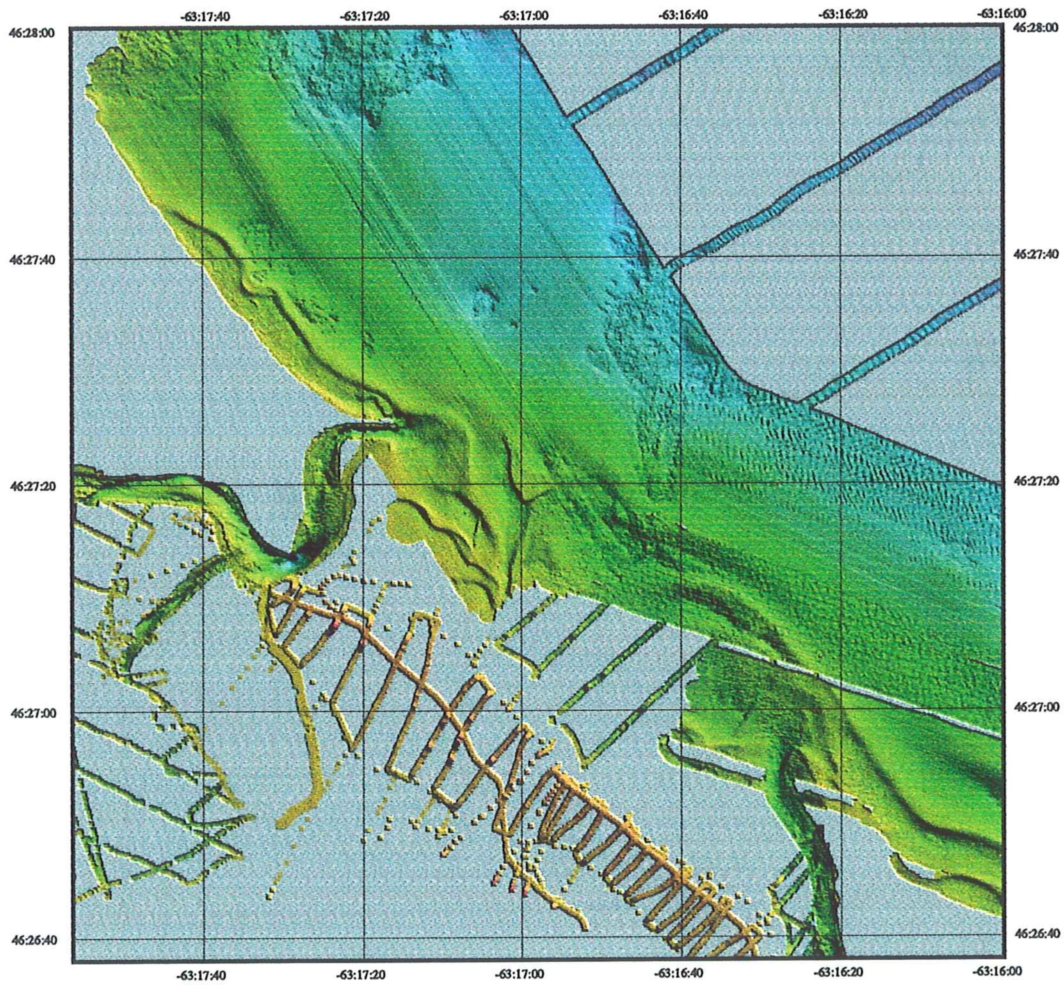
Natural Resources Canada
Ressources naturelles Canada

BATHYMETRY, BOTTOM CONDITIONS, AND TIDAL INLET STABILITY, RUSTICO BAY AND VICINITY, PRINCE EDWARD ISLAND

by

D.L. Forbes[1], S.M. Solomon[1],
D. Frobel[1], M. Goguen[2], A.G. Sherin[1], R. Parrott[1] & R. Covill[3]

[1]Geological Survey of Canada, Natural Resources Canada, Dartmouth
[2]Hydrographic Services, Public Works & Government Services Canada, Moncton
[3]Tekmap Consulting, Fall River, Nova Scotia



GEOLOGICAL SURVEY OF CANADA
OPEN FILE 3766

Geological Survey of Canada, Bedford Institute of Oceanography
1 Challenger Drive (PO Box 1006), Dartmouth, Nova Scotia, B2Y 4A2

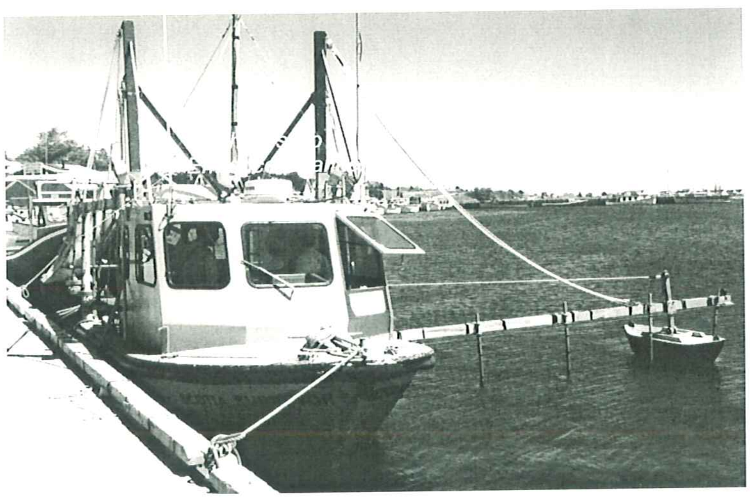
1999

Canada

BATHYMETRY, BOTTOM CONDITIONS, AND TIDAL INLET STABILITY, RUSTICO BAY AND VICINITY, PRINCE EDWARD ISLAND

D.L. Forbes[1], S.M. Solomon[1]
D. Frobel[1], M. Goguen[2], A.G. Sherin[1], R. Parrott[1] & R. Covill[3]

[1]Geological Survey of Canada, Natural Resources Canada, Dartmouth
[2]Hydrographic Services, Public Works & Government Services Canada, Moncton
[3]Tekmap Consulting, Fall River, Nova Scotia



GEOLOGICAL SURVEY OF CANADA
OPEN FILE 0000

Geological Survey of Canada (Atlantic)
Bedford Institute of Oceanography
1 Challenger Drive (PO Box 1006)
Dartmouth, Nova Scotia, Canada B2Y 4A2

1999

EXECUTIVE SUMMARY

Because of rapid changes in shoreline position and channel morphology in the outer part of Rustico Bay and adjacent nearshore waters, new surveys of water depth were needed as a basis for realistic modelling of the present estuary and proposed modifications. The most recent surveys in some parts of the bay were in 1988, while other sections of the estuary and most of the outer shoreface had not been surveyed since 1955. New surveys outside the estuary were required to establish the position and depths of nearshore bars and ebb-tide shoals, which can pose navigation hazards and limit the draft of vessels capable of entering the harbour. Nearshore profiles were also needed to determine the extent of shoreface retreat associated with inlet migration, shoreline erosion, and the loss of the west end of Rustico Island.

Three separate survey programs were undertaken in 1997 to address these needs. A ship-based multibeam bathymetric survey in water depths of about 8 to 35 m provided the first detailed images of the seafloor offshore from Rustico Bay. Water depths in the nearshore and tidal inlets were obtained using a multibeam survey launch with a boom-mounted array of transducers. Large areas of eel grass inside the bay prevented more extensive coverage with the multibeam survey launch. A small-boat program using a conventional echosounder was therefore necessary to complete the 1997 surveys. This was combined with topographic surveys of intertidal bar morphology, beach and dune growth on Dune Bar and at the causeway, and shoreline retreat at the west end of Rustico Island.

The ship-based surveys reveal large areas of rock outcrop and cobble-boulder lag surfaces on the inner shelf, with sand confined to a shoreface wedge, except where a band of sediment runs seaward along the underwater extension of the Wheatley and Hunter River valleys. North Rustico is seen to lie near the western limit of the shoreface sand body, with bedrock and a thin cover of glacial till or glaciofluvial sand and gravel at shallow depth. The inshore multibeam data and imagery provide detailed information on changes in channel location, bar morphology, and shoreface profiles since the 1955 survey. The limiting depth over the bar off North Rustico Entrance Channel is about 1.3 m Chart Datum (2.5 m HHWLT). Channel instability and migration across the west end of Rustico Island has produced large changes in the shoreline, nearshore bar positions, and ebb shoal morphology. Comparison with the 1955 field sheet shows profile changes out to 8 m water depth off Dune Bar and Rustico Island, including up to 300 m of shoreface profile retreat, with as much as 2 m or more of downcutting in some areas. Gravel is exposed in the bar troughs. Nearshore bedrock platforms occur off Rustico Island, including the area immediately west of the former Little Harbour Inlet.

Although large changes are evident in the tidal inlets, there is little evidence of change inside the bay. The abandoned flood-tide delta and channel behind the causeway remain little changed since the 1955 survey, while reference to the 1988 surveys in deeper parts of the bay indicates no significant changes. This is consistent with results of the sediment study, showing very limited mud accumulation and negligible transport potential beyond the tidal channels and their associated flood-tide deltas. Eel grass is typically best developed adjacent to channels and covers large parts of the outer bay in North Rustico Harbour and the outer Wheatley Estuary as well as marginal shallows further up the bay. Where present, it creates additional resistance to flow and reduces the sediment transport potential. Active sand transport in the tidal channels is demonstrated by the presence of large bedforms, predominantly ebb-oriented. Onshore and longshore wave transport may contribute to infilling of North Rustico Entrance Channel and constrain the development of New Channel. Tidal exchange through the latter is sufficient to maintain the channel, whereas North Rustico Entrance Channel shows a greater propensity for shoaling.

ACKNOWLEDGEMENTS

We wish to acknowledge the following individuals and groups, who have made significant contributions to the success of this project:

- Charlie O'Reilly and Glen King of CHS Tidal Section, Bedford Institute of Oceanography [BIO], DFO, Dartmouth;
- George MacHattie of BIO Positioning Shop, DFO, Dartmouth;
- Bob Murphy, Rob Comeau, Gerald Spear, and Barry Wagner of Hydrographic Services, PWGSC, Moncton;
- Charles MacDonald of Canadian Coast Guard, DFO, Charlottetown, for access to the lighthouse in North Rustico;
- Yves Gervais (Master), Elie Bureau (First Officer), Jean Labrie (First Engineer), Gilles Beaulieu (Second Engineer), and Emilian Sioch (Chef) of **CSS *Frederick G. Creed***;
- Darrell Beaver of Geological Survey of Canada (Atlantic) [GSCA] for navigation support;
- Serge Bernard, PEI Provincial Land Surveyor, Charlottetown;
- Clair Murphy, PEI Fisheries and Environment, Charlottetown, for encouragement on behalf of the PEI government;
- Richard Gallant of PEI Fisheries & Environment, Charlottetown, and Dale Small of DFO, Charlottetown, for information on aquaculture in Rustico Bay;
- past and present personnel of Parks Canada, including Harry Beach, Lary Brown, Paul Caines, André d'Entremont, Roger Hardy, Dave Lipton, Charlie Ristau, Paul Ayles and Phil McCabe, for a wide range of support and encouragement;
- Dick Pickrill (GSCA) for supportive management;
- other members of the Science Advisory Group (Rustico Island Causeway Working Group) – Carl Amos (GSCA), Derek Williamson (W.F. Baird & Associates Coastal Engineers), Mike Brylinsky (Acadia Centre for Estuarine Research), and Carl Anderson (Challenger Oceanography)– for helpful discussions and supportive collaboration;
- Michael Li (GSCA) for discussion of channel hydraulics;
- Harry Beach (Parks Canada) and Bob Taylor (GSCA) for reviewing earlier drafts of this report; and
- the people of North Rustico for their logistical assistance, sharing of local knowledge, and warm hospitality.

LIST OF CONTENTS

EXECUTIVE SUMMARY	ii
ACKNOWLEDGEMENTS	iii
1.0 INTRODUCTION	1
1.1 Objectives	1
1.2 Background	1
2.0 SURVEY DESIGN & METHODS	5
2.1 Offshore survey	5
2.2 Inshore survey	7
2.3 Estuary & nearshore survey	8
3.0 RESULTS	14
3.1 Bathymetric coverage	14
3.2 Nearshore morphology	14
3.3 Tidal channels & associated ebb- & flood-tide deltas	19
3.4 Aquatic vegetation	24
4.0 GEOLOGICAL CONTEXT & ENGINEERING ISSUES	24
4.1 Long-term marine transgression & coastal retreat	24
4.2 Short-term coastal recession & shoreface adjustment	27
4.3 Dredging requirements at Little Harbour Inlet	27
4.4 Channel size & tidal prism	27
5.0 CONCLUSIONS & RECOMMENDATIONS	34
6.0 REFERENCES	36

1.0 INTRODUCTION

1.1 Objectives

This report describes field operations and data analysis undertaken in 1997 by the Geological Survey of Canada and partners, to satisfy the need for up-to-date bathymetry and coastal morphology in Rustico Bay and adjacent waters (Figure 1). This work was commissioned and partially funded by Parks Canada, as part of a broader study of estuarine circulation, water quality, sediment stability, and coastal evolution, in support of the Rustico Island Causeway Working Group and the need for environmental assessment of proposed changes to tidal inlets in Rustico Bay (Forbes et al., 1998).

The project was initiated in response to community concerns about water quality and navigation safety in Rustico Bay (NQWF, 1995), government efforts to address these concerns (Copps, 1996), background reviews commissioned by Parks Canada (e.g. Appleby, 1997; Forbes, 1997), and a number of public meetings at which a joint approach was agreed by the various stakeholders and government agencies. At a public meeting in North Rustico in May 1997, it was agreed to proceed with scientific work as required to assess the environmental impact and viability of the proposed remedial works. One component of the work involved hydrodynamic modelling of circulation and water levels in the estuary under present conditions and for various proposed changes in the estuarine configuration. Effective hydrodynamic modelling requires a realistic bathymetric model of the estuary as it now exists. This report describes survey efforts undertaken to satisfy this need.

1.2 Background

The NQWF (1995) brief proposed a three-phase program to restore Rustico Bay, improve water quality, and enhance the safety of navigation for boats entering the bay. This envisaged reopening Little Harbour Inlet, reconstructing the west end of Rustico Island and the connecting channel behind it, and building a new breakwater at the west end of the island to stabilise the navigation channel at North Rustico. At a later date (after the 1997 scientific program had been initiated), mussel growers in Rustico Bay expressed concern about possible damage to aquaculture production if these changes are implemented (McKay et al., 1997). Leases in production in the bay cover about 190 ha with annual production in excess of $1M and growing. Commercial fish landings at North Rustico in 1994 amounted to $2.44M, of which 96% was lobster (NQWF, 1995). Tourism and the recreational fishery are also important. A significant conservation issue relates to nesting by the endangered piping plover (*Charadrius melodus*) on accreted beach deposits in front of the Little Harbour causeway and on Dune Bar (Figure 1).

Rustico Bay occupies two flooded river valleys, inundated by rising sea levels and bounded on the seaward side by a coastal barrier. The barrier across the mouth of the present bay consists of Dune Bar, Rustico Island, and the Little Harbour [*aka* Rustico Island] Causeway (Figure 1). Before construction of the causeway, the west end of Rustico Island extended across the bay in front of Anglo Rustico (Figure 2). At this time, a tidal passage existed between the two arms of the bay (the two flooded valleys of the

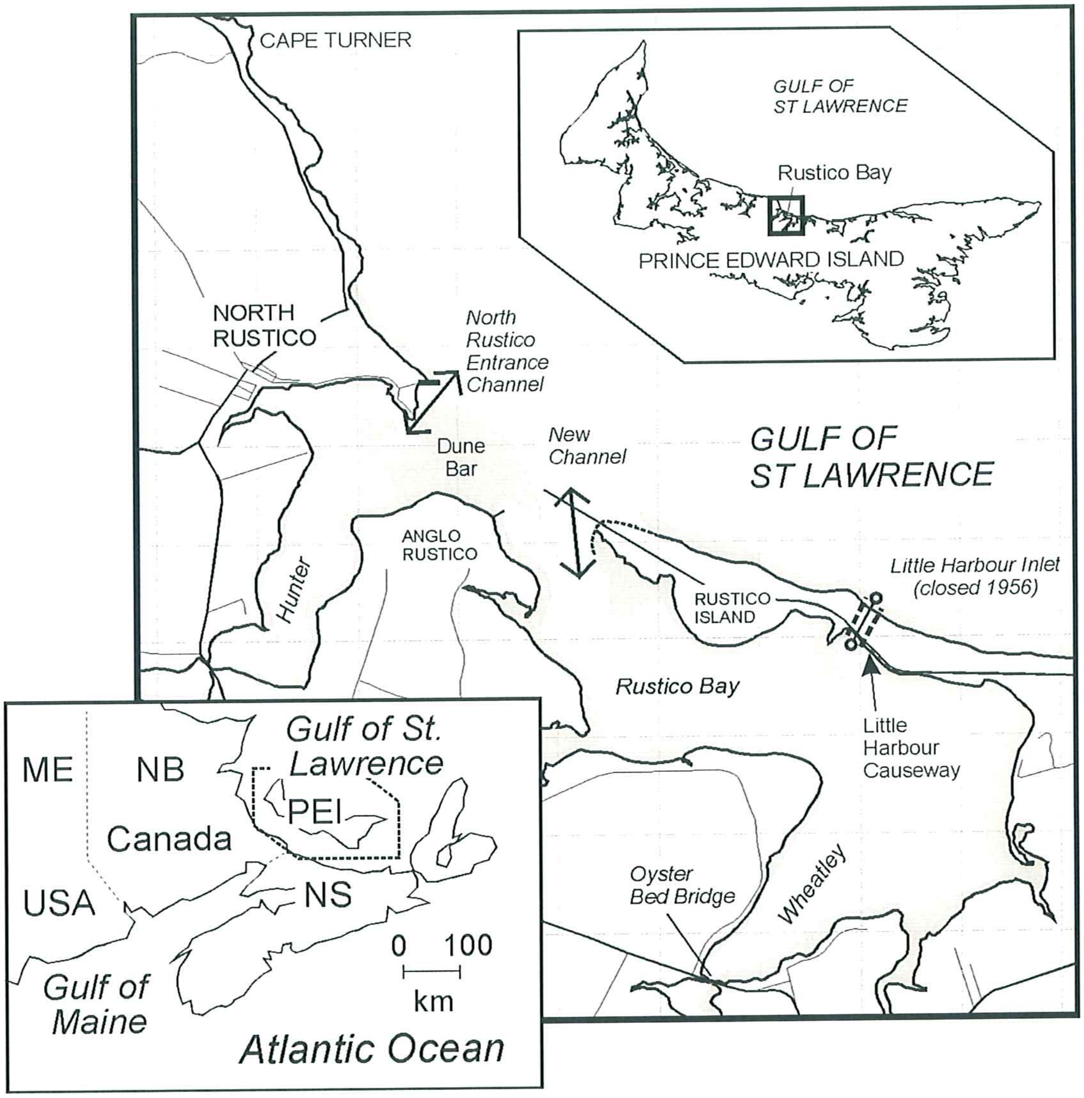


Figure 1: Rustico Bay study area (with 1 km UTM grid for scale).

Hunter and Wheatley Rivers). The 1997 and 1998 ship-based surveys off Rustico Bay (Forbes et al., 1999a, 1999b) show that these valleys formerly extended seaward and apparently converged into a single valley running out to at least 35 m present water depth in the Gulf of St. Lawrence. Other buried valleys seaward of Rustico Bay extend to maximum depths of at least 70 m below present sea level (Forbes et al., 1999b), but the age and origin of deposits infilling these valleys remain poorly defined.

The whole Rustico Bay system occupies a shallow bedrock depression in the sandstone sequence (van de Poll, 1983), expressed as a broad coastal embayment between the bedrock headlands of Cape Turner in the west and Cape Stanhope in the east. The inner shelf surveys show widespread outcrop of sandstone across the shoreface at the western and eastern ends of the study area and scattered outrcrop elsewhere. Bedrock cliffs are present just west of the former Little Harbour Inlet and west of North Rustico Beach on

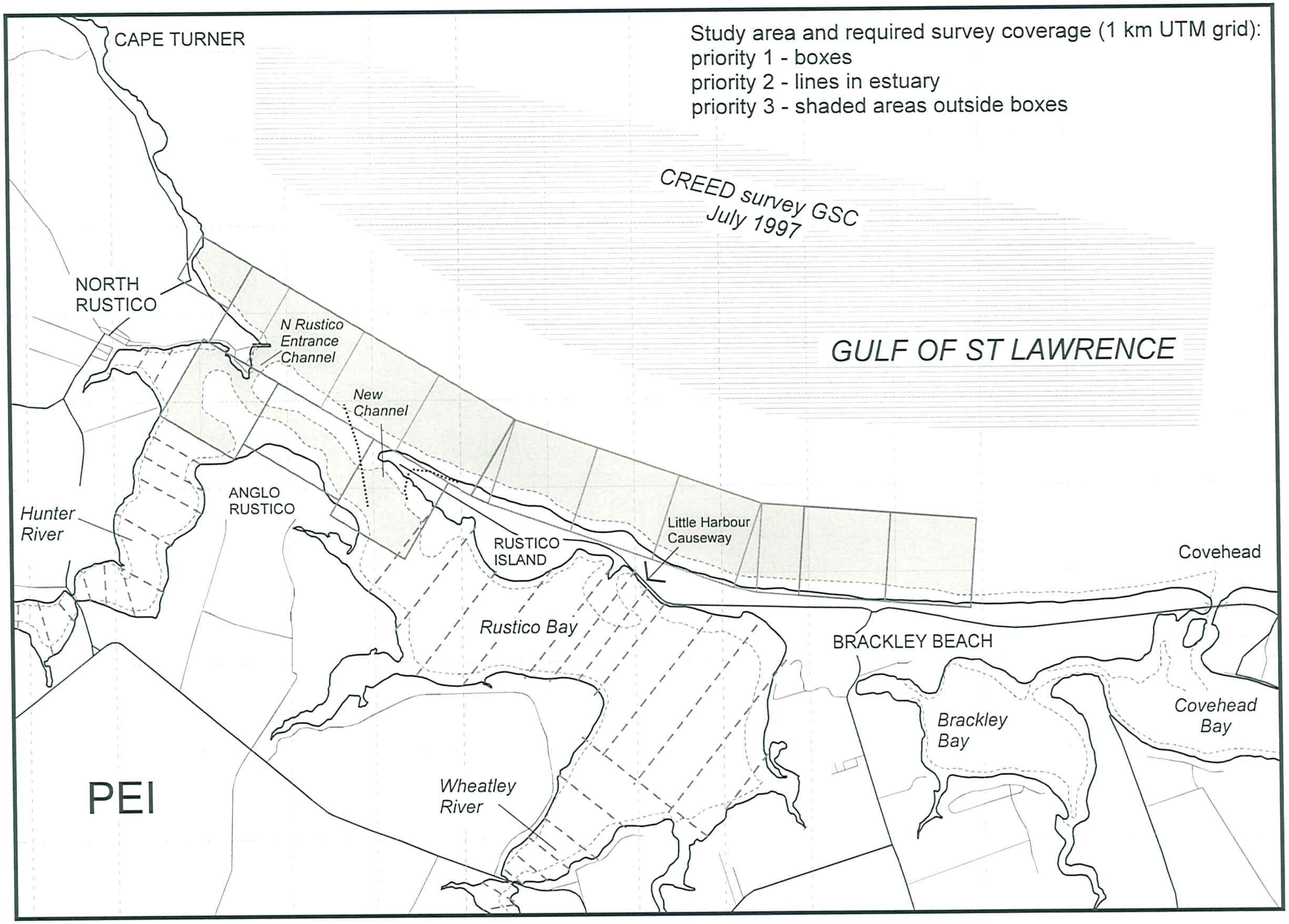


Figure 2: Proposed layout for bathymetric surveys at the beginning of the present study. Shoreline as in early 1960s, from NTS topographic basemap.

the outer coast, as well as at various places within the bay. The surficial sediment cover consists primarily of glacial till, typically less than 3 m thick but locally up to 10 m, and patches of glacial outwash sand and gravel of variable thickness (Crowl & Frankel, 1970; Prest, 1973). Wave-washed gravel and boulder lag deposits are widespread on the shoreface and inner shelf, where they overlie acoustically incoherent deposits interpreted as glacial ice-contact sediments (Forbes et al., 1999b).

Previous surveys of Rustico Bay and adjacent waters were carried out in 1955 (CHS, 1955, 1958) and 1988 (PWC, 1988). These surveys bracketed construction of the causeway between Rustico (*aka* Robinson's) Island and Brackley Beach, closing off the eastern inlet to Rustico Bay at Little Harbour (Figure 1). The causeway was intended, at least in part, to redirect the tidal exchange of the eastern (Wheatley River) arm of the bay from Little Harbour Inlet to North Rustico Entrance Channel, in order to increase the tidal prism through the latter inlet, make it self-scouring, and to improve navigation safety (Baird & Associates & Eastern Designers, 1990a; Bisaillon, 1997).

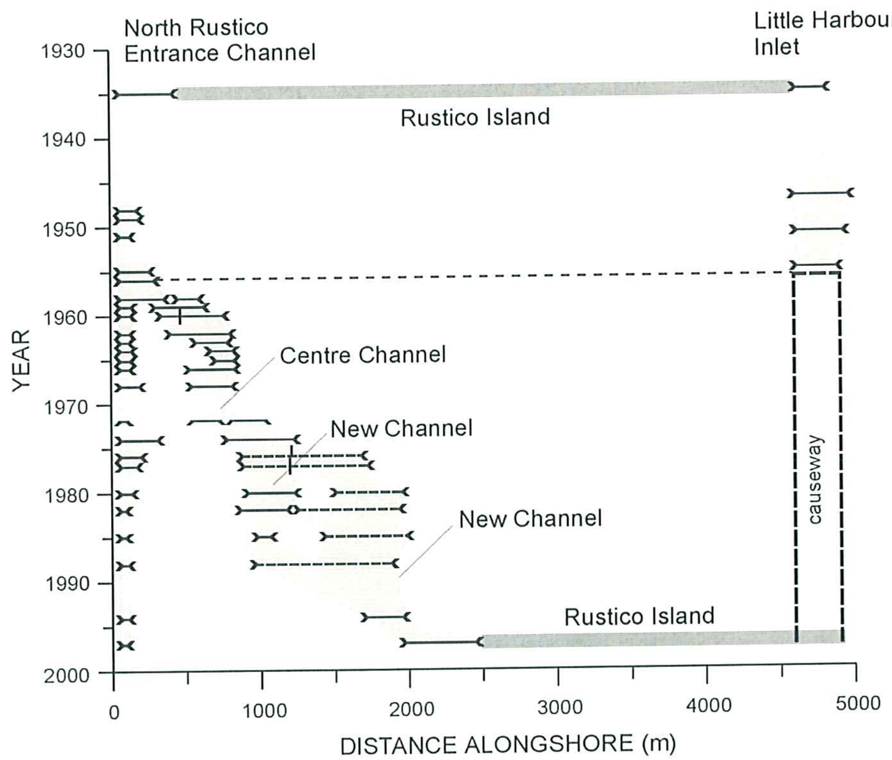


Figure 3: Time sequence of inlet width and position from airphoto records (from Forbes & Solomon, 1999).

Following closure of Little Harbour Inlet, the channel at North Rustico, which was adjusted to a much lower tidal prism, entered a phase of rapid destabilisation (Baird & Associates & Eastern Designers, 1990a, 1990b). The channel divided into two parts and the eastern channel began to migrate rapidly eastward, completely reworking the west end of Rustico Island (Figure 3; Forbes & Solomon, 1999). This channel itself divided for a time (Matsushita & McCann, 1988) before assuming the relatively stable configuration that exists at New Channel today. As the former barrier beach forming the west end of Rustico Island was destroyed by inlet migration, sediment left behind in the area between the two inlets was reworked to form a new beach (locally known as Dune Bar) further landward in front of Anglo Rustico. This deposit filled in the former Back Channel behind Rustico Island, leading to division of the bay into two completely separate estuaries, the Wheatley and the Hunter (Figure 1).

Because of the rapid changes in inlet configuration, associated sedimentation within the bay, and dramatic changes in the nearshore bathymetry along the outer shore since 1956, we could no longer rely on the previous bathymetric surveys for realistic hydrodynamic modelling. In addition, proposals to rebuild the west end of Rustico Island, to enable restoration of the Back Channel, require a clear understanding of the changes that have occurred in the nearshore profile in this area. For design purposes, it is essential to determine the volume of sediment needed to restore a stable shoreface profile and a barrier beach and dune system sufficiently high to resist washover and breaching, or alternatively to use the present profile as a basis for estimating wave energy against any structures that might be required.

The coastal and estuarine survey was planned in three parts (Figure 2):

1- to map the seabed offshore from Rustico Bay using a ship-based multibeam bathymetric system in order to define the sand budget for the Rustico Bay and Brackley Bight coastal system;
2- to acquire complete multibeam bathymetric coverage in the most rapidly changing outer reaches of the bay (both inlets) and on the shoreface along the outer shore;
3- to acquire conventional echosounder profiles across the inner bay, to identify any changes in these less dynamic areas since the previous surveys in 1955 and 1988.

In the end, much more detailed coverage was acquired in the bay, including surveys of some areas that had not been surveyed in 1988, notably the relict flood-tide delta of Little Harbour Inlet.

2.0 SURVEY DESIGN & METHODS

As described above, the program was divided into three parts covering the offshore, nearshore, and shallow bay waters. Costs were shared between Parks Canada (Canadian Heritage) and the Geological Survey of Canada (Atlantic) [GSCA] (Natural Resources Canada), with in-kind support from the Canadian Coast Guard [CCG] and Canadian Hydrographic Service [CHS] (Department of Fisheries & Oceans) and from Hydrographic Services (Public Works & Government Services Canada) [PWGSC].

2.1 Offshore survey

The offshore portion of the survey, in water depths generally greater than 9 m, was carried out by GSCA using the survey vessel **CSS** [now CCGS] ***Frederick G. Creed*** (Figure 3). For this survey, the vessel operated out of Souris, Prince Edward Island. This part of the work provided complete multibeam survey coverage out to depths greater than 30 m, using a Simrad™ EM-1000 swath bathymetry system. The data clearly delineate a shoreface sand wedge extending seaward from the coast in the broad embayment

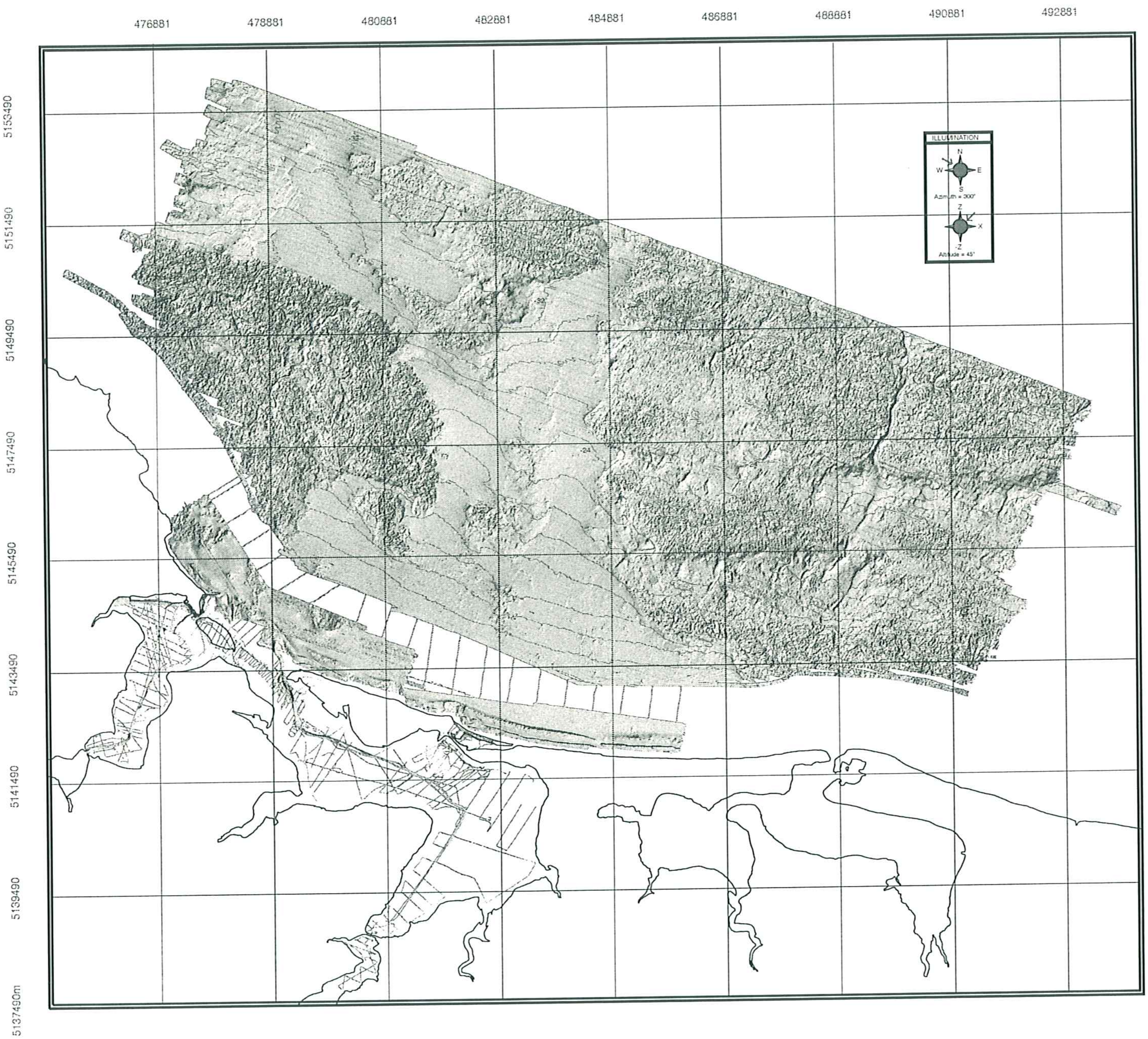


Figure 4: Shaded-relief image showing outer shoreface and inner continental shelf morphology (from Creed survey) in relation to nearshore and estuarine surveys described in this report (see Figs 10, 12, 13 for enlargements).

(informally designated Brackley Bight) between zones of rock outcrop off Orby Head and Covehead/ Cape Stanhope (Figure 4). Details of this survey are provided in a separate cruise report (Forbes et al., 1999a), which includes a more detailed interpretation of the seabed in this outer area.

2.2 Inshore survey

This part of the work was undertaken by Public Works & Government Services Canada (Hydrographic Services, Moncton) using the survey launch ***Scotia Surveyor*** (Figure 5) during three weeks in the summer (6-26 July 1997), overlapping with the science program in the estuary (Amos et al., 1998). Follow-up surveys were attempted in the Hunter Estuary (North Rustico) during September, but were frustrated by the widespread dense growth of eel grass (*Zostera marina*). Another follow-up survey was completed on 22 October 1997, using the survey launch ***Miramichi Surveyor*** to fill in a missing block on the shoreface seaward of Dune Bar and New Channel (Figure 1).

Figure 5: Public Works survey launch ***Scotia Surveyor*** alongside at North Rustico (July 1997).

Bathymetric data were collected using an ISAH-S 12-channel Navitronics™ sweep bathymetry system, consisting of a boom-mounted array of vertical-incidence transducers. Twelve transducers, at a 1.2 m separation, were deployed from the launch and its folding booms. The survey vessel operated into water depths <1 m CD [Chart Datum], covering the shallowest areas on high tides. Positioning to better than 1 m was achieved using an Ashtec™ Z-12 real-time kinematic differential global positioning system [DGPS], consisting of a mobile receiver on the launch and a base station established at the North Rustico Light (Figure 6). The elevation of a nail head on the eastern top deck corner of the lighthouse was transferred from a Canadian Hydrographic Service [CHS] benchmark on the north foundation wall of Paturel Seafood Ltd, Rustico Beach, and a temporary benchmark [TBM] at 2.22 m CD established on the adjacent wharf. Horizontal coordinates were established from nearby LRIS control points. Depths were adjusted to Chart Datum, using water level data measured directly with the DGPS system on the survey launch, verified by daily measurements from the TBM on the

Figure 6: Base station for differential GPS (Global Positioning System) navigation on the upper deck of the North Rustico Light (July 1997).

wharf. Horizontal positions were reported in NAD83 as UTM easting and northing (zone 20).

Survey data post-processing consisted of a quality-control procedure to screen out erroneous depth values and ensure correct adjustment of depths to Chart Datum. The adjusted xyz data were then transferred electronically by FTP to GSCA computers at the Bedford Institute of Oceanography in Dartmouth. Subsequent processing was carried out under UNIX on HP work stations, using GRASS and ArcInfo™ software, initially to determine the extent of survey coverage and later to construct the bathymetric maps and shaded-relief images presented in this report. The data were imported into GRASS on a 5 m grid, filled, and colour-classified in 5 m depth increments. Subsequent processing included regridding on a 2.5 m grid, integration of the echosounder data from inside the bay (see below), and colour classification in 0.2 m depth increments. Shaded-relief images were produced by illuminating the numerical bathymetric model from appropriate artificial sun angles and elevations.

2.3 Estuary & nearshore survey

As indicated above, the original survey plan called for single-transducer sounding profiles in the inner bays, with more complete sweep coverage in the vicinity of the tidal inlets and approaches. However, PWGSC were unable to collect much reliable data inside the bay because of the widespread dense growth of eel grass, which made it almost impossible to distinguish correct bottom returns using their highly automated system. It was therefore necessary to mount a separate survey effort to collect the required depth data inside the estuaries using a small boat and conventional echosounder. This work was carried out by GSCA personnel during October 1997, with logistical support from Parks Canada (PEI National Park).

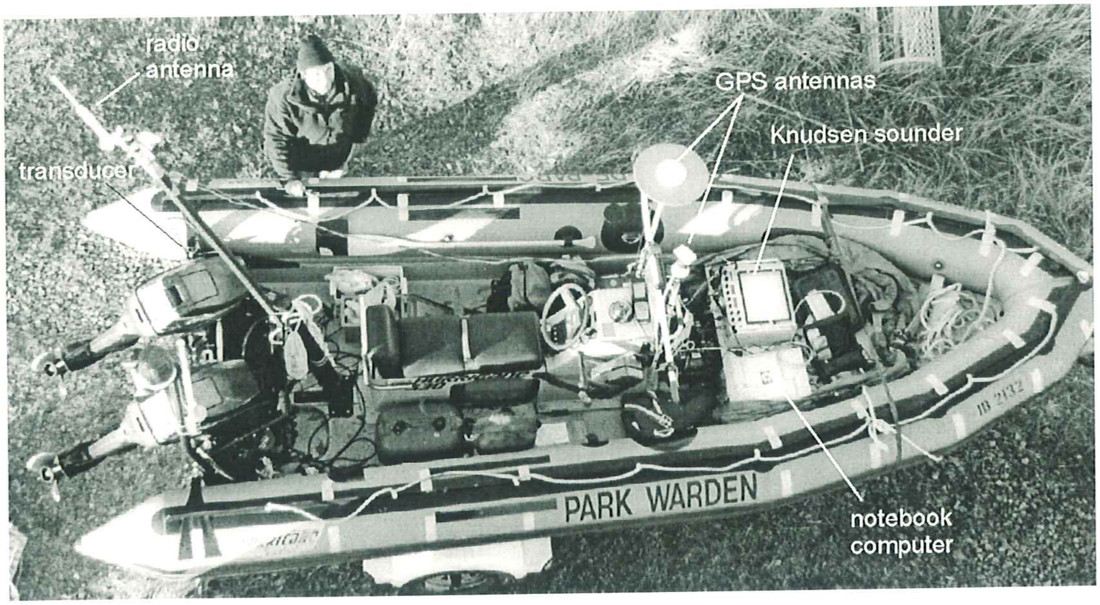


Figure 7: Rigid-hull inflatable boat used for estuarine surveys (October 1997). View from upper deck of lighthouse, showing survey and navigation equipment.

The October surveys utilised a rigid-hull inflatable 6.5 m open boat (Hurricane) belonging to Parks Canada. This boat (Figure 7), normally used for Park Warden service, was powered by twin 40 hp outboard motors, operated from a central steering console with hydraulic tilting controls, which facilitated surveys in water as shallow as 0.4 m.

Water depths were measured using a Knudsen™ 320M digital sounder operating at 200 kHz. The transducer was mounted on the outer side of the transom just inboard of the port float (Figure 7). Soundings were adjusted for transducer draft by direct measurement and sounder calibration. Sound velocity calibration was obtained by pole or lead-line measurements of water depth at intervals throughout the survey. Depth profiles were displayed in real-time on the sounder's thermal printer, annotated for date and time. Depth data were also captured digitally on a notebook computer for subsequent editing and analysis. The data were output from the Knudsen™ sounder in pseudo-NMEA format as $PKELL strings with associated times and depths. The bottom return algorithm on the sounder was generally reliable except in eel grass (*Zostera marina*), which is widespread in shallow parts of the estuary. This introduced considerable noise in the data, requiring extensive post-survey cleaning (see below), but sufficient returns from the bottom were usually present to enable interpolation of total depth through the eel grass field.

Navigation for the small-boat surveys employed one of three different DGPS systems at any one time. These were:

- a Geotracer™ 2000 real-time kinematic [RTK] survey system giving about 0.1 m accuracy in xyz, with a base station on the North Rustico Light (same location as the PWGSC base station described earlier)
- a Magnavox™ 4200D six-channel receiver giving better than 2 m accuracy, operating under Geological Survey of Canada AGCNav software control, with differential corrections received from Coast Guard transmitters at Port aux Basques (Newfoundland) and Point Escuminac (New Brunswick)
- a Garmin™ Survey II eight-channel receiver accurate to within about 8 m, also receiving corrections from Port aux Basques or Point Escuminac.

The navigation data were logged to the same notebook computer and file as the bathymetric data, creating merged and time-matched lists of depths and coordinates. The WGS84 (or equivalent NAD83) horizontal datum was used for all navigation data. An independent check on the survey accuracy was obtained by setting the boat and receiver over a GPS-ready LRIS benchmark (PEI 4068) on the Bungay- Hunter River road at 46°21'56.5383"N 63°19'30.3526"W (data courtesy of Serge Bernard, Provincial Land Surveyor, Charlottetown). This check was obtained with the Magnavox™ 4200D system, giving an error of <0.6 m in latitude and ~0.4 m in longitude.

Severe problems were encountered with apparently random loss of differential GPS on the Magnavox™ system, often at the very beginning of the survey (in one case after only five fixes). Despite setting up the system to accept only DGPS positions, this problem recurred many times and no warnings were issued. The problem was only recognized after several days of survey, requiring repetition of the surveys and a second repetition in some areas. This resulted in less complete coverage than planned. A detailed survey of the Hunter River above the bridge was excluded from the analysis because of the loss of differential GPS in that area and lack of time to repeat the coverage there.

Differential corrections for the Geotracer™ system were received using a Pacific Crest™ RFM96W radio receiver with whip antenna. The Geotracer™ base station at the North Rustico Light was equipped with a Pacific Crest™ RFM96W radio transmitter operating at 35 W. With a base station elevation of 12 m and using appropriately tuned whip antennas borrowed from the positioning shop at the Bedford Institute of Oceanography [BIO], a range of up to 15 km was obtained along the coast and up to 7 km over moderate relief to the Wheatley River upstream of Oyster Bed Bridge. Differential corrections for the Magnavox™ and Garmin™ DGPS systems were received from the Coast Guard beacons using an MBX11 receiver and whip antenna.

The most reliable and accurate navigation was obtained using the Geotracer RTK survey system, when it was not being used for onshore surveys of intertidal flats, beaches, and dunes (see below). This system also provided an independent measure of water level by determining the orthometric elevation of the echosounder transducer. Under calm conditions, the water surface elevations matched independently measured water levels, but waves and swell introduced a large variance on some days (Figure 8). Predicted tides

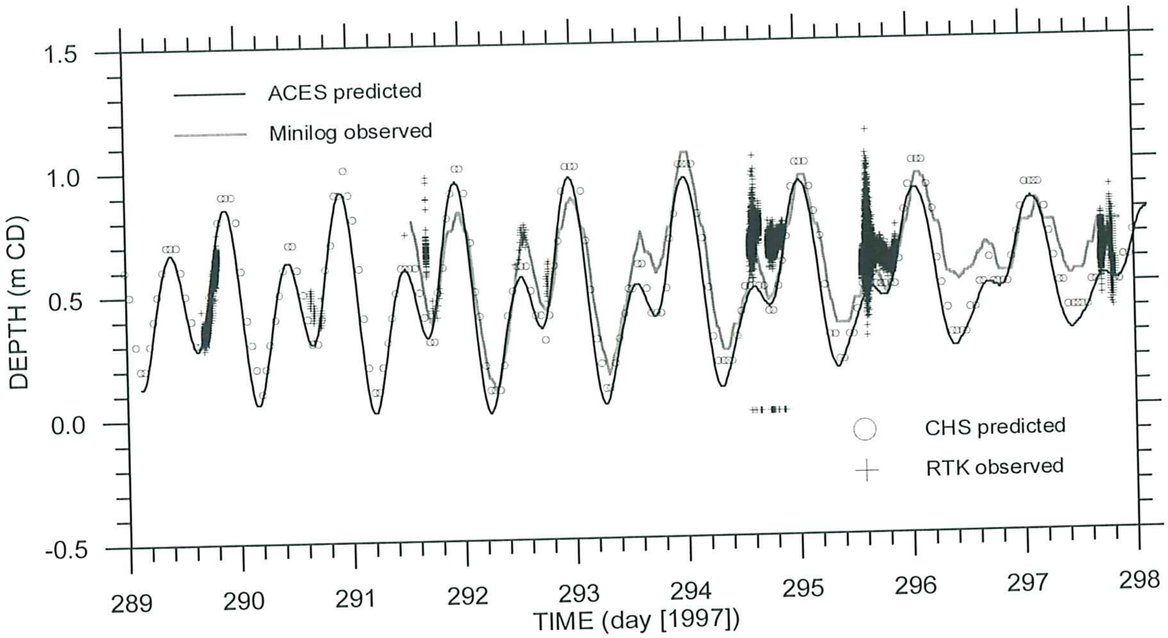


Figure 8: Time sequence of water levels at North Rustico during the small-boat survey in October 1997 (days of year 289 to 298). Tidal predictions from CHS and ACES. Observed water levels using RTK DGPS measurements and Vemco Minilog™ tide gauge.

were obtained from the Tidal Section, CHS Atlantic, BIO, and from the US Army Corps of Engineers ACES software package. A compact (20 mm diameter by 95 mm long) temperature-depth logger (Vemco™ Minilog TDR) with a 25 psi pressure transducer (nominal resolution 0.1 m) was moored on the bottom adjacent to the TBM at Rustico Beach and recorded water depths at 5 minute intervals over 6.5 days (Figure 8).

Surveys were carried on foot over intertidal shoals in Rustico Harbour, shorelines and exposed beach and dune surfaces on Dune Bar, and the same at Little Harbour. These used the same Geotracer 2000 RTK DGPS survey system employed on the boat. For direct survey work of this kind, the GPS antenna was mounted on a range pole of known height (for point surveys) or on a backpack mount (for continuous walking traverses).

Post-survey data analysis included quality control of navigation, using MapInfo™ Professional GIS software under Windows95™ on a notebook Pentium computer carried in the field. Subsequent analysis in the office used MapInfo™ and GRASS software to overlay the bathymetric data on a digital topographic base derived from the 1:10 000 scale map series for PEI. The MapInfo™ work was carried out on desktop PCs running Windows95™ and the GRASS analysis on HP workstations running UNIX and on PCs running WRQ's Reflection X™ X-windows emulator under Windows95™. The raw navigation and digital depth files were sorted and cleaned using custom routines written in MS-DOS Qbasic™. Subsequent analysis made use of MS Excel 5™ and Golden Software's Grapher™ and Surfer™ graphics and contouring packages running under Windows95™. Colour classification by depth was accomplished directly on individual survey points in MapInfo™ and was carried out on gridded data in GRASS. Other

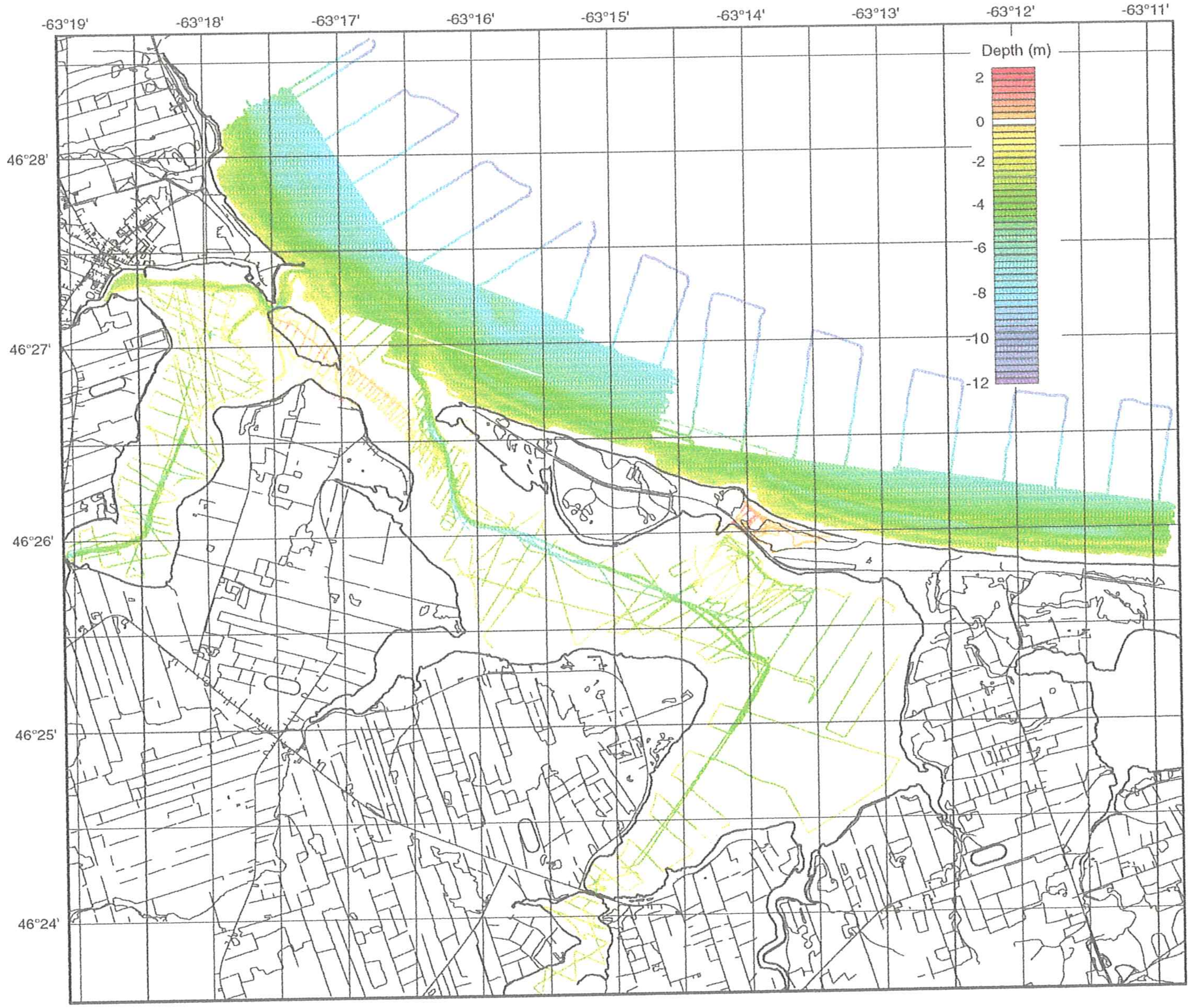


Figure 9: Colour-classified bathymetry and topography, showing entire 1997 coverage of multibeam soundings (PWGSC) and single-beam echosounding and topographic surveys (GSCA) over inshore, estuarine, and beach components of the study area (30" grid, NAD83).

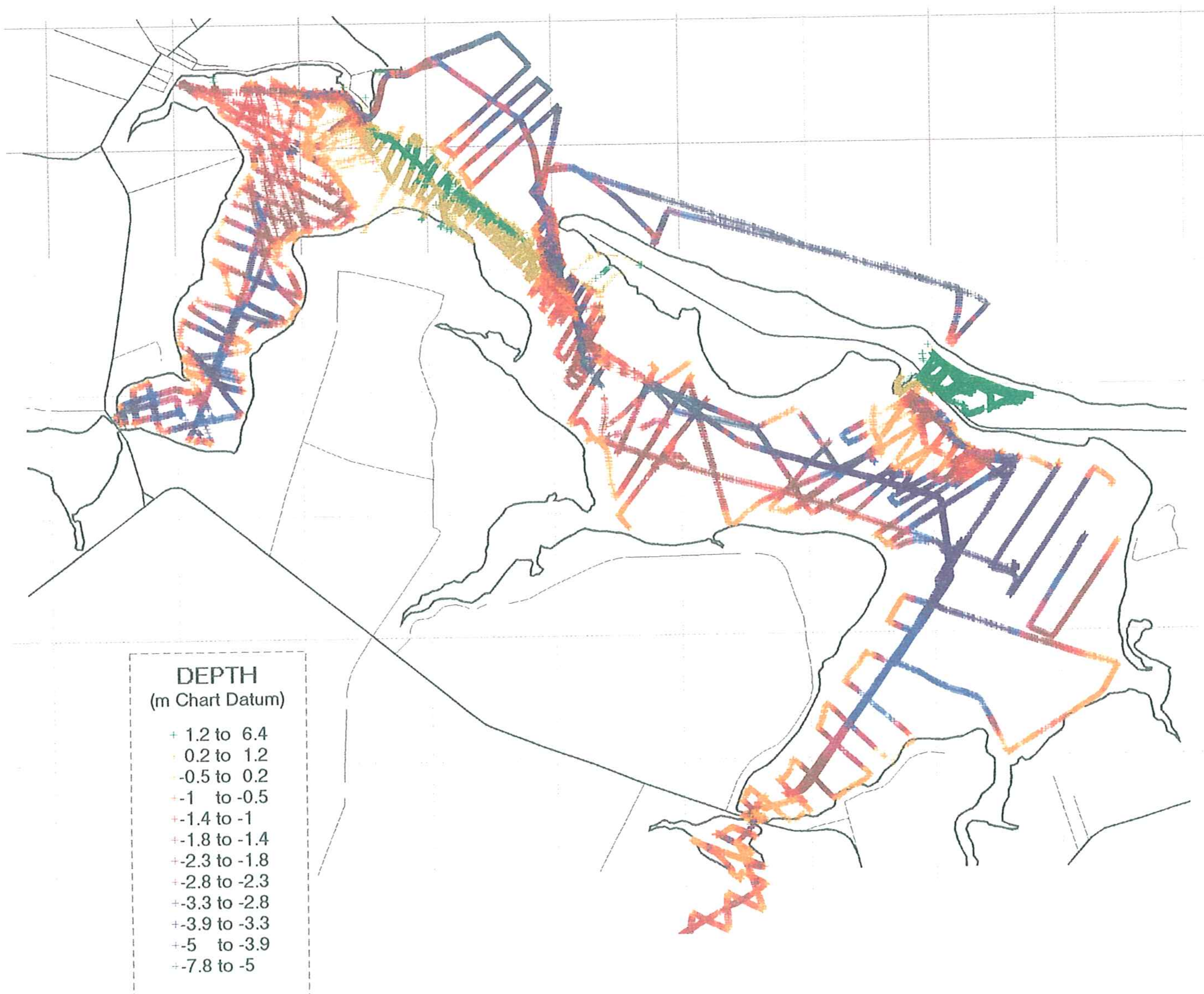


Figure 10. Colour-classified soundings and surveyed elevations (green), October 1997. Scale shown by 1 km UTM grid.

subsets of the data (at Little Harbour and on the Rustico Harbour flood-tide shoals) were gridded and contoured in Surfer™ using triangulation with linear interpolation and minimal smoothing. Sediment volumes were computed in Surfer™ and reported as the mean of results by three different methods: Trapezoidal Rule, Simpson's Rule, and Simpson's 3/8 Rule.

Bathymetric data files extracted from the navigation files were cleaned using a combination of software on the UNIX workstation. Using the AWK utility, data files were first reformatted to a set of three files, each containing time-indexed records for a single variable (time and depth, time and easting, time and northing). The time-depth file was imported into the program XMGR (v. 3.01 by P.J. Turner). This enabled interactive editing of the file by graphically choosing points to be discarded. The cleaned time-depth file was saved, then the files were reconstituted using the time index with a program written by R. Courtney (GSCA). The final xyz files were extracted using the AWK utility. The same procedure was used to extract navigation data showing the distribution of eel grass along survey tracks in the estuary.

3.0 RESULTS

3.1 Bathymetric coverage

The PWGSC multibeam sweep survey provides detailed bathymetry and seabed morphology over the nearshore bar complex from Brackley Beach to North Rustico Beach (Figure 9). This coverage, typically 500 to 1000 m wide, extends from the inner bar to depths of about 8 m. It also includes sweep surveys over the ebb-tide shoals and through the tidal inlets at North Rustico Entrance Channel and New Channel, as well as coverage over the former ebb shoal of Little Harbour Inlet. Coverage inside the Hunter and Wheatley estuaries is limited to narrow sweeps up the axis of the bays and through navigable passages cutting the Rustico Harbour flood-tide delta. Eel grass contamination of the digital depth records prevented more complete multibeam coverage inside the bays.

The small-boat echosounding surveys covered a dense network of lines inside both estuaries headward to the first bridges. Data collected above the Hunter River bridge had to be thrown out due to loss of differential corrections for GPS navigation, but good-quality coverage was obtained in the Wheatley River above Oyster Bed bridge (Figure 10). The small-boat surveys also included nearshore profiles from about 6 m water depth into depths of <1 m off the beach at Dune Bar and Rustico Island, though (again) a number of profiles had to be rejected because of navigation problems. The final compilation (Figure 10) includes only data with reliable DGPS positioning.

3.2 Nearshore morphology

The shoreface surveys confirm previous evidence for an extensive complex of two to four nearshore sand bars off most beaches along this coast (e.g. Armon & McCann, 1979; Boczar-Karakiewicz et al., 1995). Previous echosounding profiles by GSCA at Brackley Beach and other sites within and beyond the limits of the present study (e.g. Forbes, 1987) show typical bar profiles with up to 3 m relief between the second bar crest and the

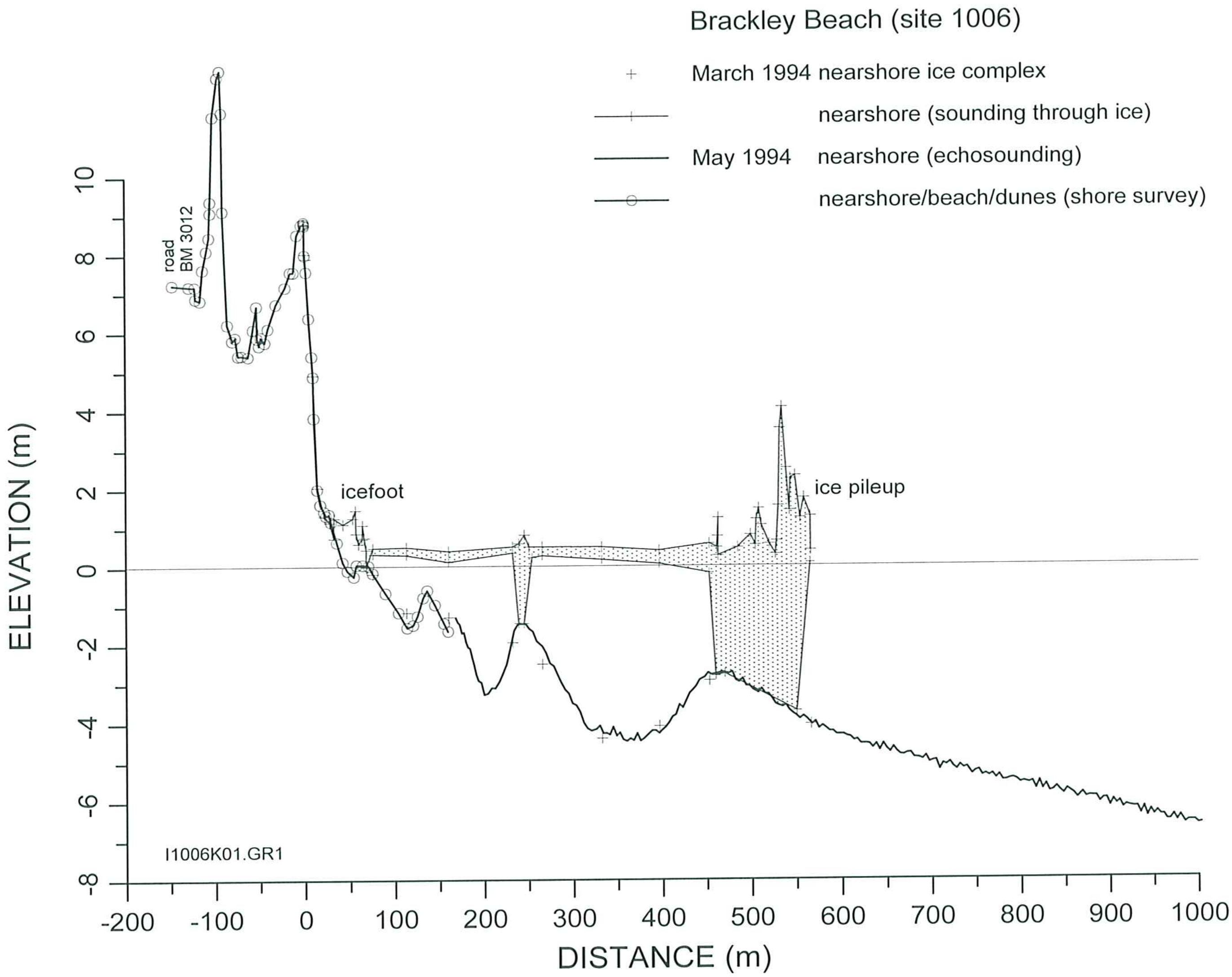


Figure 11. Shore-normal profile across dunes, beach, nearshore bars and inner shoreface at Brackley Beach (GSC site 1006 at LRIS bench-mark 3012) in May 1994. Also shows survey of icefoot and nearshore ice complex as well as lead-line soundings from the ice in March 1994. Location near eastern margin of Figure 1. Mean sea level datum.

trough to seaward. The 1994 profile at Brackley Beach (Figure 11) shows three bars, progressively smaller, shallower, and more mobile landward, with crests located about 420, 210, and 90 m seaward of the shoreline in water depths of approximately 2.7, 1.6, and 0.7 m, respectively. A small swash bar is also present on the lower beachface. The seaward slope of the outer bar is approximately exponential and concave upward, terminating at an abrupt transition to a more gently sloping surface 1000 m seaward of the beach. The Brackley Beach profile from March 1994 shows a nearshore ice complex stabilized by grounded pileups on the crest of the second bar and on the crest and seaward slope of the outer bar. A 1.5 m thick icefoot covers the lower beach. Previous work has demonstrated the presence of gravel lag surfaces and locally of bedrock exposed in bar troughs, extending under the bars (Forbes et al., 1986; Forbes, 1987).

The new survey data confirm this pattern of a sediment-starved nearshore profile, with gravel exposed in the bar troughs east of Little Harbour Inlet (Figure 12), off Rustico Island, and also off North Rustico Beach (Figure 13). Erosional bedrock platforms are present in the nearshore off Rustico Island at the headland immediately west of Little Harbour Inlet (Figure 12) and in the area off the campground. Three nearshore bars are seen off the causeway and two prominent bars off most of Rustico Island, except where interrupted by the bedrock platforms, with a third inner bar emerging at the west end of the island near New Channel (right-hand margin of Figure 13). The complex bar pattern off the causeway (Figure 12) may relate to partial preservation and reworking of a former ebb-tide shoal off Little Harbour Inlet or it may result from perturbation of the nearshore dynamics on the flank of the headland platform. Prominent ebb-tide shoals are present off New Channel and North Rustico Entrance Channel, reflecting the ebb-dominated character of both estuaries (Matsushita & McCann, 1988; Amos et al., 1998). As observed at other inlets along the North Shore, the outer bars are deformed seaward around the ebb-tide shoals and the number and complexity of the bars increase in the vicinity of the inlets. The seaward bulge of the outer bars off New Channel is centred on a point to the west of the present channel axis and ebb shoal, suggesting a lag in realignment of the outer bars following eastward migration of the channel.

At North Rustico Entrance Channel, the outer bar bulges seaward around the eastward-directed channel axis, with a limiting depth of 1.3 m CD (1.8 m at MWL and 2.5 m at HHWLT). The inner bar pattern is highly complex on the east side of the inlet off Dune Bar. This presumably relates to disturbance caused by the channel division in the late 1950s and the eastward migration of the new channel across this area since that time (Baird & Associates & Eastern Designers, 1990b). The present nearshore bar morphology consists of landward-directed lobate shoals, possibly in part recycling sediment from the North Rustico ebb-tide shoal back onto the beach to feed Dune Bar. Sediment transport and wave patterns are influenced by an artificial shoal with gravel and lag boulder cover in the area of the 1905 east breakwater, revealed by a prominent shore-normal line on the seafloor (Figure 13). The origin of a second linear feature at a slight angle to the first is unclear at this time. Sand cover on the outer shoreface in this area is discontinuous, with a prominent exposure of lag gravel or bedrock trending north-south across the area seaward of the outer bar just west of the axis of New Channel (Figure 13).

Little Harbour Causeway, Rustico Island, PEI

Natural Resources Canada / Ressources naturelles Canada

Figure 12. Grey-scale shaded-relief image of nearshore bars and rock platform in the area of Little Harbour Inlet and the causeway, with shoreline from 1:10 000 topographic base. Illumination from N40°E at an elevation of 35°.

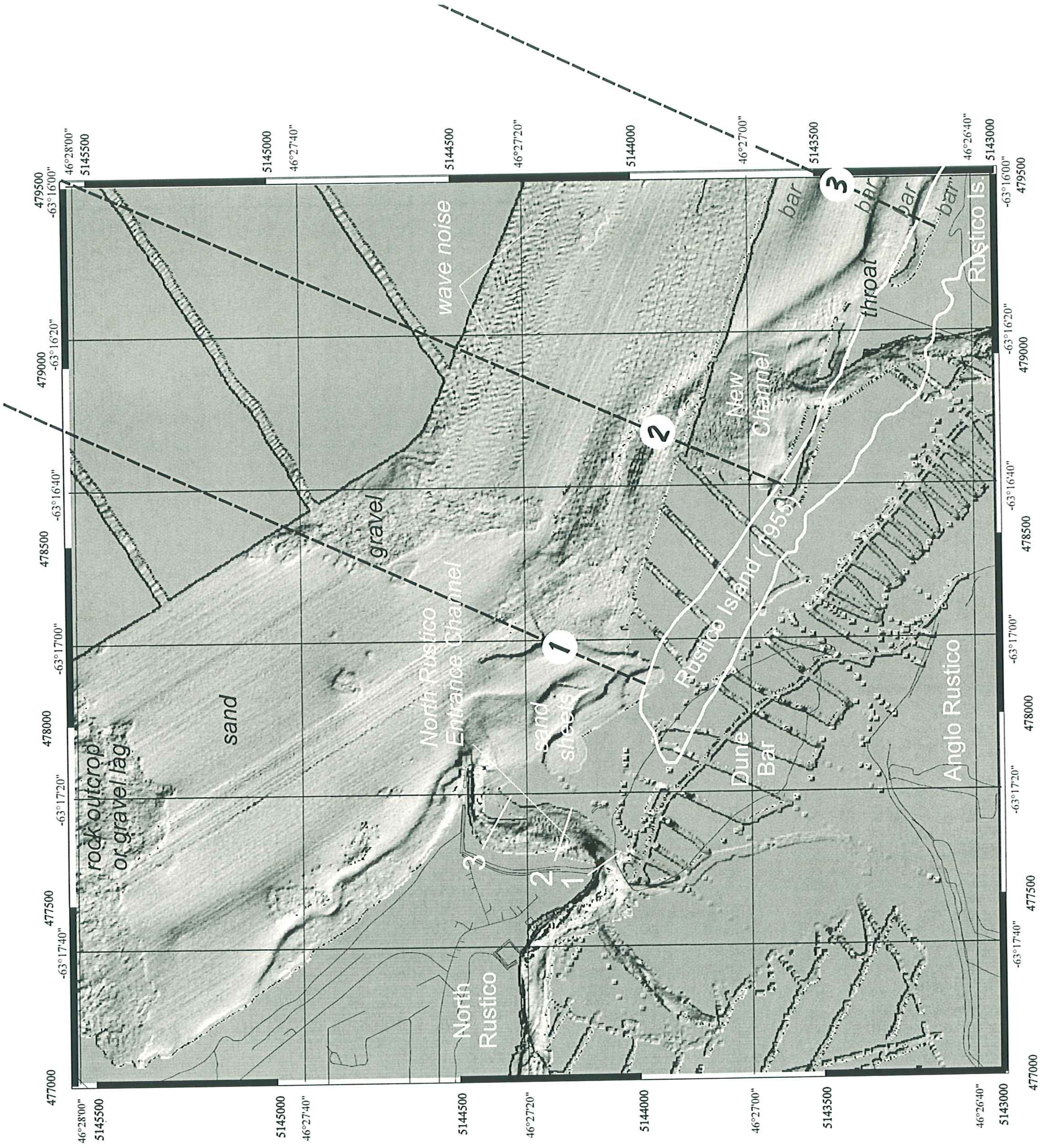


Figure 13. Grey-scale shaded-relief image of inshore area from west end of Rustico Island to North Rustico Beach, showing both active inlets to Rustico Bay. Shoreline and other details from 1:10 000 topographic base. Illumination from N40°E at 35°. Rustico Island shoreline in 1955 (from CHS field sheet) is shown as a heavy white line. Broken lines running out across shoreface (with numbers in white circles) are profile lines in Figure 20. Numbered sections in North Rustico Entrance Channel are profiles in upper panel of Figure 22.

This surface appears to extend beneath the outer bar and reappears less clearly on its landward side. The rougher surface here is partly an artefact of the sea-state at the time of the surveys, as is the pattern resembling shore-normal sandwaves east of the substrate exposure in the outer part of the survey area (Figure 13). These are not bedforms.

3.3 Tidal channels & associated ebb- & flood-tide deltas

Tidal sandwaves and superimposed dunes (or megaripples) are present in the deeper parts of New Channel (Figure 14) and dunes are present in North Rustico Entrance Channel, as described by Matsushita & McCann (1988). They are predominantly ebb-oriented, although smaller flood-oriented features occur, particularly landward of the inlet throats on the flood shoals and on the seaward side at the channel margins. Large flood-oriented sand sheets are found on the east side of North Rustico Entrance Channel (see Figure 13 and colour image on cover).

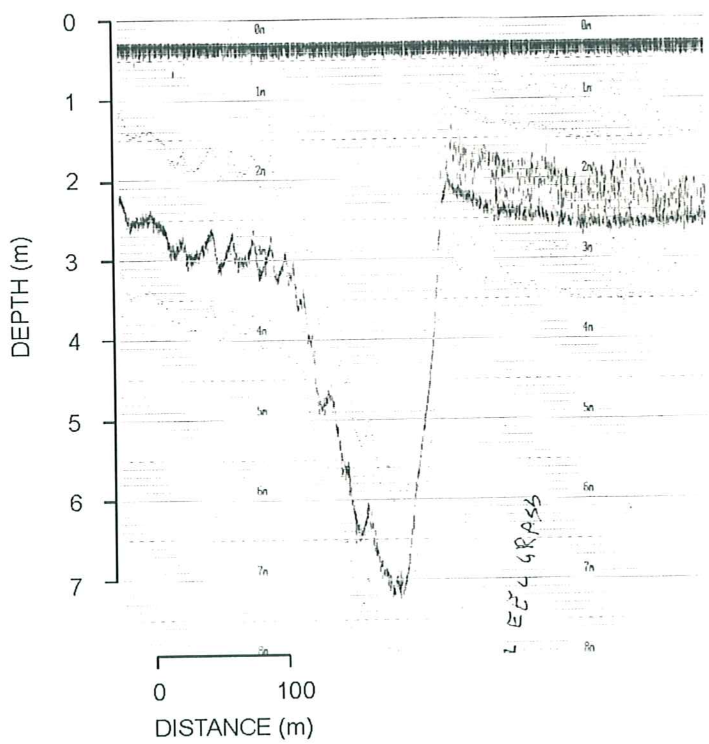


Figure 14. Knudsen 320M sounder profile on diagonal traverse across the inner end of New Channel (seaward to right), showing ebb-oriented tidal bedforms on bar, asymmetrical channel, and steep outer sidewall with a prominent levee colonized by eel grass. Bottom return is easily discerned through the eel grass.

Well-developed ebb-tidal deltas are present off both active inlets, where they cause a seaward deflection in the nearshore bar system. These deposits associated with the ebb jet are centred on the main ebb channel, which ramps up seaward to a terminal lobe (Hayes, 1980). The depth over this outer ebb shoal is the controlling depth for navigation through the inlet. This is particularly evident at North Rustico Entrance Channel, where the terminal ebb shoal pushes out through and supplants the nearshore bar (Figure 13). At New Channel, the ebb-tidal delta is asymmetrical and less well developed, in part because of the rapid eastward channel migration. The ebb delta is continually being expanded easward while it is slowly reworked by waves in the wake of the moving inlet, in the area between New Channel and North Rustico (Forbes & Solomon, 1999). Smaller flood-oriented swash bars develop on the flanks of the ebb-tidal delta, as can be seen clearly in the multibeam imagery for New Channel (Figure 13). At North Rustico Entrance Channel, the western breakwater blocks flood-tide influx from the northwest, possibly enhancing the effects of flood-tide transport on the eastern flank. The dominant flood-oriented features at this location are larger swash bars or sand sheets that build up across the west end of Dune Bar (Figure 13).

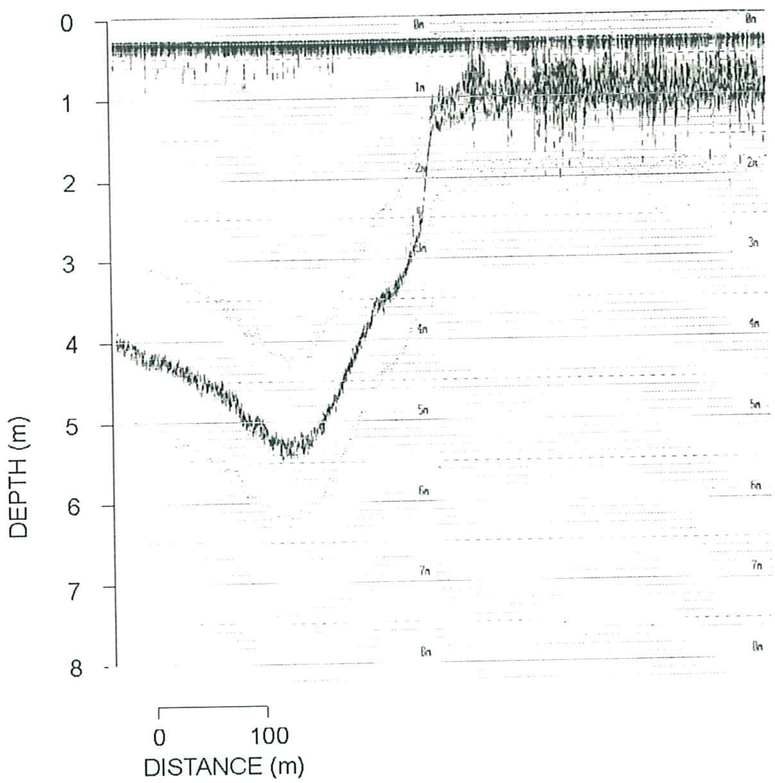


Figure 15. Knudsen 320M sounder profile across the southern flank of the relict flood-tidal delta of Little Harbour Inlet, showing steep delta flank dropping into the central basin. Note noisy record in shallow water on top of the platform, associated with aquatic vegetation cover on a coarse substrate.

Landward of the channel throats, there is no clear flood-tide delta at New Channel, but the inlet shoals headward before deepening again south of the main body of Rustico Island. The channel meanders through this transition zone. Outer channel walls on bends are steep with well-developed subtidal levees at their margins (Figure 14). The channel opens out to a broad and relatively flat basin toward the east end of Rustico Island, where it is bounded on the north by the steep-sided relict flood-tide delta of Little Harbour Inlet (Figure 15). This is very shallow (approximately 0 m CD) on its upper surface, where patchy eel grass and other species grow on a sandy substrate. The flood-delta shoal encloses a curvilinear, abandoned, tidal channel that trends parallel to the causeway and opens eastward into the bay (Figure 10). The central basin extends southward toward Oyster Bed Bridge in the eastern arm of the estuary, gradually shoaling and bounded by shallow subtidal terraces with slope breaks typically in depths <1 m CD, dropping steeply into the basin.

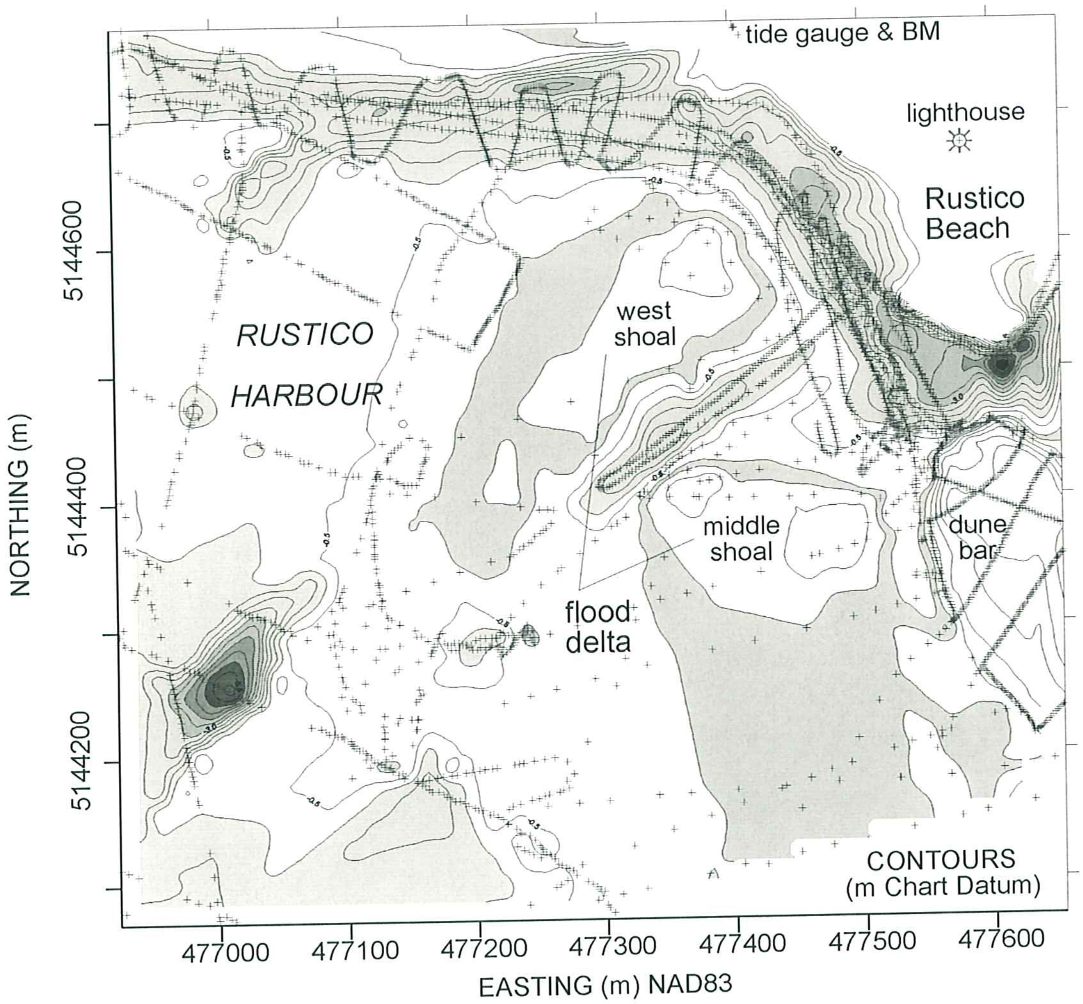


Figure 16. Topography of active flood-tide delta inside North Rustico Entrance Channel on the west side of Dune Bar. Tidal flats up to >0.5 m CD. Symbols (+) denote individual sounding records or survey points. Isobaths and contours at 0.5 m intervals except 0.2 m between 0.0 and 1.0 m CD.

In North Rustico Harbour (outer Hunter Estuary), a flood-tide delta has developed adjacent to Dune Bar, opposite the wharves at Rustico Beach (Figure 16). It displays many aspects of typical flood-delta morphology as described elsewhere (e.g. Hayes, 1980; Smith, 1984), including a broad flood ramp on Middle Shoal, opposite the inlet throat, and a bifurcating channel network across and around the shoal complex. Intertidal sand flats on this flood-tide delta rise to elevations above 0.5 m CD and the total volume of sediment above Chart Datum is approximately 53 460 m^3. The west and middle shoals are separated by a relatively deep tidal channel (-2 to -3 m CD). A shallower channel separates Middle Shoal from Dune Bar and a less well defined channel parallels the west side of West Shoal. This runs southwest from the main navigation channel (across the top of the map in Figure 16) to the south end of the channel between West and Middle Shoals. One of the deepest channel sections occurs near the junction (lower left of Figure 16), where a steep-walled channel is cut to a depth of 7 m on the sounding record (6.5 m CD). This channel (Figure 17) is flanked by shallow subaqueous flats with a heavy growth of eel grass (*Zostera marina*).

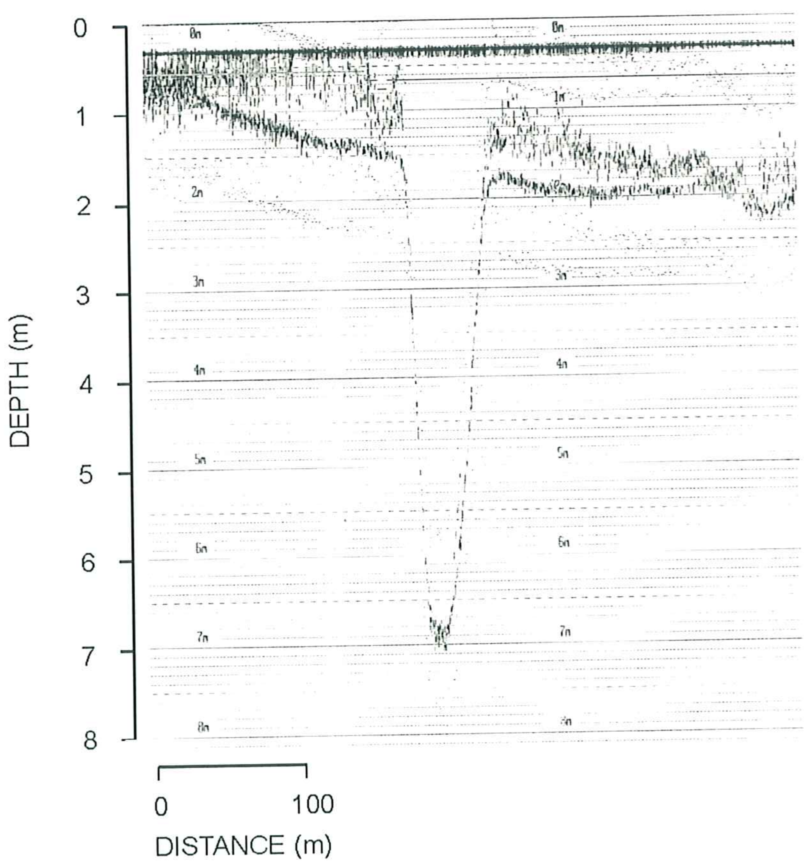


Figure 17. Knudsen 320M sounder profile across deep channel south of flood-tide delta in Rustico Harbour (Figure 16). Note steep channel walls and eel grass at channel margins, with growth diminishing away from the channel.

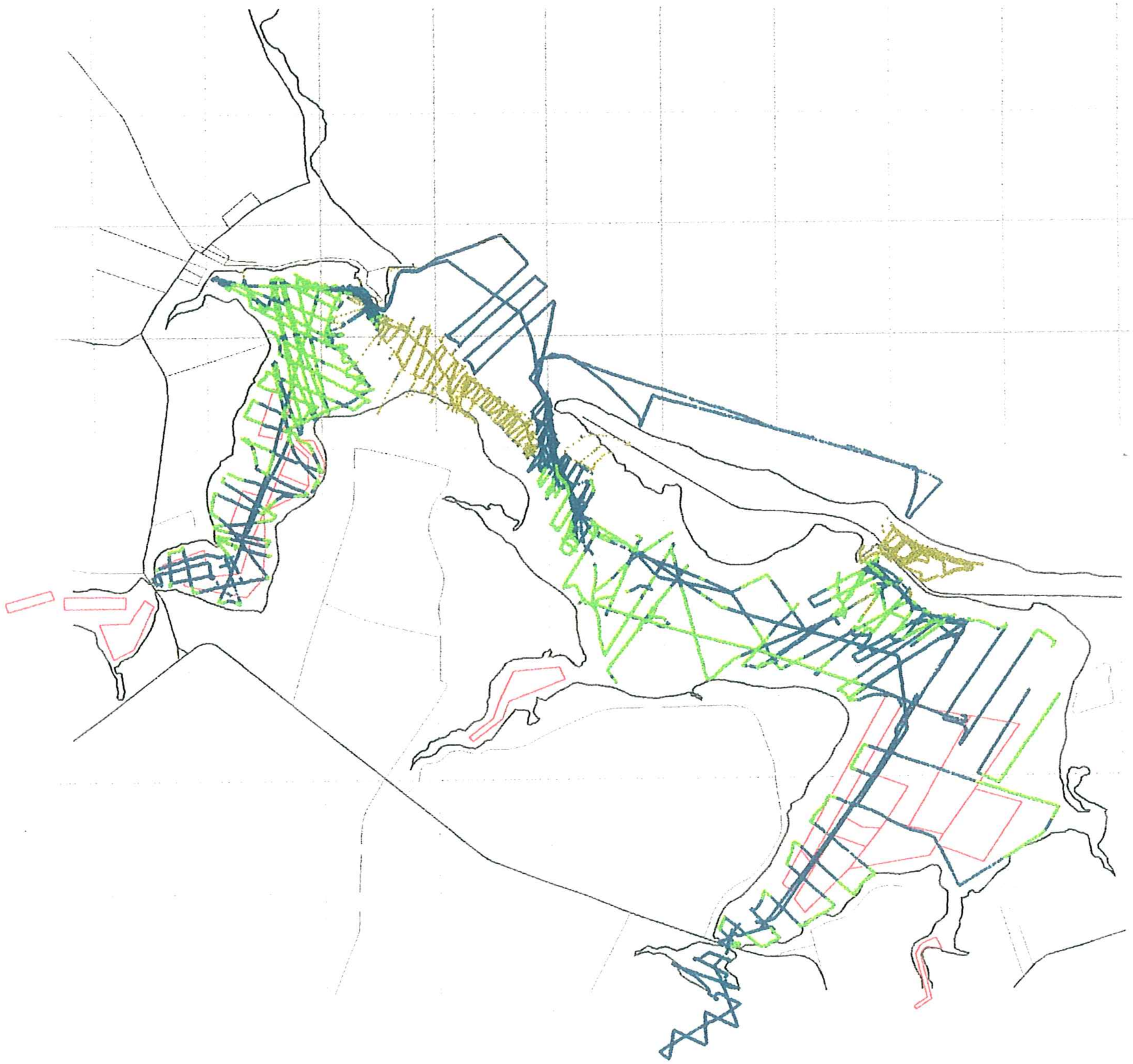


Figure 18. Benthic vegetation cover in Rustico Bay, based on echosounding data from October 1997. Green symbols indicate the presence of aquatic vegetation, predominantly eel grass (*Zostera marina*). Blue symbols denote soundings without significant vegetative cover and olive symbols denote intertidal and supratidal survey points. Red lines show the limits of existing mussel farming leases (courtesy Dale Small, Department of Fisheries & Oceans, Charlottetown).

3.4 Aquatic vegetation

The clear definition of vegetation in the echosounding records (Figures 14 & 17), as well as problems encountered in use of the sweep bathymetric system in this environment, suggested that there might be some value in documenting the distribution of benthic flora as observed in the Knudsen sounder records. Preliminary work of this kind has also been reported in the USA (Sabol et al., 1997). Although most of the vegetation mapped in this way (Figure 18) is *Zostera marina*, a small proportion may be sea lettuce (*Ulva lactuca*), which is abundant in the Wheatley River above Oyster Bed Bridge (note, however, that this growth was differentiated and omitted from the eel grass mapping in Figure 18). The results show eel grass concentrated in shallow water (typically <3 m) along the bay margins in both the Hunter and the Wheatley, with more extensive cover over the relict flood-tide delta of Little Harbour Inlet and over the broad shallow bottom outside the channel in the lower Wheatley. The lower Hunter Estuary (Rustico Harbour) has a heavy and extensive grass cover, although shallow flats in depths <0.3 m CD show abrupt termination of *Zostera* cover and are largely unvegetated. There may be a correlation between bottom sediment type and eel grass occurrence, although this may result primarily from a joint correlation with water depth. At present, however, due to a lack of samples in eel grass habitat, we have insufficient data to explore this hypothesis. The most vigourous *Zostera* growth is often found along subtidal channel margins (Figure 17).

4.0 GEOLOGICAL CONTEXT & ENGINEERING ISSUES

4.1 Long-term marine transgression & coastal retreat

The north shore of Prince Edward Island is slowly retreating landward under a combination of sea-level rise and land subsidence. Tide-gauge data show that relative mean sea level in the central PEI area is rising at a rate of 20 to 30 cm/century (Carrera & Vaníček, 1988; Shaw & Forbes, 1990; Shaw et al., 1993), leading to a general onshore movement of sediment in the barrier and estuary systems (e.g. Armon & McCann, 1979). The most obvious result of this long-term trend is the flooded-valley morphology of estuaries throughout PEI, including Rustico Bay. Unpublished shallow seismic data, obtained by the Geological Survey of Canada in support of the 1990 North Rustico harbour study and more recently in the fall of 1998 (Forbes et al., 1999b) show that estuarine valley fill deposits are present beneath the seafloor seaward of Rustico Bay. The trend of this sediment-filled valley is clearly indicated in the multibeam image acquired as part of the offshore mapping program in 1997 (Figure 4). This shows a broad shoreface sand body passing seaward into a narrower band of sand that extends down the valley axis to depths >30 m. This sand sheet represents lower shoreface sediment abandoned on the inner shelf as the coast has migrated onshore (up-valley) over the past several thousand years.

Although some results of the 1990 North Rustico Harbour study suggest seaward transport paths for nearshore sand (Baird & Associates & Eastern Designers, 1990b), most sand is maintained by nearshore wave dynamics in a narrow zone close to the present coast (Forbes, 1987; Aagaard & Greenwood, 1995; Boczar-Karakiewicz et al., 1995) and the largest volumes of sand are contained in the coastal dune system.

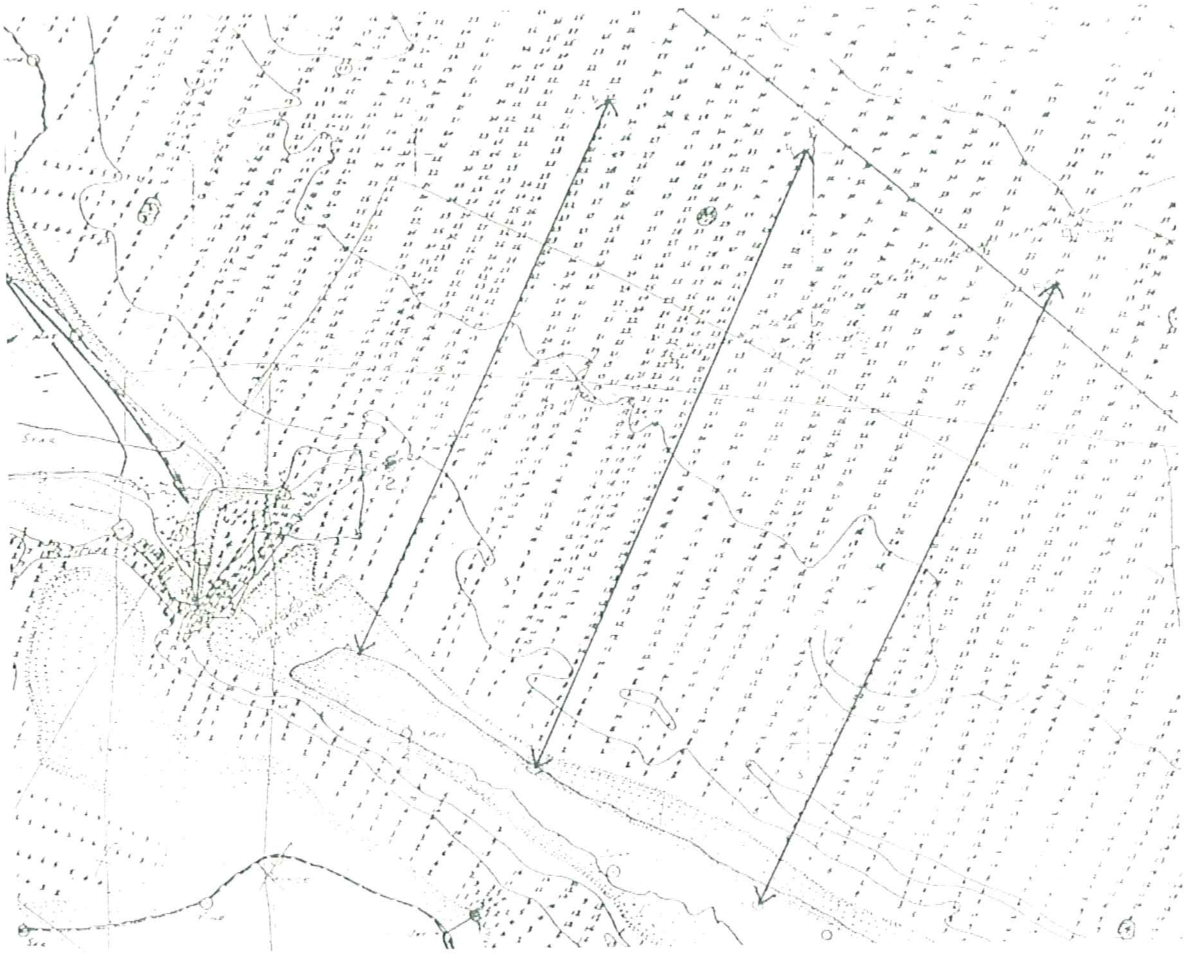


Figure 19. Part of 1955 field sheet for outer Rustico Bay, including former west end of Rustico (Robinson's) Island, showing locations of profiles 1, 2, 3 (from left to right) plotted in Figure 20.

Historical map evidence indicates that Little Harbour Inlet did not exist in the mid-1700s, when Rustico Bay and Covehead Bay were connected behind Brackley Beach (Figure 2). By 1798, landward movement of the barrier had closed off this connection (in the way that the two arms of Rustico Bay are now separated) and Little Harbour Inlet opened sometime between 1798 and 1852 (Baird & Associates & Eastern Designers, 1990b).

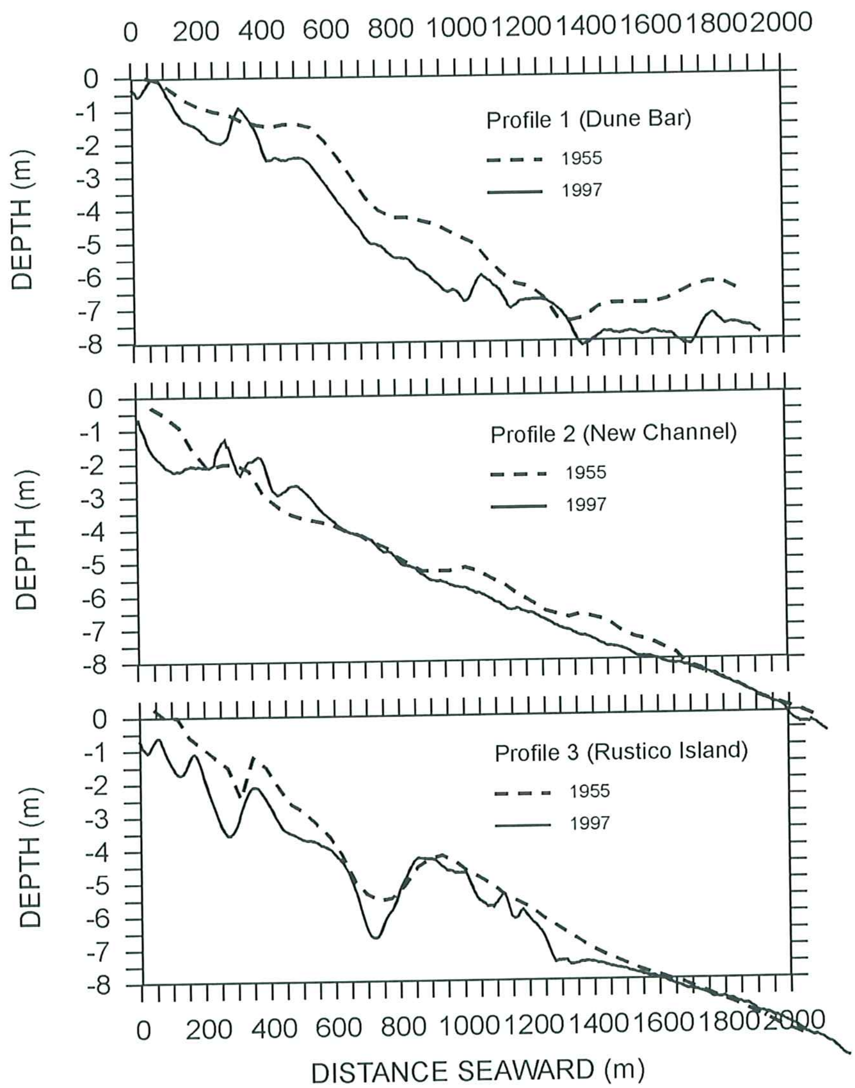


Figure 20. Shore-normal profiles in 1955 and 1997, showing (A) profile 1 (west) near the former west end of Rustico Island, with up to 300 m of profile retreat and 1 m or more of down-cutting; (B) profile 2 (middle) with accretion reflecting growth of new ebb-tidal delta off New Channel; and (C) profile 3 (east) with up to 2 m of down-cutting across the nearshore bar system near the present west end of Rustico Island. See Figures 13 and 19 for locations.

Overwash and instability along the west end of Rustico Island was initiated in the 1940s and 1950s (before Little Harbour Inlet was closed) and continued at a much more rapid pace since 1956. Although partly a continuation of the natural process of coastal retreat, this was undoubtedly accelerated by construction of the causeway (Forbes & Solomon, 1999).

4.2 Short-term coastal recession & shoreface adjustment

In Rustico Bay, navigation problems and other issues have raised public awareness and led to the proposal (NQWF, 1995) calling for a stabilisation of the coast in the condition and location existing in the 1950s before construction of the causeway. It is important to recognise that the coastal retreat along the west end of Rustico Island since the mid-1950s (Figure 19) has involved not only changes at the shoreline, but a general retreat and downcutting across the nearshore profile out to water depths of at least 8 m (Figure 20). Preliminary comparison of depths on the 1955 field sheet (with positions adjusted to the NAD83 datum) and incomplete data collected in summer 1997 show up to 2 m or more of downcutting on profile 3 (Figure 20). The associated horizontal retreat, while difficult to measure precisely because of the complex bar morphology, exceeds 100 m on parts of profiles 2 and 3 and up to 300 m on profile 1. This has significant implications for any proposed reconstruction of a barrier beach comparable to the former west end of Rustico Island. Either massive quantities of sand are required to rebuild the beach and dunes to a level high enough to prevent wave overwash and to reconstruct the nearshore profile; or an artificial barrier must be built to occupy the narrower remaining space in front of Anglo Rustico.

4.3 Dredging requirements at Little Harbour Inlet

Opening Little Harbour Inlet would require dredging a channel roughly 60 m wide, 2.4 m deep, and 200-300 m long (Baird & Associates, 1998). The 1997 topographic surveys of the beach and dunes in the area of the former inlet (Figure 21) show that the highest dunes have developed toward the west end of the causeway, in the area formerly occupied by the inlet channel. Cutting a new channel to Chart Datum would require removal of approximately 47 000 m^3 of beach and dune sand. Dredging the channel to 2.4 m would involve a further 30 000 m^3 or more (not accounting for dredging in the nearshore or widening of the channel on the landward side). The total volume to be dredged is therefore approximately 77 000 m^3.

4.4 Channel size & tidal prism

The size of the tidal channels in Rustico Bay depends on the tidal prism (volume of water exchanged between the bay and the ocean on a single tide), as well as on a number of other factors. These include maximum tidal velocity and shear stress, flood and ebb tidal current duration, freshwater discharge, ocean wave conditions, and sediment transport across and through the inlet (e.g. Escoffier, 1940; Bruun & Gerritsen, 1960; Bruun, 1978; Matsushita & McCann, 1988; Gao & Collins, 1994). A number of studies, following LeConte (1905) and O'Brien (1931, 1969), have reported various versions of the dimensional power function

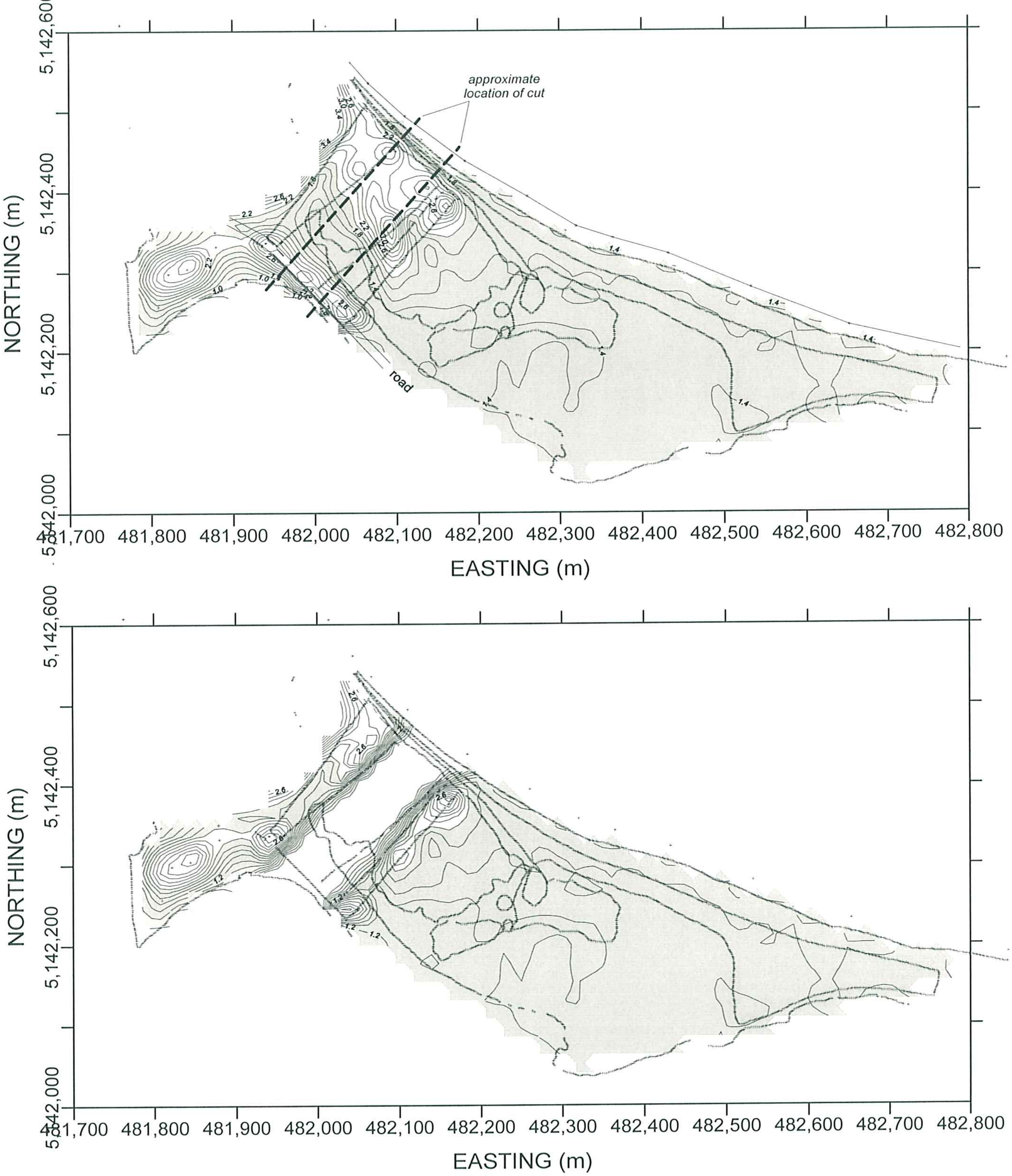


Figure 21. Contour maps with survey points superimposed, showing Rustico Island Causeway and accreted beach-dune system infilling former Little Harbour Inlet (cf. Figure 12). Upper panel shows October 1997 status, with broken lines indicating approximate location of the proposed cut to reopen the inlet. Lower panel shows anticipated topography after opening of inlet (the basis for the dredging volume estimate presented in the text).

$$A = c \cdot \Omega^{n} \quad (1)$$

where A (m^2) is the channel cross-section area at the throat or narrowest section, Ω(m^3) is the tidal prism, and c and n are empirical constants. A is defined for mean water level and Ω is taken for large tides. Jarrett (1976) developed regression relations for 68 inlets on all three US coasts,

$$A = 1.58\times10^{-4} \cdot \Omega^{0.95}, \quad (2)$$

and for 35 US Atlantic coast tidal inlets (including jettied channels),

$$A = 3.04\times10^{-5} \cdot \Omega^{1.05}, \quad (3)$$

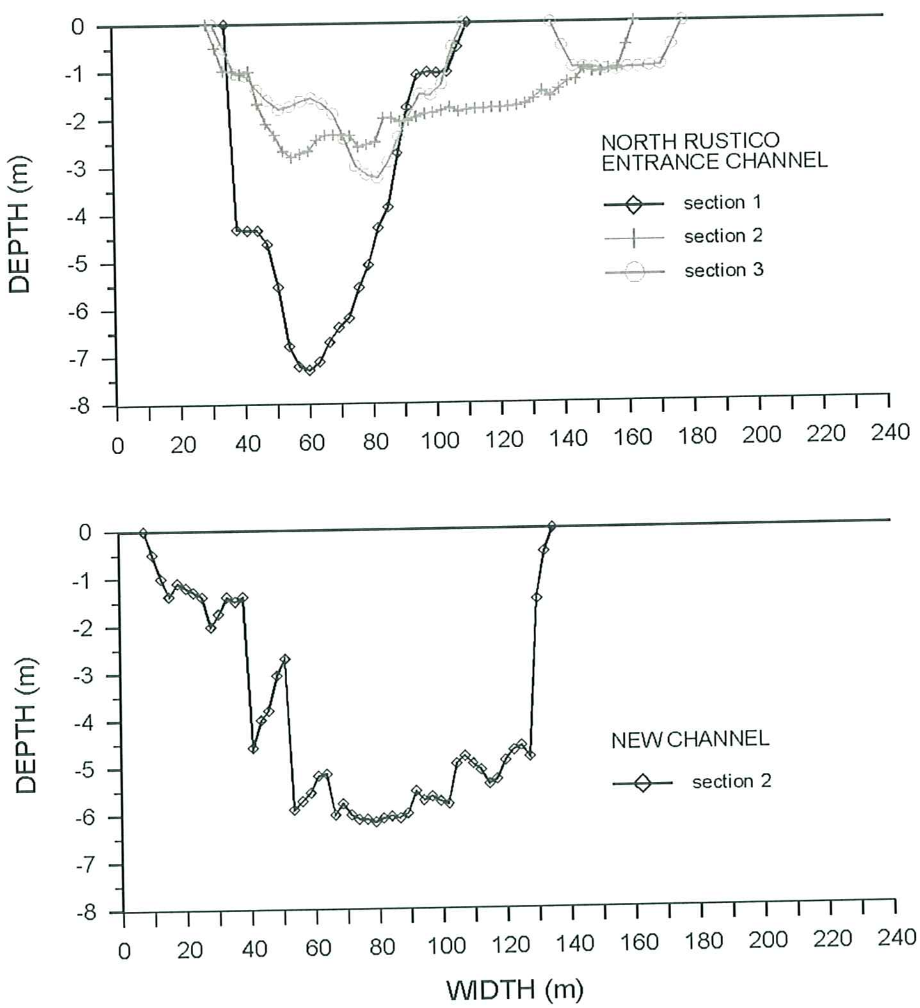


Figure 22. Cross sections in throat and seaward reach at North Rustico Entrance Channel (upper panel) and inlet throat at New Channel (lower panel), from 1997 bathymetry obtained in this study. See Figure 13 for locations (New Channel section marked 'throat').

while Hume & Herdendorf (1987) presented a similar relation for barrier inlets in New Zealand,

$$A = 1.95\times10^{-4}\cdot\Omega^{0.94}, \qquad (4)$$

among several distinct types they identified (Hume & Herdendorf, 1992). Empirical scatter about these relations may result from short-term fluctuations in tidal prism as well as other factors, such as the potential for choking by longshore sediment transport. The latter may be expressed in terms of the ratio Ω/M_T between the tidal prism and the total annual longshore sand transport volume, M_T (m^3) (Bruun & Gerritsen, 1960).

Table 1 presents historical data on channel dimensions and associated tidal prisms for the various inlets to Rustico Bay since 1881 and, in particular, for the changes in inlet morphology since construction of the Rustico Island Causeway in 1956. Data for 1997 were taken from surveys described in this report. Sources for other data are given in the table. Cross-section profiles (Figure 22) in the throat and seaward portions of North Rustico Entrance Channel and the throat section of New Channel were extracted using GRASS from the PWGSC and GSCA bathymetric data sets (Figures 10 to 13) and the channel cross-section area (A), width (W), and maximum depth (D_{max}) were then computed. Mean depth D_{mean} for estimation of the inlet aspect ratio (Marino & Mehta, 1987) was computed as A/W, such that the aspect ratio

$$R_A = W/D_{mean} = W^2/A. \qquad (5)$$

Wide variations in aspect ratio are reported in the literature (e.g. Marino & Mehta, 1987; Hume & Herdendorf, 1992). Unjettied and single-jettied inlets on the US Eastern Seaboard have an average ratio of 337, but double-jettied inlets are typically deeper with $R_A = 67$ (Jarrett, 1976). The historical values for North Rustico Entrance Channel show a wide range from 67 to 258 before 1956 (Table 1) and very low values in 1988 and 1997. These are interpreted to reflect enhanced scour where the channel is constricted by the corner crib on one side and progradation of Dune Bar on the other. Dredging may have played a role in maintaining channel width in earlier years. Little Harbour Inlet was characterized by large values, $366 \leq R_A \leq 372$, before closure in 1949 to 1952, while New Channel has seen a change from 353 in 1988 to 32 in 1997. This dramatic narrowing and deepening may suggest a diminished tendency for migration and reflect development of a relatively straight channel, but may also relate to the orientation of the channel and more effective constriction by spit deposition at the end of Rustico Island.

Inlet throat cross-sectional area and tidal prism data for Rustico Bay inlets (Table 1) are plotted in Figure 23, which also shows the published relations for US and New Zealand inlets (equations 2 to 4) and 95% confidence limits on equation 2 (Jarrett, 1976). North Rustico Entrance Channel prior to 1956 falls close to and below the predicted channel

TABLE 1

Historical morphometric and tidal prism data for Rustico Bay tidal inlets

throat section	channel depth[a] D_{max}	channel width[a] W	channel area[a] A	aspect ratio W/D_{mean}	tidal prism[b] Ω
North Rustico					
~1881	5.8 m	237 m	594 m^2	94	8 000 000 m^3
1912	6.4 m	368 m	525 m^2	258	8 000 000 m^3
1914	4.6 m	373 m	543 m^2	256	8 000 000 m^3
1948	7.6 m	172 m	384 m^2	77	8 000 000 m^3
1949	6.1 m	175 m	457 m^2	67	8 000 000 m^3
1955	7.0 m	222 m	438 m^2	112	7 900 000 m^3
1956 closed			~440 m^2		19 000 000 m^3
1985	7.7 m	~56 m	~297 m^2	~11	4 100 000 m^3
1988	7.3 m	84 m	226 m^2	31	5 500 000 m^3
1997	7.3 m	76 m	312 m^2	18	4 900 000 m^3
Little Harbour					
1949	3.7 m	455 m	566 m^2	366	11 000 000 m^3
1952	3.7 m	400 m	430 m^2	372	10 900 000 m^3
New Channel					
1985	5.5 m	~119 m	~454 m^2	~31	12 100 000 m^3
1988	3.0 m	573 m	929 m^2	353	14 000 000 m^3
1997	6.2 m	127 m	515 m^2	32	13 900 000 m^3

[a] 1881-1988 data from Baird & Associates (1990d [Appendix I]);
1985 data from Matsushita & McCann (1988); 1997 data this study.

[b] 1881-1949 and 1988 data from Baird & Associates (1990d [Appendix I]);
1956 after closure from Baird & Associates (1990a); 1955 and 1997 data from Baird & Associates (1996); 1985 data from Matsushita and McCann (1988).

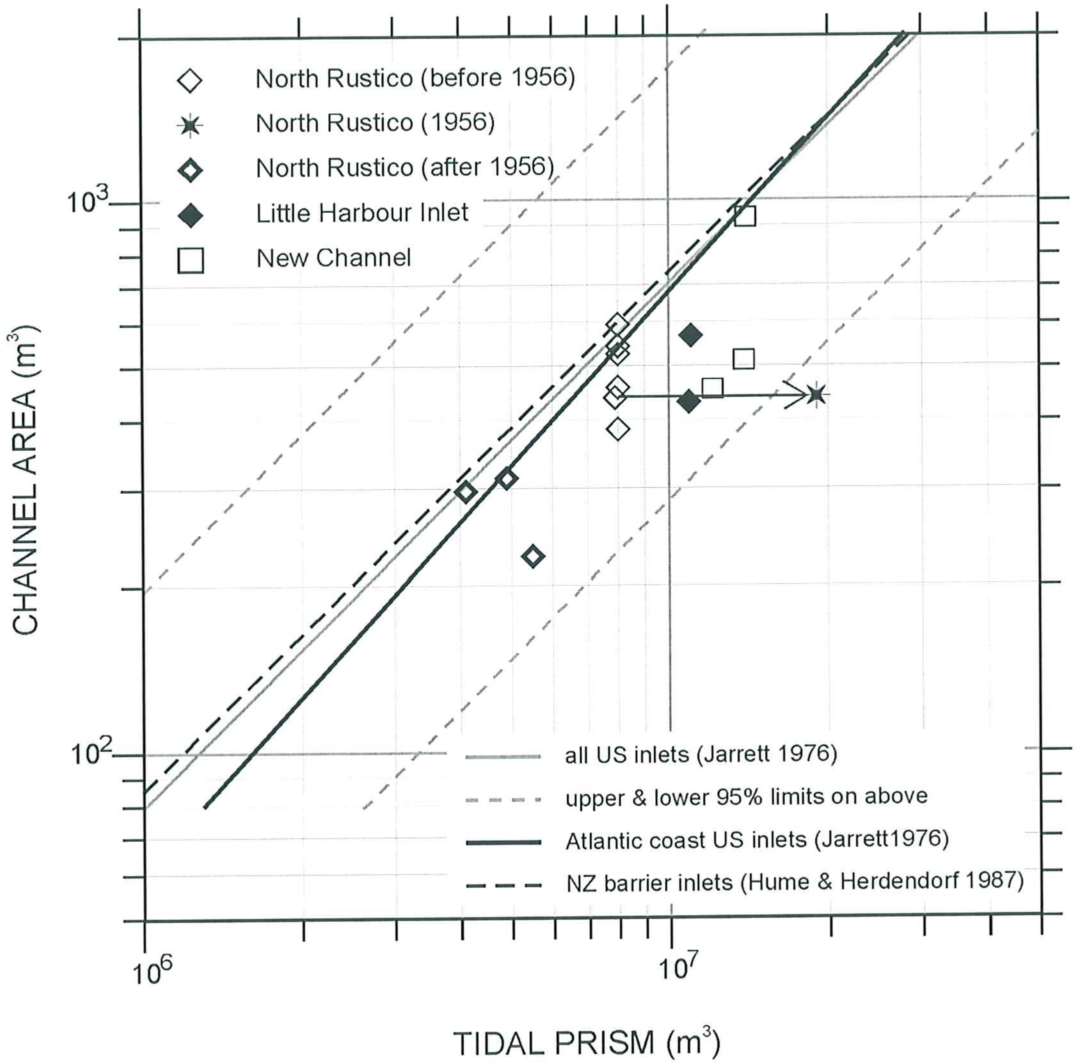


Figure 23. Inlet throat cross-sectional area as a function of tidal prism. Historical data for Little Harbour Inlet, North Rustico Entrance Channel, and New Channel, compared to empirical relations published for 68 inlets on all three US coasts and the 35 Atlantic coast inlets only (Jarrett, 1976) and for 34 New Zealand barrier inlets on littoral drift shores (Hume & Herdendorff, 1987). Horizontal line and arrow denotes abrupt shift in tidal prism at North Rustico on closure of Little Harbour Inlet.

area, but well within the 95% confidence band, bearing in mind the likelihood of some variation in tidal prism. The three lower values are from 1948 to 1955. Little Harbour Inlet in 1948 and 1952 plots on a similar curve. After completion of the Rustico Island Causeway in 1956, the tidal prism at North Rustico Entrance Channel increased immediately to almost 19×10^6 m^3, clearly demanding increased channel capacity (Figure 23). Maximum ebb velocities are estimated to have more than doubled, from 0.40 to

0.85 m/s, with ebb and flood peak discharge increasing from 320 to 660 m^3/s and from 240 to 510 m^3/s, respectively (Baird & Asssociates, 1990e). Rapid channel widening, division, and eastward migration ensued (Forbes & Solomon, 1999).

As to why the channel widened rather than becoming deeper, the answer may lie in part with the underlying stratigraphy, although the lack of structural confinement on the east side, along with a modest aspect ratio, W/D_{mean}= 112, in 1955 (Table 1), may also have tended to discourage scour. Drilling results summarized by Baird & Associates (1990b) show bedrock as deep as 10 to 20 m in the area of the North Rustico inlet, but jet-probing met refusal at depths of 5 m or less CD. This suggests that channel erosion may be partly limited by resistant glacial till. Because most of the added tidal prism was flowing in the back-barrier channel behind Rustico Island, this may also have encouraged eastward expansion of the channel.

Channel division was well established by 1959 (Figure 3) and a new eastern channel (Centre Channel), equivalent in size to North Rustico Entrance Channel, had developed by 1962 (Forbes & Solomon, 1999). New Channel was developing by the mid- to late-1970s and the two parts of the estuary were effectively separated by the mid-1980s (Matsushita & McCann, 1988). By this time, New Channel had captured a larger portion of the total Rustico Bay tidal prism than originally carried by Little Harbour Inlet, leaving North Rustico Entrance Channel with a smaller prism than before the 1956 inlet closure (Figure 23).

Inlet stability depends not only on tidal prism but also on the potential for sediment choking in the channel. Baird & Associates (1990c) presented a range of estimates for annual longshore sediment transport in the study area based on a 31-year wave hindcast analysis (1953-1983) and various assumptions of sediment supply. The lowest estimate, which they suggested might still be excessive, was 300 000 m^3 eastward and 80 000 m^3 toward the west. Taking a conservative estimate of half these values, we obtain an estimated annual gross transport rate M_T= 190 000 m^3.

Values of the ratio Ω/M_T for 1997 data at North Rustico and New Channel are 25 and 73, respectively. The latter falls within the range identifed by Bruun (1978: 376) as having a "rather large" entrance bar or shoals which "may be penetrated by a channel improving navigation [although] breaking … may take place … during storm[s]". In this category, $50 \leq \Omega/M_T < 100$, inlets are considered quasi-stable. On the other hand, North Rustico Entrance Channel falls within the range $20 \leq \Omega/M_T < 50$, described by Bruun as "unreliable and dangerous [with] waves break[ing] over the bar during most storms." Sediment trapping by the western breakwater is obviously helpful at North Rustico, but evidence for sediment influx across Dune Bar on the east side points to a need for some intervention there.

Bruun (1978) suggested that inlets with low Ω/M_T ratios may be maintained by occasional short-term increases in discharge such as runoff from large rainfall events. At North Rustico, this might take the form of spring snowmelt discharge from the Hunter River. Continuing tidal exchange in winter, when sea ice limits wave activity and associated sediment transport, may also be important. In addition, short-term increases in tidal prism related to positive storm surges can have a significant impact on microtidal coasts such as the North Shore of PEI. Parkes et al. (1997) reported an average of 10 surges per year higher than 0.6 m at North Rustico and 2.7 events per year greater than 1.0 m, demonstrating a potential for occasional large increases in tidal exchange.

Forbes & Solomon (1999) present a brief analysis of boundary shear stress and sediment transport potential in New Channel and North Rustico Entrance Channel. Large bedforms and high peak ebb velocities, $u_e \approx 1.1$ m /s, in New Channel point to strong sediment flushing, but peak ebb shear velocities, $u_* \approx 0.14$ m/s, reported by Matsushita & McCann (1988) appear to incorporate a large form roughness component. From the relation

$$u_*^2 = \tau_o / \rho = C_D u_e^2 \qquad (6)$$

where τ_o (N/m^2) is the shear stress at the bed, ρ (kg/m^3) is fluid density, and C_D is a drag coefficient appropriate for the bottom roughness, we estimate a lower value of $u_* \approx 0.06$ m/s for New Channel using typical drag coefficient $C_D = 0.0026$ for a sand bed (Soulsby, 1983). While lower, this value remains high enough to maintain substantial bedload transport in the channel for much of the ebb flow. On the other hand, estimates of peak ebb shear velocity in North Rustico Entrance Channel (Forbes & Solomon, 1999) indicate much lower values, $u_* < 0.02$ m/s, only marginally competent for transport fine sand (see e.g. Inman, 1949; Komar & Wang, 1984). This implies a much greater propensity for channel shoaling at North Rustico Entrance Channel.

5.0 CONCLUSIONS & RECOMMENDATIONS

Updated surveys of coastal bathymetry in and adjacent to Rustico Bay were needed to evaluate proposed changes in this complex tidal inlet system. These were required to support numerical model studies of tidal circulation and sediment transport under various remediation scenarios (Forbes et al., 1998). Nearshore profiles were also needed to determine the extent of shoreface retreat associated with inlet migration, shoreline erosion, and the loss of the west end of Rustico Island. Three separate survey programs were undertaken in 1997 to address these needs.

A ship-based multibeam bathymetric survey (Forbes et al., 1999a) provided the first detailed images of the seafloor offshore from Rustico Bay. These show large areas of rock and lag gravel exposure, with sand confined to a shoreface wedge and a band of sediment running seaward along the underwater extension of the Wheatley and Hunter River valleys. This survey demonstrates that North Rustico lies near the western limit of the shoreface sand body, with glacial till and/or bedrock present at shallow depth. It also shows that coastal retreat is an ongoing and long-term process in this region and that Rustico Bay formerly extended at least 4 km seaward of the present coast.

Water depths in the nearshore and tidal inlets were obtained using a multibeam survey launch with a boom-mounted array of transducers. The resulting data and imagery provide detailed information on changes in channel location, bar morphology, and shoreface profiles since the last outer shore surveys in 1955. The limiting depth over the bars off North Rustico Entrance Channel is about 1.3 m CD or 2.5 m at HHWLT. Channel instability and migration across the west end of Rustico Island has produced large changes in the shoreline, nearshore bar positions, and ebb shoal morphology. Comparison with the 1955 field sheet shows up to 300 m of shoreface profile retreat, with downcutting of as much as 2 m or more and profile changes out to 8 m water depth off Dune Bar and Rustico Island. Gravel is exposed in the bar troughs. Nearshore bedrock platforms occur off Rustico Island, including the area immediately west of the former Little Harbour Inlet. Further retreat and adjustment of nearshore profiles can be expected in response to wave climate variance, sea-level rise, and any changes made in the tidal inlets. Regular surveys of the shoreface in the vicinity of all active inlets should be an integral part of any remediation and management program. Inlet throat sections should also be resurveyed at intervals to determine the extent of depth and channel size adjustments to changes in tidal prism. Video monitoring of shoreline morphology, nearshore dynamics, and ice development is another option that may provide useful information for harbour management, monitoring of structures, scientific analysis of nearshore morphodynamics, and other applications such as tourism promotion.

The small-boat program completed the bathymetric surveys in the inner bays. This was combined with topographic surveys of intertidal bar morphology, beach and dune growth on Dune Bar and at the causeway, and shoreline retreat at the west end of Rustico Island. Although large changes were evident at the coast and near the tidal inlets, there was little evidence of change inside the bays. The abandoned Little Harbour Inlet flood-tide delta and channel behind the causeway remain little changed since the last survey in 1955, while reference to the 1988 surveys in deeper parts of the bay showed no significant changes. This is consistent with results of the sediment study, which show very limited mud accumulation and negligible transport potential beyond the tidal channels and their associated flood-tide deltas.

Eel grass is typically best developed adjacent to channels and covers large parts of the outer bay in Rustico Harbour and the outer Wheatley Estuary as well as marginal shallows further up the bay. Where present, it creates additional resistance to flow and reduces the sediment transport potential.

Active sand transport in the tidal inlet channels is demonstrated by the presence of sandwaves, predominantly ebb-oriented. The channel throat cross-sectional areas are near or below equilibrium size for the tidal prism, in part reflecting wave-driven sand influx (onshore and longshore transport). This conclusion is supported by low ratios of tidal prism to gross annual wave-driven sediment transport, particularly at North Rustico Entrance Channel. An eastern breakwater at North Rustico Entrance Channel would limit inputs from Dune Bar. Estimates of shear velocity in New Channel and North Rustico Entrance Channel indicate a potential for significant bedload transport in the former, but much more limited tansport competence at North Rustico.

6.0 REFERENCES

Aagaard, T. & Greenwood, B. 1995. Longshore and cross-shore suspended sediment transport at far infragravity frequencies in a barred environment. Continental Shelf Research, 15, 1235-1249.

Amos, C.L., Anderson, C., & LeCouturier, M. 1998. The Rustico Inlet study, PEI - field results. Geological Survey of Canada, Open File 3579; report submitted to Parks Canada, Halifax, 28 p., 117 figs & appendix.

Anderson, C. 1998. Sediment stability in Rustico Bay and the Hunter River, PEI. Unpublished contract report to Geological Survey of Canada, Dartmouth. Challenger Oceanography, Dartmouth, 13 p. & 58 figs.

Appleby, J. 1997. Environmental issues and options, Rustico Bay and Robinson's Island, Prince Edward Island National Park. Draft discussion paper, Environmental Services, Public Works and Government Services Canada, 7 p.

Armon, J.W. & McCann, S.B. 1979. Morphology and landward sediment transfer in a transgressive barrier island system, southern Gulf of St. Lawrence, Canada. Marine Geology, 31, 333-344.

Baird, W.F. & Associates, Coastal Engineers Ltd; Eastern Designers Co. Ltd. 1990a. North Rustico sediment transport study, North Rustico, PEI. Executive Summary. Contract report to Public Works Canada, Charlottetown, v+23 p.

Baird, W.F. & Associates, Coastal Engineers Ltd; Eastern Designers Co. Ltd. 1990b. North Rustico sediment transport study, North Rustico, PEI. Main report. Final report to Public Works Canada, Charlottetown, vii+60 p. & 87 figs with 5 appendices (separate volumes).

Baird, W.F. & Associates, Coastal Engineers Ltd. 1990c. Rustico Harbour sediment transport study, North Rustico, PEI. Appendix C: Description of the wind, wave and sediment transport regime. Contract report to Public Works Canada, Charlottetown, iv+16 p. & 11 figs with 2 appendices.

Baird, W.F. & Associates, Coastal Engineers Ltd. 1990d. Rustico Harbour sediment transport study, North Rustico, PEI. Appendix D: Physical model study. Contract report to Public Works Canada, Charlottetown, ix+56 p. & 101 figs with 1 appendix.

Baird, W.F. & Associates, Coastal Engineers Ltd. 1990e. Rustico Harbour sediment transport study, North Rustico, PEI. Appendix E: Numerical simulation of tides at North Rustico, PEI. Contract report to Public Works Canada, Charlottetown, iv+17 p., 10 tables & 24 figs.

Baird, W.F. & Associates Ltd. 1996. Numerical modelling of Rustico Inlet, P.E.I. Final report to Parks Canada, Canadian Heritage, 9 p. & 13 figs with 4 appendices.

Baird, W.F. & Associates Ltd. 1998. Computer modelling of Rustico Bay hydrodynamics. Unpublished contract report to Parks Canada, Halifax. Prepared by D. Williamson, W.F. Baird & Associates, Coastal Engineers, Ottawa.

Bisaillon, Laura M. 1997. The effects of external development decisions on a rural community: the Greater Rustico area, Prince Edward Island. Unpublished supervised research project, School of Urban Planning, McGill University, Montreal, 106 p., 5 appendices, & endnotes.

Boczar-Karakiewicz, B., Forbes, D.L. & Drapeau, G. 1995. Nearshore bar development in southern Gulf of St. Lawrence. Journal of Waterway, Port, Coastal, and Ocean Engineering, 121, 49-60.

Bruun, P. 1978. Stability of tidal inlets — Theory and engineering. Elsevier, Amsterdam, 510 p.

Bruun, P. & Gerritsen, F. 1960. Stability of coastal inlets. North Holland, Amsterdam, 123 p.

Brylinsky, M. 1998. Assessment of potential water quality impacts resulting from removal of Rustico Island Little Harbour Causeway, Prince Edward Island. Acadia Centre for Estuarine Research, Acadia University, Wolfville, Publication 48, v+50 p.

CHS [Canadian Hydrographic Service]. 1955. Bathymetric field sheet no. 2598, 1 sheet (scale ~1:20 000).
CHS [Canadian Hydrographic Service]. 1958. Rustico Bay and New London Bay, Prince Edward Island (North Shore). Chart 4467, surveyed by R.F. Logan and assistants, 1955, 1 sheet (scale 1:15 000).
Carrera, G. & Vaníček, P. 1988. A comparison of present sea level linear trends from tide gauge data and radiocarbon curves in eastern Canada. Palaeogeography, Palaeoclimatology, Palaeoecology, 68, 127-134.
Copps, S. 1996. Letter to Mr James D. Gallant, President, North Queens Wildlife Federation, Rusticoville, PEI. Office of Deputy Prime Minister, Ottawa, 28 February 1996, 1 p.
Crowl, G.H. & Frankel, L. 1970. Surficial geology of Rustico map-area, Prince Edward Island (11L/6). Geological Survey of Canada, Paper 70-39, 15 p. & map.
Escoffier, E.F. 1940. The stability of tidal inlets. Shore and Beach, 8, 114-115.
Forbes, D.L. 1987. Shoreface sediment distribution and sand supply at C^2S^2 sites in the southern Gulf of St. Lawrence. Proceedings, Coastal Sediments '87 (New Orleans). American Society of Civil Engineers, New York, 694-709.
Forbes, D.L. 1997. Comments on a discussion paper (Appleby 1997) and brief (NQWF 1995) concerning proposed removal of the Little Harbour causeway and other changes in Rustico Bay, Prince Edward Island. Report submitted by Geological Survey of Canada to Parks Canada, Halifax, 7 p.
Forbes, D.L. & Solomon, S.M. 1999. Inlet division and coastal instability following tidal prism diversion. Proceedings, Coastal Sediments '99 (Long Island). American Society of Civil Engineers, Reston, *in press*.
Forbes, D.L., Frobel, D., Heffler, D.E., Dickie, K. and Shiels, C. 1986. Surficial geology, sediment mobility and transport processes in the coastal zone at two sites in the southern Gulf of St. Lawrence: Pte Sapin (NB) and Stanhope Lane (PEI). National Research Council Canada, Canadian Coastal Sediment Study, Report C2S2-20, iii+27 p.
Forbes, D.L., Sherin, A.G., Beaver, D., Frobel, D. & Covill, R. 1999a. Multibeam bathymetric surveys off the central north shore of Prince Edward Island (**NSC [NGCC] *Frederick G. Creed*** cruises BIO97093 and IML98034B). Geological Survey of Canada, Open File.
Forbes, D.L., Solomon, S.M., Sherin, A.G., Beaver, D., Atkinson, A., Dickson, C., Uyesugi, M., Harrison, P. & Covill, R. 1999b. Hydrographic and marine geological surveys off the central North Shore of Prince Edward Island (**CCGS *Matthew*** and **CSL *Plover*** cruise 98049). Geological Survey of Canada, Open File.
Forbes, D.L., Williamson, D., Amos, C.L., Brylinsky, M. & Anderson, C. 1998. Summary of scientific results and analysis of remediation options, Rustico Bay, PEI. Unpublished report to Rustico Island Causeway Working Group (North Rustico) and Parks Canada (Charlottetown & Halifax), 14 p.
Gao, S. & Collins, M. 1994. Tidal inlet equilibrium in relation to cross-sectional area and sediment transport patterns. Estuarine, Coastal and Shelf Science, 38, 157-172.
Hayes, M.O. 1980. General morphology and sediment patterns in tidal inlets. Sedimentary Geology, 26, 139-156.
Hume, T.M. & Herdendorf, C.E. 1987. Tidal inlet stability: a workshop background paper. In: Tidal inlet stability: Proceedings of a Seminar (Christchurch, 4 December 1985). National Water and Soil Conservation Authority, Wellington, Water & Soil Miscellaneous Publication 108, 8-32.
Hume, T.M. & Herdendorf, C.E. 1992. Factors controlling tidal inlet characteristics on low drift coasts. Journal of Coastal Research, 8, 355-375.
Inman, D.L. 1949. Sorting of sediments in the light of fluid mechanics. Journal of Sedimentary Petrology, 19, 51-70.

Jarrett, J.T. 1976. Tidal prism — inlet area relationships. US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, GITI Report 3, 54 p.

Komar, P.D. & Wang, C. 1984. Processes of selective grain transport and the formation of placers on beaches. Journal of Geology, 92, 637-655.

LeConte, L.J. 1905. Discussion of "Notes on the improvement of river and harbour outlets in the United States" by D.A. Watts (Paper No. 1909). Transactions, American Society of Civil Engineers, 55, 306-308.

McKay, Kent; Johnson, David; MacLeod, Gordon; Andrew, Basil; Montgomery, Merrill; Jollimore, Karl; & Jollimore, Kenneth. 1997. Changes to Rustico Island causeway located in the PEI National Park and changes to the tidal flow in Rustico Bay. Letter to Premier of Prince Edward Island and others from Mussel Growers in Rustico Bay, 19 June 1997, 3 p. & annex.

Marino, J.N. & Mehta, A.J. 1987. Inlet ebb shoals related to coastal parameters. Proceedings, Coastal Sediments '87 (New Orleans). American Society of Civil Engineers, New York, 1608-1623.

Matsushita, P.N. & McCann, S.B. 1988. Large bedforms and associated hydraulic conditions within microtidal-inlet channels, southern Gulf of St. Lawrence, Canada. Canadian Journal of Earth Sciences, 25, 916-922.

NQWF [North Queens Wildlife Federation]. 1995. The removal of the Little Harbour causeway and subsequent restoration of Robinson's Island. Brief submitted to Hon. Sheila Copps, Deputy Prime Minister & Minister of Environment, Ottawa, n.p.

O'Brien, M.P. 1931. Estuary tidal prisms related to entrance area. Civil Engineering, 1(8), 738-739.

O'Brien, M.P. 1969. Equilibrium flow areas of inlets on sandy coasts. Journal, Waterways and Harbors Division, American Society of Civil Engineers, 95, 43-52.

Parkes, G.S., Ketch, L.A. & O'Reilly, C.T. 1997. Storm surge events in the Maritimes. Proceedings, Canadian Coastal Conference 1997 (Guelph). Canadian Coastal Science and Engineering Association, Ottawa, 115-129.

Prest, V.K. 1973. Surficial deposits of Prince Edward Island. Geological Survey of Canada, Map 1366A, 1 sheet (scale 1:126 720) with accompanying map and text on reverse.

PWC [Public Works Canada]. 1988. Bathymetry, Rustico Bay, 6 sheets (scale 1:5000), 2 sheets (scale 1:1000).

Sabol, B., McCarthy, E. & Rocha, K. 1997. Hydroacoustic basis for detection and characterization of eelgrass (*Zostera marina*). Proceedings, Fourth Conference on Remote Sensing for Marine and Coastal Environments (Orlando), I679-I693.

Shaw, J. & Forbes, D.L. 1990. Short- and long-term relative sea-level trends in Atlantic Canada. Proceedings, Canadian Coastal Conference 1990 (Kingston). National Research Council, Associate Committee on Shorelines, Ottawa, 291-305.

Shaw, J., Taylor, R.B. & Forbes, D.L. 1993. Impact of the Holocene transgression on the Atlantic coastline of Nova Scotia. Géographie physique et Quaternaire, 47, 221-238.

Smith, D.B. 1984. The hydrology and geomorphology of tidal basins. In: The closure of tidal basins (van Aalst, W., editor). Delft University Press, Delft, 85-109.

Soulsby, R.L. 1983. The bottom boundary layer of shelf seas. In: Physical oceanography of coastal and shelf seas (Johns, B., editor). Elsevier, Amsterdam, 189-266.

van de Poll, H.W. 1983. Geology of Prince Edward Island. PEI Department of Energy & Forestry, Energy & Minerals Branch, Charlottetown, Paper 83-1.

Vincent, C.L. & Corson, W.D. 1981. Geometry of tidal inlets: empirical equations. Journal of Waterway, Port and Coastal Engineering Division, American Society of Civil Engineers, 107 (WW1), 1-9.