/s in October. Since fishing takes place during this period, improvements to navigation conditions should be made with these discharges in mind.

Since the saltwater layer acts as a sand trap, the only way to achieve greater depths is by flushing the saltwater from the system. This can be accomplished either by increasing the river flow or by restricting the discharge to a narrower channel. The first option is impractical because it would require the regulation of the river flow. The second option can be applied to the outer shoal by a dyke system as shown in Figure 23. This system would restrict the channel to about one-third its natural LW width. The confinement would increase the thickness of the combined surface and intermediate layers, thus causing erosion at the shoal. The exact depth which will be achieved over the shoal cannot yet be stated with certainty, but by considering Figure 20 it is reasonable to assume that during a median summer discharge of 20 m^3/s the minimum depth can be improved from 0.8 m to about 1.2 m at LW. For discharges in excess of 35 m^3/s, the navigation depths should exceed 2 m. The layout of the dyke will depend on the type of structure chosen to withstand the heavy wave action. The location shown in Figure 23 is based on the proximity of the underlying bedrock.

The installation of a dyke system at the outlet of the channel will modify the current structure in the basin. This may cause additional sedimentation at the shoal near the entrance to the channel where navigation depths were only 1.1 m at LW during the 1976 survey. To prevent this and to increase the existing depth, a change in the flow distribution through the two channels of the rock ledge is suggested (Fig. 24) by filling in the gully in the eastern channel to near the LW level. This modification is designed to increase the flow in the southern channel during lower discharges but maintain the present distribution during higher discharges. The increase in the discharge along the west and south shore should scour the area of the shoal.

It is obvious that there is a number of other factors which affect the sand transport and shoaling. These are secondary motions which occur at bends, oscillating and reflecting currents, internal waves and the

Fig. 23 - Proposed Dykes

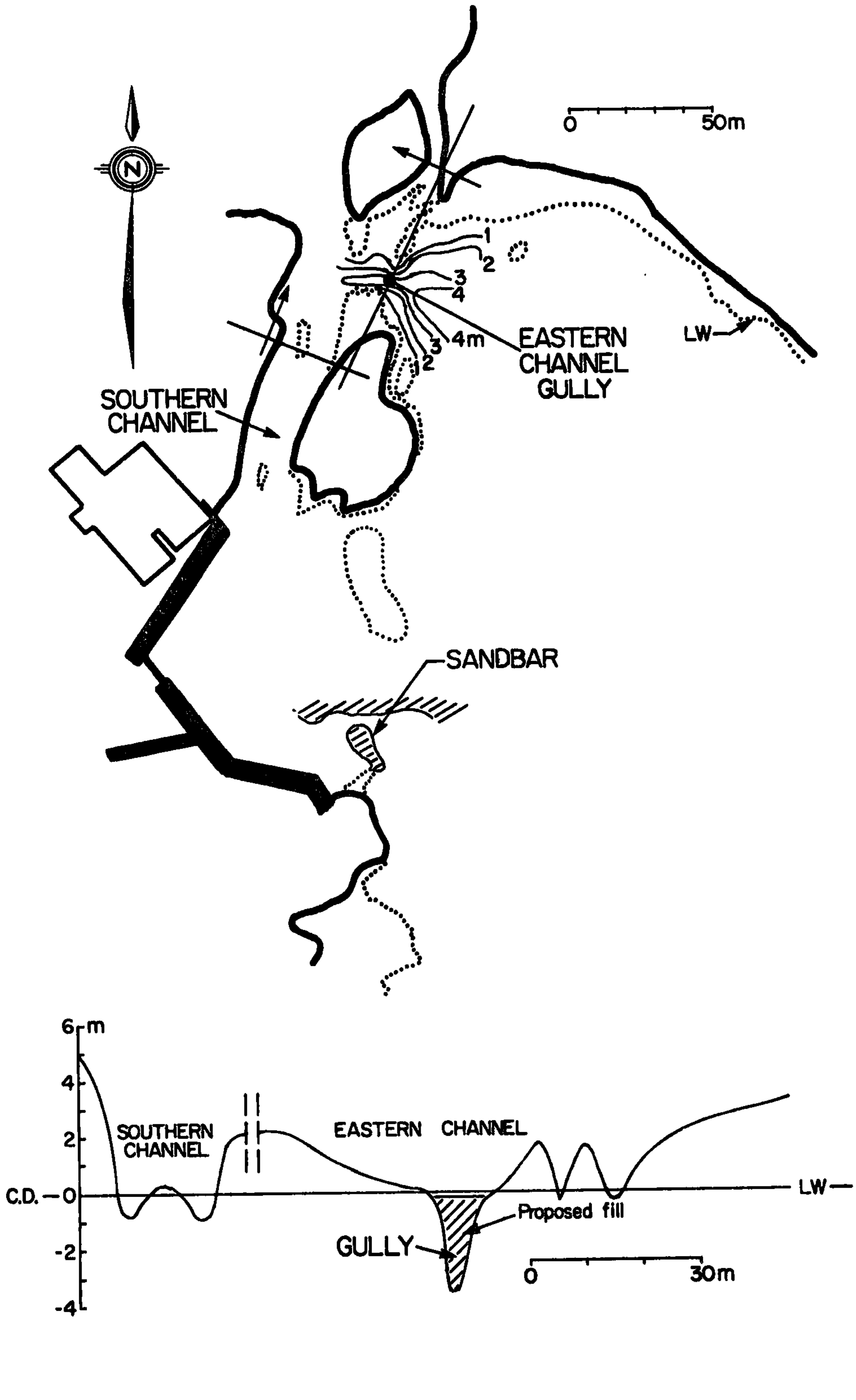

Fig. 24 - Proposed Modification to Eastern Channel

interaction of the two main currents through the harbour as they enter the outlet channel. The significance of these factors cannot be assessed in this report. Their effect can only be studied in a physical model. It is therefore suggested that such an investigation be conducted in which these findings can be verified or disproven and where the effects of the other factors can be evaluated and incorporated in the design.

6.0 ACKNOWLEDGEMENT

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