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Article abstract

Prince Edward Island has an area of 5700 km2 , with a length of approximately 217 km and an average width of 27 km. Numerous coastal indentations account for a total coastline of over 1,770 km. Shallow bays and estuaries cut deeply into the landmass and nearly dissect it in several places. Man has established his major communities, industries, and recreational activities along the coastline and is being drawn there in increasing numbers, thereby placing undue pressure on the vevy environmental qualities which formed the original attraction.

The estuaries produce large quantities of organic materials, and act as sediment traps and reservoirs for nutrients and chemicals. The processes of trapping, concentrating, producing and recycling sediments are of first order importance.

Sediments in the estuaries and lagoons range from clay to coarse sand and gravel. They are contributed by marginal, internal and external sources. Sediment accumulation averages 0.4 cm/year. Fluvial waters transport and contribute the majority of the sediments to these environments. Tidal flow contributes to the resuspension and redistribution of river-borne sediments. Agglomeration, flocculation and deflocculation occurring in these estuaries have important affects on siltation and pollutant concentration. Organic constituents in the sediments are derived from pelagic, epi- and infaunas. The inorganic constituents are derived from a variety of sources.

Concentrations of suspended particulate matter decrease from about 180 mg/l in upper estuaries to less than 3 mg/l in the lower estuary-lagoon complex. The organic matter content is highest (-3 to 5%) in fine-grained sediments. Heavy metals such as Cu, Pb and In are strongly associated with organic matter.

River flow and the flood and ebb of tidal currents are the most obvious water motions in these environments. However, strong winds cause turbulence in shallow (< 5 m) waters. This turbulence initiates resuspension of previously deposited organic and inorganic materials. Depending upon the relative directions of wind and tide, winds may cause an increase or decrease in surface current velocities.

Reports

DEPOSITIONAL ENVIRONMENTS AND SEDIMENTS IN THE COASTAL ZONE OF PRINCE EDWARD ISLAND, CANADA

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Prince Edward Island has an area of 5,700 km^2*, with a length of approximately 217 km, and an average width of 27 km. Numerous coastal indentations account for a total coastline of over 1,770 km. Shallow bays and estuaries cut deeply into the landmass and nearly dissect it in several places. Man has established his major communities, industries, and recreational activities along the coastline and is being drawn there in increasing numbers, thereby placing undue pressure on the very environmental qualities which formed the original attraction.*

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Sediments in the estuaries and lagoons range from clay to coarse sand and gravel. They are contributed by marginal, internal and external sources. Sediment accumulation averages 0.4 cm/year. Fluvial waters transport and contribute the majority of the sediments to these environments. Tidal flow contributes to the resuspension and redistribution of river-borne sediments. Agglomeration, flocculation and deflocculation occurring in these estuaries have important affects on siltation and pollutant concentration. Organic constituents in the sediments are derived from pelagic, epi- and infaunas. The inorganic constituents are derived from a variety of sources.

Concentrations of suspended particulate matter decrease from about 180 mg/l in upper estuaries to less than 3 mg/l in the lower estuary-lagoon complex. The organic matter content is highest (~3 to 5%) in fine-grained sediments. Heavy metals such as Cu, Pb and Zn are strongly associated with organic matter.

River flow and the flood and ebb of tidal currents are the most obvious water motions in these environments. However, strong winds cause turbulence in shallow (< 5 m) waters. This turbulence initiates resuspension of previously deposited organic and inorganic materials. Depending upon the relative directions of wind and tide, winds may cause an increase or decrease in surface current velocities.

INTRODUCTION

The coastal (marginal marine) zone includes over 80 percent of the prime recreational land in Atlantic Canada, and the economy of Prince Edward Island is becoming increasingly dependent on its associated revenues ($18 million in 1972 and $42 million in 1976). It is a valuable and limited resource, but the human activities involved in its use frequently impose excessive and competing demands. Often these serve only to detract from the intrinsic qualities that make this environment attractive. It is imperative that these activities be properly and wisely managed to insure the coexistence of economic development and ecologic preservation. An understanding of the geological framework is the first important step.

The coastaline of Prince Edward Island, including its many indentations, (Fig. 1) is over 1,770 km in length. It is commonly composed of easily eroded Permo-Carboniferous sedimentary rocks consisting mostly of sandstone with lesser amounts of siltstone, shale and conglomerate. The major glacial deposits are sand-rich ablation ground moraine. A large portion of the coastline, especially along the northeastern and southeastern shore, is composed of sand dunes and well developed baymouth bars. Comparable features have existed, perhaps intermittently, along the Atlantic continental margin since at least Cretaceous time (Bartlett and Smith 1971).

Study file 961-2-1-71 (DREE 1969) on coastal erosion on the north shore of Prince Edward Island indicates that rock faced cliffs may retreat only a few centimetres per year, whereas coastlines with unconsolidated sediment may retreat several metres per year. In sheltered areas, such as estuaries or behind sand bars and spits, very little erosion can be detected (Daly 1976). In the past 25 years sediment accumulation in these areas has increased by 100 to 400 times (from less than 0.01 cm/year to greater than 4 cm/year) as a result of a combination of both natural and man-induced processes.

A detailed water and sediment sampling and monitoring program was initiated on May 1, 1972 and continued through May 30, 1977 in Summerside Harbour, Charlottetwon Harbour, Cardigan Bay and environs and Souris Harbour (Figs. 1, 2). This investigation represented a continuation of the 10-year reconnaissance and mapping program in the Atlantic coastal zone reported by Bartlett and Usher (1972a, b).

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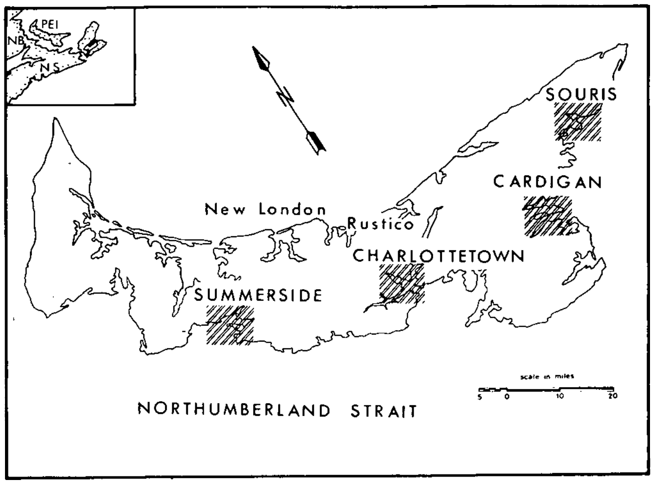


FIG. 1 An outline of Prince Edward Island showing the location of the coastal zone environments monitored during this investigation.

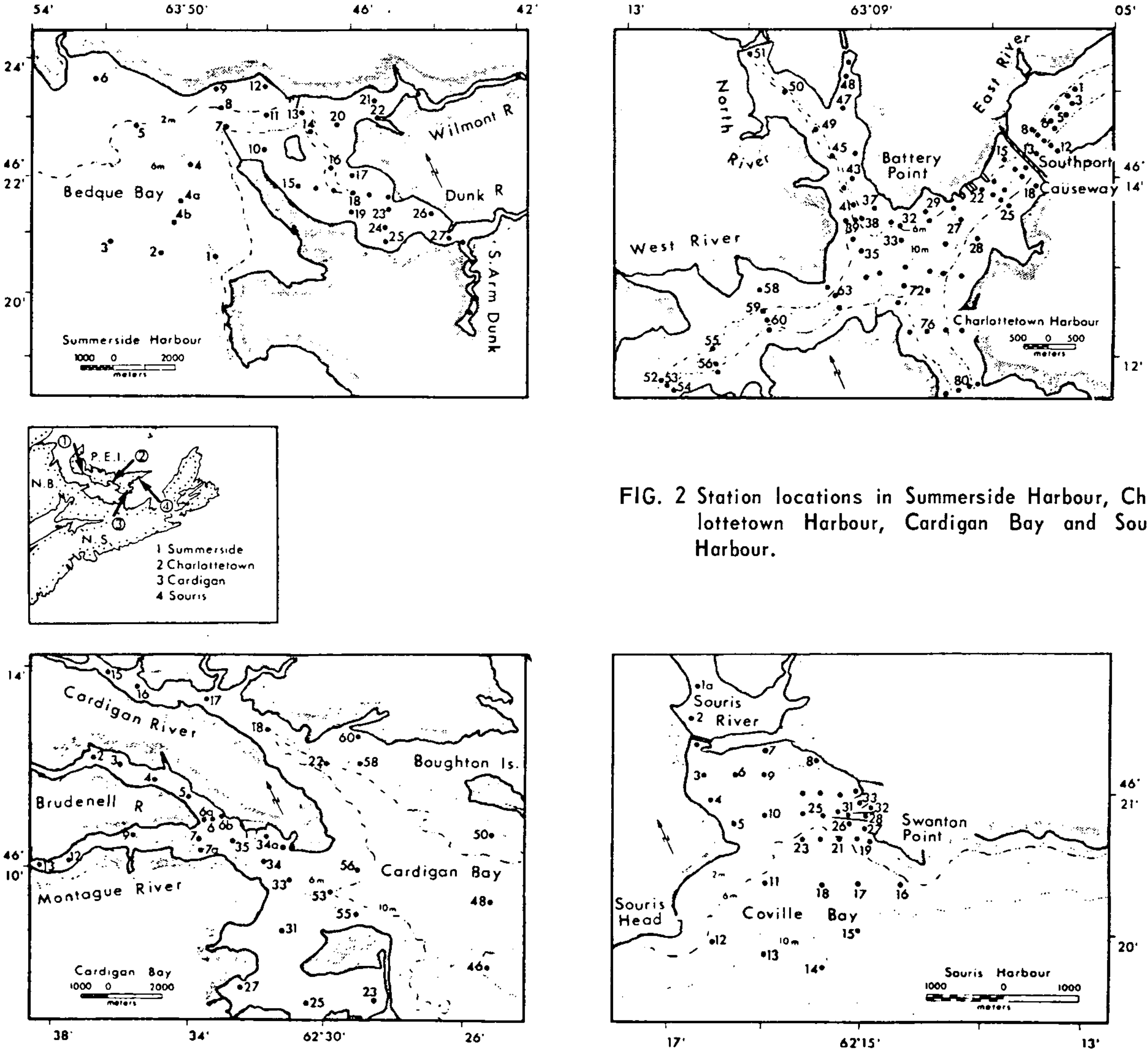


FIG. 2 Station locations in Summerside Harbour, Charlottetown Harbour, Cardigan Bay and Souris Harbour.

All stations when accessible were monitored at least once a month. Additional sampling was done approximately every 10 to 14 days at selected 'indicator' stations or on specific traverses. Numerous 24-hour stations were monitored in order to observe hourly changes in physical, chemical and biological entities. Most parameters show significant variations within these 24-hour periods, which suggests that extreme caution should be exercised if "instant in time" samples are used for environmental interpretation.

SAMPLING AND ANALYSIS

Field

Bottom sediment samples were stored wet in Nalgene 250 ml bottles and kept at approximately 4°C. A Benthos gravity corer (6.6 cm I.D.) and Phleger corer (3.5 cm I.D.) were used during the coring program and penetration of 100 to 200 cm was attained at most localities having silty clay substrates. Ekman-Birge Dredges (sample area approximately 230 cm^2) Dietz-LaFond (sample surface area 77 cm^2) bottom samplers and SCUBA diving techniques were used to obtain bottom sediments at the sediment-water interface. Sediments carried in suspension were collected with traps (lm x lm x 10 cm) and 6- or 12-litre horizontal Van Dorn bottles. Bottom sediment sampling techniques have previously been described by Sly (1969). Water samples were collected with one-litre Nansen, and 3- to 6-litre Van Dorn water bottles. Collections were obtained using standard sampling techniques. Beckman RS-5 and Y.S.I. conductivity metres were used to measure conductivity, salinity and temperature, and Metrohm or Orion pH, Eh and O_2 metres were used to measure pH, Eh and O_2 in the field. These measurements were considered to be the most readily recorded "in situ". Volume flow, current velocities and directions were measured with mechanical or electronic current metres and fluorescing dyes. Dispersal patterns or Rhodamine "B" were detected with a fluormeter. In addition dye and float migration were photographed from a helicopter and dispersal patterns were determined with a timed sequence of photographs.

Laboratory

The water and sediments were processed for the investigation of (1) various sediment parameters related to provenance, hydraulics and dispersal patterns (2) trace elements and (3) clay mineralogy. Sediments were sieved and pipetted for size analysis, and the organic carbon, calcium carbonate, sodium, magnesium, potassium, iron, copper, lead and heavy mineral content determined. Total carbon content was determined with a LECO (Laboratory Equipment Corporation) WR-12 Automatic Carbon Determinator. Replicate samples were treated with dilute hydrochloric acid to remove the carbonates, and run on the LECO to determine the organic carbon content.

At the laboratory, most samples were freeze-dried and stored at 4°C to await analysis. The preparation and grain size analysis of the sediments were performed according to the methods proposed by Royse (1970), utilizing dry sieving for the fraction coarser than 4 ø, followed by sedimentation for the fraction finer than 4 ø (in settling tubes at constant temperature). This enabled the separation of all sediment samples into whole-phi fractions. A micropore filter candle, described by Daly (1976) was used to separate the dissolved salts from the sediment-water mixture. The filter candle was successful in removing all liquid plus colloids from the sediment.

In some instances a simple size analysis to determine the sand/silt/clay ratio was performed. The F.A.S.T. (Fast Analyses of Sediment Texture) method (Rukavina and Duncan 1970) provides a rapid and precise method of determining this ratio. The precision of the F.A.S.T. method for our samples, using replicates is ± 2 to 5 percent.

Trace metal analyses (copper, lead, and zinc) were conducted using atomic absorption techniques (Instrumentation Laboratory Atomic Absorption Unit). Five millilitres of aqua regia (1.0 ml of nitric acid and 4.0 ml of hydrochloric acid) are added to a test tube containing 250 mgm of dried sample. The mixture is heated slowly until the contents evaporate to dryness (36 to 48 hours). Ten millilitres of 1.0 M hydrochloric acid are used to leach the material over low heat and the residue is allowed to settle overnight (12 to 14 hours). The solution is than aspirated directly into the flame. The detailed results of these analyses are described in a subsequent report.

Copper and lead analyses were determined for the suspended particulate matter (SPM). A vapour-phase oxidation technique was used to dissolve the SPM. Trace metal analyses were determined on a custom-built atomic absorption unit equipped with a Perkin Elmer HGA 2000 Flameless Atomizer. The method is described by Travers (1975). A detailed discussion of SPM in coastal zone environments in Atlantic Canada is given in a subsequent report.

Relative rates of sedimentation have been determined from sediment trap accumulation, graduated stakes and living/dead foraminiferal ratios. Carbon-14 dating of core samples has been used to determine sedimentation rates during the past 10,000 years.

PREVIOUS WORK

Information on physical characteristics and sediments of estuarine-lagoonal environments in the Atlantic Provinces is scarce. However, some estuaries have been discussed by the following: (1) St. Lawrence River Estuary (MacGregor 1956, Lauzier *et al* 1957, Farquharson 1963, Forrester 1964, Nota and Loring 1964, Loring and Nota 1966, and 1972, Conolly *et al* 1967, d'Anglejan 1969, d'Anglejan and Smith 1973, Costello 1970, Monahan 1971, Bartlett and Molinsky 1972); (2) Miramichi River Estuary (Bousfield 1955, Bartlett 1966; Herzer 1966, Tapley 1969); (3) Bideford River Estuary (Buckley 1969); (4) Riviere Bonaventure Estuary (Pirie 1965); (5) Charlottetown Harbour Estuary (Bartlett and Usher 1972a); (6) Summserside Harbour Estuary (Bartlett and Usher 1972b); (7) LaHave River Estuary (Cranston and Buckley 1972).

A thorough review and discussion of estuaries and estuarine processes may be found in Emery and Stevenson (1957), Lauff (1967), Schubel (1971) Barnes and Green (1972), and Bartlett and Usher (1972a, b). Discussions of sedimentation in coastal zone environments may be found in Van Stratten (1960), Folger (1962), Guilcher (1963), Pirie (1965), Ippen (1966), Bowden (1967), Postma (1967), Rusnak (1967), Schubel (1968, 1969, 1971, 1972), Meade (1969, 1972), Folger (1972), Nichols (1972), Bartlett (1973) and Daly (1976) to name only a few. Yalin (1972) has thoroughly discussed the mechanics of sediment transport and Myers and Quinn (1974) have described organic matter on clay minerals and marine sediments. This report, although presenting details of a specific 5-year study, contains information derived from both reconnaissance and detailed investigations into coastal zone processes in Atlantic Canada during the past 15 years. A detailed statistical account of coastal zone sediments in Prince Edward Island is in progress. Reports on the geochemistry of waters, SPM and bottom sediments, and the microfauna in the bottom sediments will appear as subsequent reports. The sedimentary parameters discussed in the following report show a distinct relationship to source material, geographic position (adjoining sewer outfalls, main channels or shallows, etc) and dynamics related to the currents resulting from river flow and the ebb and flow of the tide.

GEOLOGY: BEDROCK AND SURFICIAL DEPOSITS AS SOURCE MATERIAL

Summerside Harbour

The bedrock and surficial geology of the Malpeque-Summerside area was investigated during the present study and has been described recently by Prest (1972). He indicates that calcareous mudstone breccia is widespread. Conglomerates are composed of gravel-sized material that displays a great variety of shapes including numerous well rounded ovoid, discoid and spindle forms. These pebbles are composed of acid to intermediate, streaky banded to massive, porphyritic flowstones, with quartzite, quartz and a scattering of other rock types.

Glacio-fluvial and glacio-lacustrine deposits are uncommon in the Summerside region. Sand deposits along the Dunk River are considered to be valley-train deposits formed by meltwaters from the last ice remnants on the western flank of the central uplands.

The postglacial marine invasion of coastal parts of the Summerside region resulted in the formation of beaches, bars, spits and shallow-water beds that extend over a wide area. These deposits are generally composed of sand and are derived mainly from the local till mantle and the bedrock.

Charlottetown Harbour

The bedrock types in the Charlottetown area (Prest 1964), are sandstone, siltstone and claystone. Lenses of claystone breccia appear locally. Red in colour (because of the presence of a ferruginous cement), the strata are essentially flat lying. Exposures are limited in the study area to the narrows connecting Chrlottetown Harbour and Hillsborough Bay. The glacial deposits, which mantle the bedrock, vary in thickness from one foot to 25 feet (0.3 to 8m) and are subdivided into basal tills and ablation tills with ice-sloughed debris. These tills and ice-sloughed debris are distributed in patches throughout the draft mantle and occur mainly in the western regions of the study area.

The glacio-fluvial deposits vary from well sorted sand through gravels, to rather bouldery and poorly sorted materials. These are restricted to the banks of Hyde Creek (which drains from North River into West River) and to isolated areas near Roseband and Sea Trout Point.

Organic deposits (i.e. salt marsh or swamp deposits) were not found within the area sampled. However, mud deposits do occur in the eastern regions of the Hillsborough (East) River, near Bunbury.

Cardigan Bay

The geology of the Cardigan Bay area as outlined by Frankel (1966) was confirmed in the present investigation. Unit B (Frankel 1966) crops out sporadically in the Cardigan Bay area. Dominant rock types are conglomerates, conglomeratic sandstones, greywacke, lithic sandstones, arkose, feldspathic sandstones, siltstones, shales, claystones, and calcareous claystone breccias. The poorly indurated conflomgerate and sandstone beds readily disintegrate, especially when exposed to wave action. The age of Unit B is not definitely known but is assumed to be Permo-Carboniferous.

Quartz is the dominant mineral in the glacial deposits and in the bottom sediments of the harbour. Feldspar (orthoclase, microcline, and sodic plagioclase) is normally present in excess of 10 percent. Muscovite and biotite are the most common accessory minerals. Also present are ilmenite, leucoxene, apatite, amphibole, chlorite, magnetite and garnet. Ferruginous material is generally present as detrital fragments and as a cementing agent. Manganese oxide is usually present and manganese concentrations are variable (less than 0.05 ppm) throughout the harbour waters and bottom sediments.

The glacio-fluvial deposits (ice-contact, stratified drift) in the area are kames, kame terraces and valley-edge kames composed of well to poorly sorted sand and gravel, with local areas characterized by washed till. Well developed, discontinuous deposits occur along the Montague, Cardigan and Brudenell Rivers and provide most of the sediment available to the marine environment.

Souris Harbour

The Souris map area was described by Crowl (1969). According to Crowl (1969) the entire area was covered by ice during the Wisconsin glaciation. Thin till covers the uplands and thicker glacio-fluvial and alluvial deposits floor the valleys. Much of the area is forested, and abandoned framland is rapidly reverting to forest.

Conglomerate crops out along the north shore of Souris Harbour. The area is covered by glacial drift and is dominated by sandy till. Outwash and other glacio-fluvial deposits exhibiting little topographic form flank the Souris River above the causeway. Sandy shore deposits typify the causeway in marked contrast to the steep cliffs fronting the town of Souris. The drift is derived from local sandstones and mudstones, and is reddish. The glacio-fluvial deposits consist of sand with varying amounts of clay and silt.

Organic podsol soils are common in the area. Soil profiles are best developed in flat or gently sloping land where erosion is at a minimum and leaching predominates. In cultivated areas, such light soils are subject to serious erosion and are the major source of estuarine sediments.

Recent submergence in eastern Prince Edward Island, possibly due to eustatic rise of sea level, has been reported by Frankel and Crowl (1961). Peat and tree stumps approximately two metres below high tide level (one metre below low tide) were reported to be dated at 915 ±70 years B.P. Evidence of this submergence is widespread along the southeast coast of the Island. The submergence has played an important role in the development of beach ridges, spits and bars, and in the siltation of estuaries, in addition to contributing substantially to the development of "drowned river" and "bar built" estuaries throughout the region.

PHYSICAL AND CHEMICAL SETTING

Several estuarine-lagoonal environments in Prince Edward Island (Fig. 1) have been monitored on a diurnal, seasonal and annual basis. Diurnal changes are associated with tidal ebb and flow, and river and effluent flow. Distinct variations are recorded between the spring and late summer. During mid summer (July-August) and winter (December-February) with decreased runoff and negligible soil erosion, a stable environment develops. Over the years there has been a slight increase (0.01 to 1 ppm) in most nutrients and trace elements and a major increase (up to 4 cm/year) in siltation in populated areas (harbours) and regions with intensive cultivation or highway construction.

The estuary-lagoon environments of Prince Edward Island are drowned river valleys with the majority having sand and gravel baymouth bars associated with them. According to Dyer (1973) drowned river valleys (also referred to as costal plain estuaries) seldom have depths greater than 30 m. These environments deepen and widen in a seaward (lower estuary) direction. They also have a central channel which is commonly sinuous.

In the past, estuaries have been classified by using at least one of the following schemes:

1) Classification by mode of formation of the basin (e.g. drowned river valleys, fjords, bar-built estuaries etc.).

2) Classification by the dominant driving force in the system (e.g. wind, fluvial, marine).

3) Classification on the basis of the characteristic circulation pattern (salt wedge, partially mixed, vertically homogeneous and sectionally homogeneous).

The use of circulation patterns (Pritchard, 1967) has thus far emerged as the most consistent method of classifying these environments. The drowned river valley estuarine-lagoon complexes of Prince Edward Island have a wide variation in circulation patterns. However, there is a sequence of types ranging from a highly stratified salt-wedge estuary to a well mixed, vertically homogeneous type.

Generally, the incoming tidal seawater extends up the estuary at sea level. In fluvial dominated systems (e.g. Charlottetown, Cardigan) the fresh river water rides over the denser salt-water. This salt-water body is commonly referred to as the "salt-water wedge", and the estuaries in which this circulation pattern occurs are referred to as a "salt-wedge" estuary of a "Type A" using the scheme of Pritchard and Carter (1971).

If the tidal forces become stronger (or fluvial inflow decreases) and the interface between fresh-water and salt-water wedge is disrupted, mixing of the two water bodies occurs. This is a partially mixed "Type B" system, (Pritchard and Carter 1971). Due to the Coriolis effect, it is common for the flow of river water in the northern hemisphere to be more predominant on the right hand side of the estuary (looking seaward) whereas salt-water is dominant on the left.

A further increase in tidal forces causes the salt-water wedge to be disrupted to the extent that the estuary becomes vertically homogeneous with respect to salinity. The salinity is slightly higher (0.05 to 1.0 o/oo) on the left side (looking seaward) of the estuary. This is a "Type C" estuary (Pritchard and Carter 1971).

The end member in the circulation pattern classification is the sectionally homogenous or "Type D" estuary (Pritchard and Carter 1971). Here, the tidal forces completely dominate river flow and the water is sectionally homogeneous laterally and vertically with respect to salinity.

None of the Prince Edward Island estuaries were consistently one "type" during the period of investigation. Salt-wedge or Type A patterns predominate throughout during spring break-up (March-April) and in the upper estuary with salinities between 4.0 o/oo and 16.0 o/oo. During the remainder of the year partially mixed or Type B patterns were most common especially in mid and upper estuarine regions (salinities 10.0 o/ooto 25.0 o/oo). During this same period there was a gradual progression to a vertically homogeneous or Type C pattern in the lower estuary (salinities 25.0 o/oo to 32.0 o/oo). During periods of extremely low river flow or in the vicinity of restriction such as causeways, sectionally homogeneous or Type D circulation patterns occurred intermittently.

Suspended particulate matter, bed load and bottom sediment distribution patterns are directly related to the circulation pattern developed in each estuary. It is apparent therefore, that the sedimentation pattern is a transient feature that depends upon sediment supply, the season and the energy available from either the fluvial or marine watermass or a combination of both.

The Cardigan Estuary-Lagoon complex (Tables 1-3) covers the largest area; 75 km^2 and contains the largest volume of water 673,750 x 10^3 m^3), has moderate currents (slightly in excess of one knot) and has a predominantly medium to coarse sand-grain substrate.

The Summerside Estuary (Tables 1-3) is the second largest area (40 km^2) under discussion with a water volume of 190,000 x 10^3 m^3. The largest volume of water also occurs in the lower estuary (145,320 x 10^3 m^3) where current velocities range from 1 to 1.5 knots. The substrate in the lower estuary is dominantly sand. The estuaries of the Charlottetown system (Tables 1-3) occupy an area of 26 km^2, with a water volume of 206,300 x 10^3 m^3. The strongest current velocities are recorded in this system reaching 1.5 to 2.5 knots in the lower estuary. The largest volume of water is maintained in the upper estuarine environments of the three rivers which are collectively occupied by 133,500 x 10^3 m^3 of water. Substrates in these regions are predominantly fine sand, silt, silty-clay and clay.

The estuary of the Souris area (Tables 1-3) is very small (10 km^2) and contains only 74,360 x 10^3 m^3 of water. The lower estuary contains 64,250 x 10^3 m^3 of water and is characterized by a coarse-grained sand substrate. Fluvial influences are minimal in this area.

On the average, Summerside is the shallowest environment, averaging 5 m, whereas Charlottetown is the deepest, averaging 14 m.

According to Bartlett (1971, 1973) salinity ranges from 4.0 o/oo to 32.0 o/oo in the estuarine-lagoonal complexes investigated in Prince Edward Island. Maximum variations (Table 4) are recorded in the Upper estuary during the diurnal to semi-diurnal ebb and flow of the tides. Tides in the area are mixed, but mainly semi-diurnal, with a tidal range of approximately one m.

Penetration of marine water (salt-water wedge) upstream may vary from a few tens of metres diurnally to a few hundreds of metres seasonally. This movement is strongly influenced by river size, precipitation, rate of upland flow, watershed area, water depth, baymouth features and tidal cycle. Maximum penetration of the salt-water wedge occurs during mid-summer (July-August) and mid-winter (December-January), with minimum penetration in spring (March-April) and late-autumn (October-November).

In all systems the lateral and vertical variations in salinity are related primarily to the dynamics of tidal flow and fluxes in the fluvial systems. The concentration of suspended particulate matter (SPM) is directly related to salinity which is, in turn, a consequence of the dynamics of the various flow regimes operating in the system.

The total concentrations of suspended particulate matter and resultant turbidity decreases from approximately 180 mg/l in the upper regions of estuaries to less than 3 mg/l in the lower estuary-lagoonal complex. These concentrations are highest in all regions during March, April, May, October and November, and during periods when high rates of precipitation are coincident with cultivation or construction. Phytoplankton blooms in the late spring, and in early and late summer increase the organic component of the SPM by as much as 20 percent. Concentrations of suspended particulate material generally increase from the air-sea interface to the sediment-water interface. However, the lateral and vertical position of the salt-water wedge has an important affect on the concentration, dispersal and final deposition of the suspended material.

Suspended material from the near-bottom zone is dominantly resuspended inorganic sediment (clay- and silt-size material 4 Ø to 12 Ø) but, based on random Scanning Electron Microscope (SEM) analyses this suspended load also contains some associated organic and humic material, diatom frustules and broken micro-shells. Surface (0 to 2 m) and mid-water (2 to 5 m) suspended particulate material is predominantly composed of diatom frustules, plant debris and the test of micro-organisms. The surface layer may contain more than 80 percent organics and less than 20 percent inorganics whereas in the near-bottom layer the reverse in concentrations may occur.

TABLE I Physical characteristics of the four estuaries in order of decreasing volume

Estuary	Area (Km^2)	Volume (10^3 m^3)	Current Velocity (cm/sec)
Cardigan	75	673,750	12- 85
Charlottetown	26	206,300	15-150
Summerside	40	190,000	10-100
Souris	10	74,360	10- 60

TABLE 2 Volume of water in the major physiographic regions of each estuary

Estuary	Volume (10^3 m^3)		
	Lower	Middle	Upper
Cardigan	434,250	133,500	106,000
Charlottetown	32,800	40,000	133,500
Summerside	145,320	29,680	15,000
Souris	64,250	9,840	250

TABLE 3. Area of each physiographic region in order of decreasing magnitude

Estuary	Area (km^2)			
	Lower (Depth m)	Middle (Depth m)	Upper (Depth m)	Average (Depth m)
Cardigan	36 (16-20)	14 (6 -12)	25 (0.5-6)	8
Summerside	24 (1- 9)	6 (-.5-10)	10 (0.5-5)	5
Charlottetown	2 (8-27)	4 (7 -18)	20 (0.5-19)	14
Souris	6 (6-20)	3 (1 - 6)	1 (<1)	10

TABLE 4. Seasonal ranges in salinity (o/oo) in estuarine-lagoonal complexes

	WINTER	SPRING	SUMMER	AUTUMN
Top	7.50 - 28.28	7.21 - 28.08	17.42 - 28.76	12.53 - 28.64
Bottom	8.16 - 29.76	7.52 - 29.70	25.66 - 30.93	16.25 - 28.75
Average Top	24.10	23.97	26.90	26.14
Average Bottom	25.92	25.84	29.00	26.90

TABLE 5. Variations in salinity (o/oo) with depth and from the upper to lower estuary: West River-Charlottetown estuarine complex

Depth (m)	STATION							
	53		56		60		63	
	Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood
0	11.17	16.10	18.42	20.16	24.10	26.94	26.12	28.04
1	12.45	16.72	18.67	21.30	24.12	27.10	26.35	28.32
2			19.25	22.24	25.16	27.44	26.52	28.45
5			21.73	22.94	26.34	29.15	27.14	29.20
8					27.40	29.70	27.90	29.87
10					28.47	29.84	28.50	30.16

TABLE 6. Seasonal ranges in temperature (^{o}C) in estuarine lagoonal complexes

	WINTER	SPRING	SUMMER	AUTUMN
Top	-1.32-4.60	6.54-14.64	16.11-26.78	16.83-20.34
Bottom	2.84-5.30	5.30-11.20	16.01-24.86	16.58-21.61
Average Top	4.00	9.69	19.50	18.37
Average Bottom	4.50	8.45	18.00	17.75

Temperature variations are most significant on a seasonal basis (Table 6). Temperatures range from -1.32°C in January and February to 26°C in late July and early August. The ebb and flow of the tide has the greatest effect in altering temperatures during the summer months. Throughout the study area surface waters have more variable temperatures than do bottom waters. Bottom water at depths less than 5 m may undergo diurnal variations of 5°C, whereas bottom waters greater than 10 m deep seldom have a diurnal variation of more than 2°C.

The hydrogen-ion concentration (pH) ranges from 8.2 to 7.2, and everywhere the surface water has a higher value than the bottom water directly below. The values are consistently higher in open bays and outer lagoons than in estuaries. Lowest values are recorded near the head waters of these environments. A shallow "life zone" of 1 cm to 10 cm in depth exists at the sediment-water interface. Here the sediments are well oxygenated, have positive Eh and high pH values, and generally support prolific microfaunas and macrofaunas. Below this zone the pH values of interstitial waters and bottom sediments seldom exceed 7.2 and values as low as 5.6 have been recorded. Methane and hydrogen-sulfide are emitted from sediments with low pH values.

The oxidation-reduction potential (Eh) - a measure of the oxidizing or reducing qualities of the medium - has been consistently positive in bar-built and drowned-river estuaries, ranging between +125 to +475 m.v. Oxygen readings are consistently between 7 and 10 ml/l in areas less than 25 m in depth. No evidence has been found to indicate stagnant conditions in either the watermass or the sediments at the sediment-water interface at any locality. It is apparent, therefore, that atmospheric exchange, shallow water depths (less than 25 m) and the flushing due to river flow and tidal circulation provide adequate aeration in the watermasses and bottom sediments of all the marginal marine environments of Prince Edward Island.

Waters in the estuarine-lagoonal complexes of Prince Edward Island range in depth from >1.0 m to greater than 25 m. These estuaries are partially or completely covered by ice during at least one to four months of the year. Water depth and ice cover directly and indirectly affect all of the physical, chemical and biological processes in the estuarine environment.

CIRCULATION

The most widely accepted definition of an estuary is that of Pritchard (1967) which is: "An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which seawater is measurably diluted with freshwater derived from land drainage."

As pointed out by Bowden (1967) the normal estuarine circulation may be taken to be that which is determined solely by the fresh-water inflow and the mixing with sea-water, as influenced by tidal currents. However, numerous studies have shown that the wind, especially in shallow estuaries, can have an important influence on circulation and mixing. The stress exerted on the surface can generate waves which increase turbulence and therefore the degree of vertical mixing, and can produce a net transport of water in the direction of the wind. Normal seaward flow is increased if the wind is blowing down-estuary, and decreased or even reversed in direction if the wind is up-estuary. Consequently, compensating currents will develop in deeper layers and cause increased mixing. Changes in the salinity structure will alter normal stratification patterns and resultant sedimentation.

CURRENT CHARACTERISTICS

The current flow velocities in several estuarine-lagoon systems were measured intermittently with mechanical and electrical flow metres, and patterns were mapped using fluorescent dyes and floats. Velocity and direction were commonly measured at the surface, at the salt-fresh water interface, and immediately (15 cm) above the sediment-water interface. Current measurements were also taken vertically at 1-m intervals during 24-hour monitoring programs. Dye and float dispersal patterns were photographed from a helicopter, using a 35 mm Pentax or Leicaflex SL camera and Fujichrome film with an ASA of 100 or Kodachrome 64, with an ASA of 64.

Current velocity readings through a complete tidal cycle at selected stations generally agree with short-term readings at those stations. However, these current velocities vary widely between and within each of the various types of estuarine under investigation. Cardigan Bay estuary (Fig. 3) is used as an example.

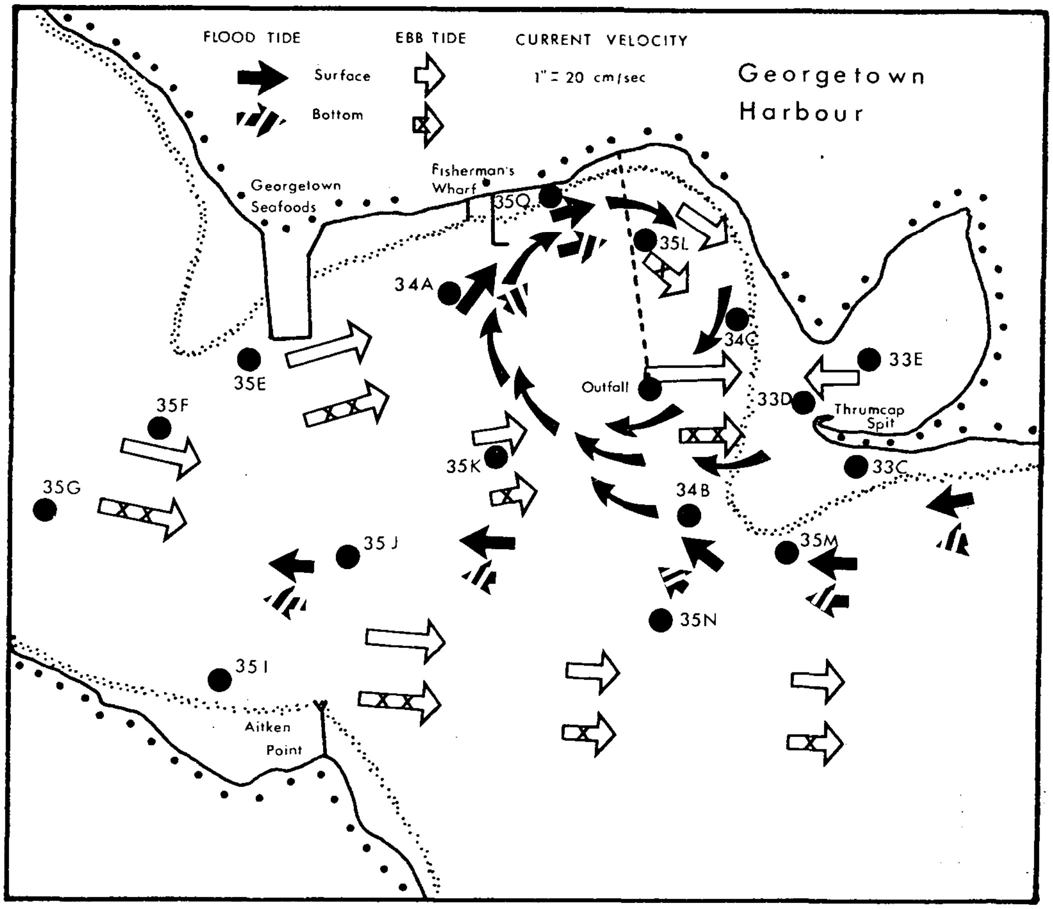


FIG. 3 Flow patterns and current velocities during flood and ebb tides in Georgetown Harbour at the mouth of the Cardigan Bay estuary. Note the clockwide gyre adjoining Thrumcap Spit and the main harbour during flood tide. Sewage and sediments are dispersed by the currents associated with this gyre.

Current velocities during flood tide range from 10 cm/s to 25 cm/s in surface waters and from 12 cm/s to 25 cm/s in bottom waters (3 to 15 m in depth). At every station the surface current is comparable to, or slightly greater than the bottom current. At intermediate depths (3 to 5 m below the surface) the currents may be greater or less than at the surface. The currents at the intermediate depths are commonly associated with salinity differences related to two-layer circulation. The net volume transport during flood tide is towards the harbour in a north-northeasterly direction. An intermittent clockwise gyre was noted in the region of stations 34A, 35K and 35Q, with a resultant two-dimensional pluming effect at the sewer outfall. Flood currents sweep around Thrumcap Shoal and deposit sediments derived from a seaward direction in this region. Sediments dumped here during a dredging operation were immediately transported along the spit. Those that were not deposited on the shoals were transported back into the harbour.

Current velocities in surface waters during ebb tide range from 12 cm/s (Station 35J) near the right bank of the main channel to 30 cm/s (Station 34C), whereas bottom velocities range from 18 cm/s at a depth of 8 m (Station 33B) immediately outside Thrumcap Spit to more than 60 cm/s at a depth of 12 m (Station 35J). Maximum velocities would be expected in this region during ebb tide because of basin configuration and the effects of the Coriolis force. Velocities are uniform from the surface to the bottom (10 cm/s) at Station 35C and at other more shoreward and up-river stations used in the study. The greatest change from top to bottom was recorded at the most westerly station (35J) where the surface velocity was 12 cm/s and bottom velocity was 60 cm/s.

Currents associated with the ebb tide flow in an east-southeasterly direction, toward Cardigan Bay. In the inner harbour, adjoining the outfall and at Station 34C, the main current trends are along shore, southeast to south, and northeast, with a "piling up" inside Thrumcap Spit. This movement entraps river-borne sediment, harbour refuse and sewer effluent in the small inlet and salt marsh formed originally as a result of the development of Thrumcap Spit.

The dispersion patterns of Rhodamine B dye (Fig. 3) substantiate the current metre readings. Two-dimensional flow is generally associated with the sewer outfall because of initial vertical dispersal, whereas horizontal flow depends on the state of

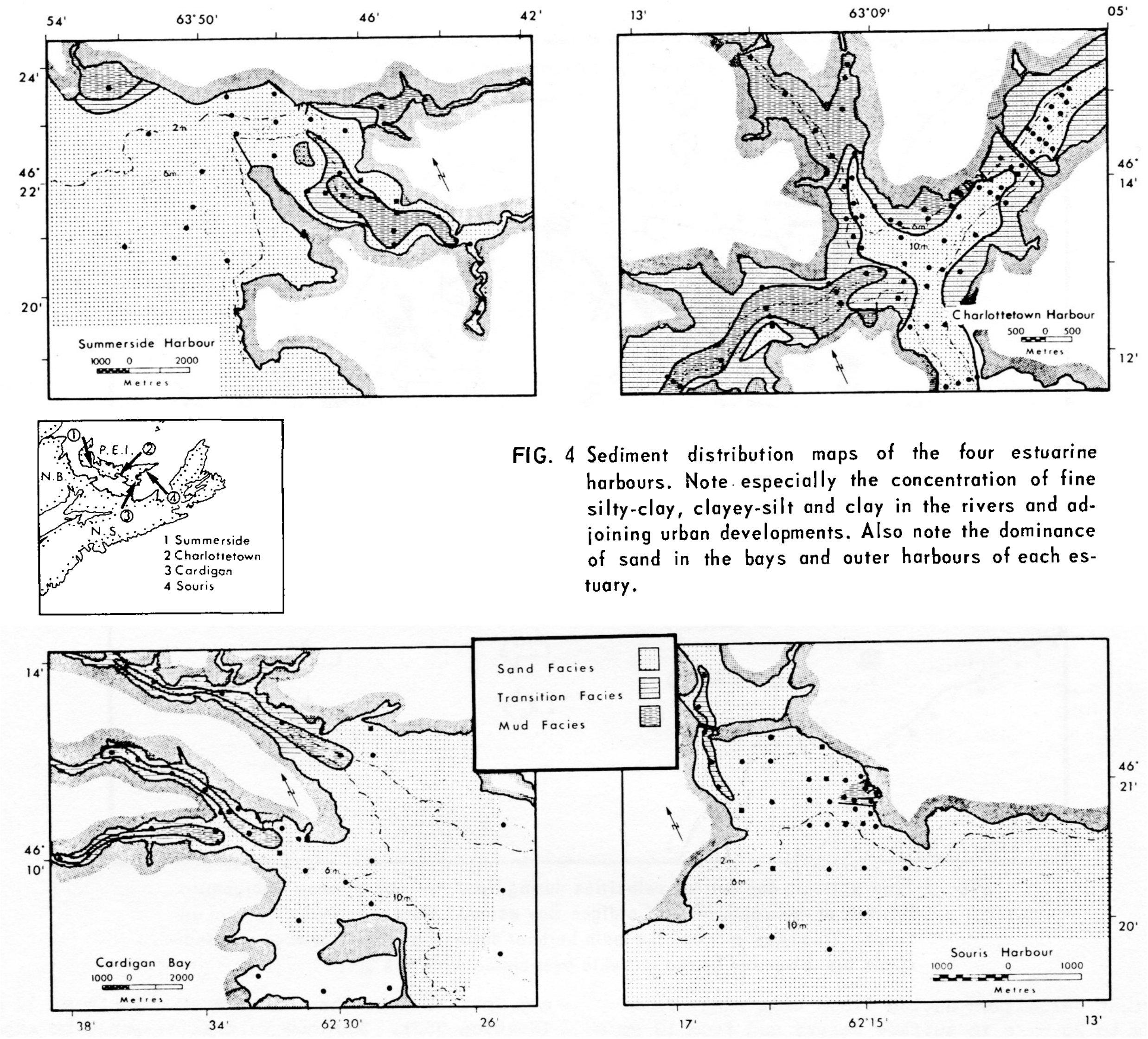


FIG. 4 Sediment distribution maps of the four estuarine harbours. Note especially the concentration of fine silty-clay, clayey-silt and clay in the rivers and adjoining urban developments. Also note the dominance of sand in the bays and outer harbours of each estuary.

ebb or flood tide. Initially, dispersion is relatively slow, although completed within 45 minutes. Is is believed that a net non-tidal circulation pattern is superimposed on the tidal currents. This is characterized by a seaward flow in the upper layers (above 4 m) and a reverse flow below this level. In order to preserve continuity salt water, which flows into the fluvial system in the deeper layers, must be partially returned seaward in the upper layers. Consequently, there must be a net vertical flow directed upward. This flow, which is believed to be quite small in this area, has not yet been determined and requires further study.

The surface of no-net motion varies in depth across the estuary and is deeper on the western side than on the eastern side. Therefore the layer of net seaward drift extends to the greatest depths on the western side of the estuary, while layers with a net flow upstream are nearest the surface on the eastern (harbour) side of the estuary. This has an important bearing on fish migration, the necessity and disposition of dredging operations and the distribution of river- and marine-borne sediments and sewage within the estuary.

The limit of salt intrusion (and of sediment dispersal seawards) moves upstream and downstream in response to changes in both river flow and tidal penetration. Suspended material which descends from the surface layers into the lower layers is returned upstream several tens, or even several hundred metres and commonly accumulates there rather than downstream or seaward from the original landward source.

There are at least four distinct activities in the coastal zone of Prince Edward Island that affect estuarine-lagoonal dynamics and the resultant sedimentation patterns. These are:

(1) The construction of dams and causeways that control and (or) modify the freshwater inflow into the marine environment.

(2) Dredging in channels and harbours with subsequent dumping in or adjoining the main "in harbour" circulation regime, causing the development of extensive shoals.

(3) Industrial, municipal and agricultural use of those environments for waste disposal.

(4) Harbour infilling and land reclamation.

SEDIMENTS

The sediment input to an estuarine-lagoon system is a result of internal (biological), external (marine and fluvial), and (or) marginal (shore erosion) activities. The exact extent and quantity of sediment supplied by each activity is not yet definitely known, but in all environments under investigation, sedimentation is a function of all three variables with fluvial processes contributing over 75 percent of the total volume (Fig. 4).

Baymouth barriers at Summerside and Cardigan are built from material originating along shore and from the adjacent offshore bottom. Most commonly, this material is sand size or coarser. It is apparent from Kranck's (1971) study that sediments adjacent to Bedeque Bay are dominantly Buctouche Sand and Gravel. However, at the harbour entrance Pugwash Mud (muddy sand with 50 percent to 95 percent sand) is common. The fine-grained sediment is evidently derived from coastal erosion and the Dunk and Wilmot Rivers, which empty into the harbour. Hillsborough Bay is also bordered by Buctouche Sand and Pugwash Mud. Here, the sandy mud only contains 5 to 50 percent sand. Cardigan Bay and Colville Bay are also bordered by a narrow (1 to 4 km) band of Buctouche Sand and Gravel with Pugwash Mud lying seaward beyond the nearshore zone.

Despite the net up-stream (landward) flow of the salt-water layer, transport of sediment to any degree landward only occurs if a suitable supply of fine sediment is available.

Upland discharge (i.e. fluvial origin) is usually the prime source of fine-grained sediment in the estuaries of Prince Edward Island (particularly in the upper reaches). The amount of fluvially contributed material, representing at least 75 percent of the total, in the four estuarine harbours, depends on:

(1) Flow of the river - temporal variations in the flow rate e.g. spring breakup results in sudden influxes of runoff material into the estuary with reworking and resuspension of previously deposited sediments.

(2) Geology of the drainage basin - unconsolidated glacial overburden and semiconsolidated Permo-Carboniferous sandstone and conglomerates are easily eroded by runoff and added to the river.

(3) Climate of the drainage basin - persistent and intermittent high rates of rainfall result in increased discharge with large volumes of sediment.

(4) Man's activities - erosion of land in the drainage basin cleared for agricultural or construction purposes has tremendously increased (100 to 400 times) runoff loads. The construction of bridges, causeways, or wharves results in both restricted and increased current velocities, thereby inducing sedimentation and shoaling and (or) erosion.

SEDIMENT CLASSIFICATION

The classification of sediment particle diameters used in the following discussion is based on the convention shown in Table 7.

TABLE 7 Textural classification of sediment particles*

Particle Type	Diameter (mm)	Diameter (Ø)
Gravel	>2.00	<-1.0
Very Coarse Sand	2.00 to 1.00	-1.0 to 0.0
Coarse Sand	1.00 to 0.50	0.0 to 1.0
Medium Sand	0.50 to 0.25	1.0 to 2.0
Fine Sand	0.25 to 0.125	2.0 to 3.0
Very Fine Sand	0.125 to 0.062	3.0 to 4.0
Coarse Silt	0.062 to 0.031	4.0 to 5.0
Medium Silt	0.031 to 0.016	5.0 to 6.0
Fine Silt	0.016 to 0.008	6.0 to 7.0
Very Fine Silt	0.008 to 0.004	7.0 to 8.0
Coarse Clay	0.004 to 0.002	8.0 to 9.0
Medium Clay	0.002 to 0.001	9.0 to 10.0
Fine Clay	<0.001	>10.0

*The phi class weight percentages are available from the author.

Visual examination of the entire grain-size distributions was accomplished by plotting the cumulative frequency percentages against the corresponding phi sizes on arithmetic probability paper (Krumbein 1938). The resulting plots were used to determine the significant percentiles, which were then used to calculate median, mean, sorting, skewness and kurtosis.

A factor analysis was performed on the total grain-size data and will be presented in a subsequent report. Details of the mathematical computations involved in derived factorial solutions are given by Harman (1967) and Cattell (1965). The rationale behind, and the basic computations of factorial methods are supplied by Klovan (1975).

The ternary diagram is one of the most commonly employed methods of representing grain-size data in both modern and ancient sediments. The percentages of sand, silt and clay are the most common end-members used. This approach is taken in the present investigation because these plots are efficient in relating gross textural information especially for engineering or comparative purposes (Link 1966). Consequently, ternary plots can be routinely used to classify lacustrine, fluviatile, marine and terrestrial sediments. The textural data from this study are plotted on the classification diagram (Fig. 5) proposed by Shepard (1954).

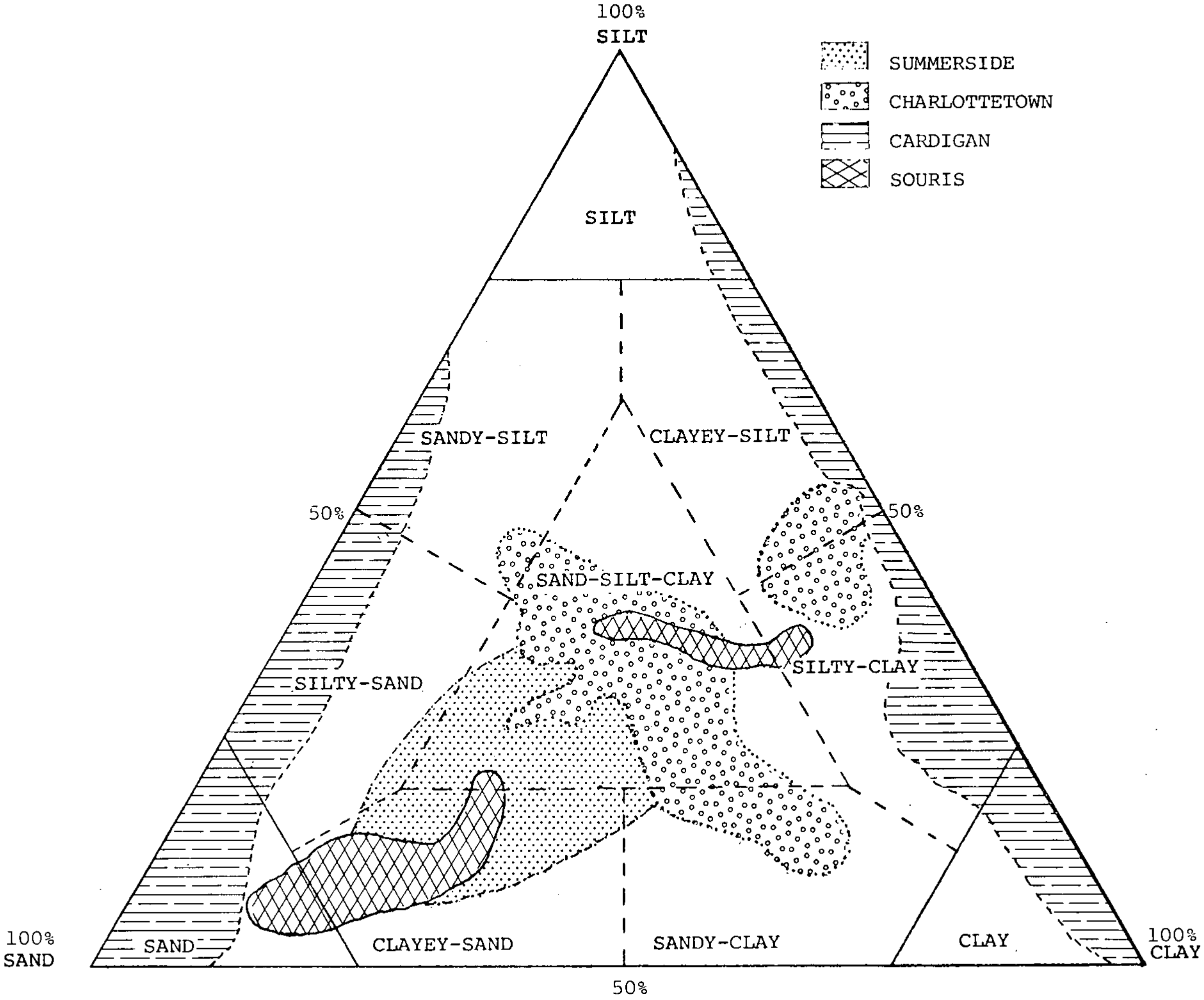


FIG. 5 A composite ternary plot of the sediment distribution in each estuarine harbour. Note especially the "sediment specific" nature of each estuary. A bias towards finer-grained sediments with higher organic matter content results from the present location of monitoring stations near suspected environmentally deterioriating environments "hot spots" adjoining wharves and outfalls in all harbours

ESTUARINE HARBOURS

Summerside Harbour

SEDIMENT DISTRIBUTION. In the late spring to early summer, Summerside Harbour sediments (Figs. 4 and 6) show a considerable increase in the percentage of silt and clay as a result of decreased turbulence and an influx of finer particles from river sources. Also, construction adjoining the harbour and the periodic breakthrough of dams in the watershed are thought to be principal causes of the recent increase of fine fractions in the bottom sediment and in suspension. Sand-sized material appears to be consistently derived from the surrounding bedrock, glacial overburden and the Buctouche Sand in the adjoining Northumberland Strait.

The high siltation rates (10 cm) during the winter and early spring of 1972 were a result of the breakthrough of the dam at Scales Pond. The increased sedimentation directly contributed to the demise of the oyster population in Dunk River. The oyster industry in Summerside (in particular, Dunk River) continuously suffers from detrimental man-induced influences as a result of rapid changes in the physical environment.

The most obvious change in sediment distribution is the introduction of finer fractions into the environment immediately following spring freshets. As the summer progresses more fines accumulate, principally in channels and basins in the harbour bottom (Stations 1A, 18A, and 26). This influx of fine material into the sediment might be expected, because maximum turbidity of the harbour waters occurs from spring thaw (March and April) until mid-June (Bartlett and Usher 1972b). After June, when the watermasses stabilize, fine particles settle more readily and begin to appear more abundantly in the samples.

Figure 6 illustrates the distribution of sediment types on a generalized classification of sand, transition and mud facies, the latter being concentrated in basins and channels, with some prominence in somewhat restricted areas of the harbour (e.g. Stations 21 and 22). This composite map has been compiled using five years of data from the July to August sampling period because this period represents the interval which is characterized by the most stable facies distribution.

The majority of the harbour approaches and most of the inner harbour (mainly along the shoreline) consist of a sand substrate. The mud facies, as mentioned earlier, is concentrated along the channels of the harbour (e.g. Stations 16, 18, 24 and 26) in basins and in restricted areas (Stations 6, 21 and 22). The transition facies, consisting of silty sand, occupies the majority of the sediment surface area of the inner harbour. Sediments are consistently 5YR 3/4 to 5YR 4/4 on the G.S.A. Munsell colour chart.

The river samples (salinities less than 4 o/oo) exhibit a singularly uniform sediment facies consisting of sand to silty sand. However, these data do not represent bottom sediments accurately in regions where the river is wide and (or) deep at the point of sampling. River sediment samples were collected by hand, and hence the stations chosen were dependent upon sample accessibility. Samples were commonly collected from the margin of the river channel, and thus may not be representative of the central channel sediments. This discrepancy is particularly relevant at the following stations: South Arm 3B, 4, 5A and 6; Dunk River 6, 12, 15, 17, 18, 19B and 20; Wilmot River 8 and 9. Because the effect of this discrepancy is a substitution, in many cases, of silty sand when the channel sediment might consist of boulders, undue emphasis on the classification and statistical examination of the river stations is avoided.

RATE OF SEDIMENTATION. The relative rate of sedimentation in Summerside Harbour ranges from less than 0.01 cm to 0.89 cm/year. The average rate of sedimentation is 0.28 cm/year. The highest average rate of sedimentation (0.37 cm/year) occurs during spring and autumn whereas the lowest average rate (0.14 cm/year) occurs during mid-summer. Areas of greatest sediment accumulation include the inner harbour, Stations 12, 13 and 14, and the Dunk River Stations 15 through 19 and Stations 24 and 25. Accumulations of fine silt and clay in both Dunk River and Wilmot River have induced shallowing and covered several oyster beds. The prolific growth of algae and seaweed is actively trapping sediment in all regions less than two metres deep.

On a seasonal basis, fluctuating conditions, because of the spring breakup of ice, exist during March and April with greatest sediment deposition occurring in the main channel toward Bedeque Bay, Stations 4 through 7, and in Dunk River, Stations 14 through 18. A much more uniform sedimentation pattern develops during mid to late summer with greatest accumulations occurring in Dunk and Wilmot Rivers. Fine silt and clay are typically deposited during this period. Increased precipitation during the autumn in conjunction with harvesting and ploughing results in significantly higher rates of sedimentation. For example, an area with accumulations of less than 0.01 cm/month during the summer may increase to 0.40 to 0.75 cm/month during autumn. Sediments are reworked but accumulations are commonly reduced to less than 0.01 cm/month throughout winter freeze-up.

Charlottetown Harbour

SEDIMENT DISTRIBUTION. The Charlottetown Harbour bottom sediments (Figs. 4 and 7) range from fine silty clay to coarse sand and gravel, and do not differ markedly in character from those recorded during previous sampling programs. Sand is dominant in the main channel of the Hillsborough River except in an area immediately downstream from the Charlottetown-Southport Causeway. Silt and clay are dominant in both North and West Rivers. Transitional sediments consisting almost entirely of silt to silty fine-grained sand flank all main channels and much of the waterfront area, and represent unstable conditions of sedimentation. The sediments are consistently 5YR 3/4 to 5YR 4/4 on the G.S.A. Munsell colour chart.

The sediments in the harbour are derived from both land and marine sources. The land contributes surficial sedimentary material naturally and in increased amounts due to deforestation, construction and cultivation. Sediments from Hillsborough Bay are contributed during flood tides and onshore storm conditions. Suspended material is consistently present in Charlottetown Harbour. The maximum suspended load, consisting of both organic and inorganic material, is present during spring break-up, during and after heavy rains, and during periods of turbulence caused by wind and tidal action. Penetration of marine sands into the estuary is principally due to transport within the salt-water wedge. This load is thought to be a minor contributor in the main harbour because of the strong scouring currents (1.5 to 2.5 knots) during ebb tide. The suspended particulate material is transported by both flood and ebb tides; it is deposited and eroded many times before settling permanently. Although the problem of the source of this sediment is often very complex it is mainly fluvially derived and inorganic in content.

Sediment characteristics at a few stations changed markedly from month to month. The major change in the sedimentary environment occurs from May to June. This is a result of redistribution of the sediments introduced during spring break-up. Over 75 percent of all fluvially derived sediments are contributed to the estuary during this 10- to 14-day period in March and April. The main physical process during the remainder of the year is redistribution. Only 10 to 25 percent of these fluvially derived sediments escape the estuary; moreover, less than 10 to 25 percent of estuarine sediments are derived from marine sources. Stability at the sediment-water interface during July and August may be attributed to decreased erosion and runoff, and to soil holdfast due to growth of cultivated crops.

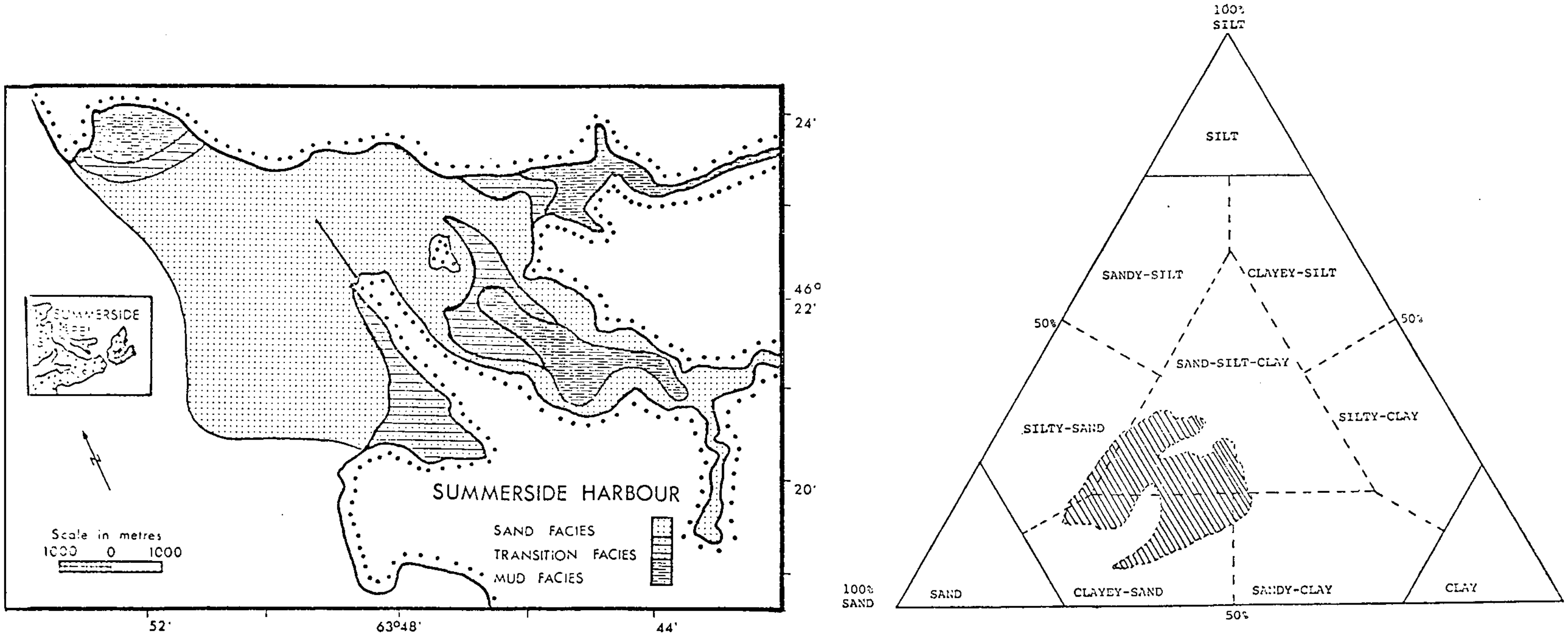


FIG. 6 Ternary plot and lateral distribution map of sediments in Summerside Harbour. Note the dominance of sand in the transition facies being reflected in the ternary diagram.

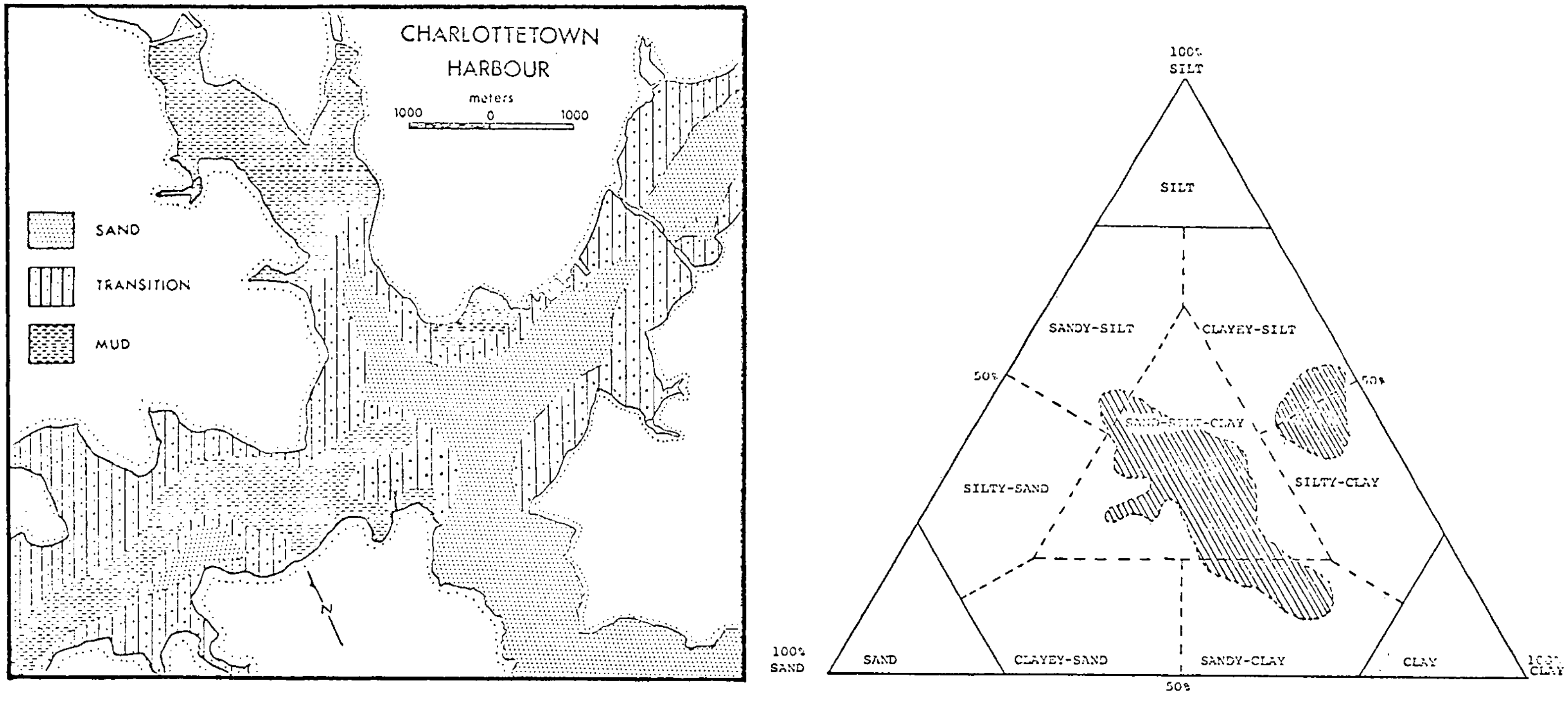


FIG. 7 Ternary plot and lateral distribution map of sediments in the Charlottetown Harbour estuaries. Fine grained silt and clay (mud) are common in North and West Rivers and adjoining areas with urban development.

RATE OF SEDIMENTATION. The relative rate of sedimentation in Charlottetown Harbour ranges from 0.12 cm to 0.94 cm/year. The average rate of sedimentation is 0.39 cm/year. Areas of greatest sediment accumulation include the inner harbour, Stations 15 to 30, in particular, Stations 15, 22, 26, 29, 30 and North River, especially in regions approaching Stations 38 through 45 and 51. Fine silt and clay in the upper reaches of North River have induced shallowing and the prolific growth of algae and seaweed which, in turn, are actively trapping sediment and forming a natural environment that is undergoing rapid stagnation. In West River, Stations 59, 60, 63, 65 and 66 are receiving sediments most rapidly. However, average sedimentation rates of less than .20 cm/year exist in this region.

On a seasonal basis, fluctuating conditions exist during the spring with isolated, increased deposition at Stations 15 through 20, 24, 25, 28, 35, 39, 42, 43, 58, 59 and 60. Approximately 15 to 25 percent of the estuarine material is being contributed to Hillsborough Bay. During late spring and early summer, increased sedimentation takes place immediately inside the North River Causeway at Stations 50 and 51, above the Charlottetown-Southport Causeway at Stations 3 through 12; at Stations 25 and 28 in the transition facies and immediately seaward from the waterfront at Stations 26, 29, 30 and 32.

A much more uniform sedimentation pattern develops during middle to late summer with greatest accumulation in the area represented by the intersection of the three main tributaries, e.g. Stations 34, 72 and 63. Significantly higher accumulations of fine sediment were recorded in North River from Station 45 to the North River Causeway and in West River at Stations 52, 53 and 54; duplicating the general trends recognized during all sampling periods.

Increased accumulations of sediment were recorded during late summer, early autumn, adjoining the Charlottetown-Southport Causeway and in North River, especially adjoining the causeway. Major changes were also noted in the mud facies in West River (Stations 59, 60, 63, 65, 66 and 71), and the transition facies of the inner harbour (Stations 18, 25, 28 and 70). Excluding the availability and supply of source material and watermass stratification the main reasons for increased siltation in Charlottetown Harbour and environs are the presence of the causeways, wharves, thermal and sewage effluents, algae and seaweed.

There is a distinct change in mineral composition from the upper reaches of all tributaries towards Hillsborough Bay. This change may result from diagenetic modifications (transformation of clay minerals) because of the transition from fresh to salt water. However, the change may also be due to differential settling, perhaps assisted by differential flocculation and agglomeration, and to a change in the source which may alternate between fluvial and marine. The edge of the salt-water wedge forms the boundary between various deposits such as the transition and mud facies. However, the wedge moves with the ebb and flow of the tide and it is unlikely that sharp sedimentary boundaries will be developed for a long period (see Fig. 4).

Cardigan Bay

SEDIMENT DISTRIBUTION. Sediments in the Cardgian Bay estuary (Fig. 8) are also derived from external, marginal and internal sources. They are contributed by natural and man-induced shore erosion, dredging and dumping practices, biological activity, tributaries and the substrate in the adjoining Northumberland Strait.

Sediments range from fine-grained silty clay (sand 1%, silt 37%, clay 62%) to coarse-grained sand and gravel (sand 80% to 100%). The colour is consistently 5YR 3/4 to 5YR 4/4 on the G.S.A. Munsell colour chart and is a reflection of the nearby source rocks. Sediments at every station contain dead grass and worm tubes. All substrates are reduced and emit hydrogen sulphide or methane from layers 0.5 to 2.0 cm below the oxidized sediment-water interface. Channel deposits vary from silty clay to silty sand and sandy silt. Nearshore and intertidal deposits are composed of silty clay, silty sand, sand and gravel.

RATE OF SEDIMENTATION. The rate of sediment accumulation in the entire estuarine complex (except during periods of dredging) ranges from 0.03 cm/year (Station 15) to 0.95 cm/year (Station 3). The average rate of sedimentation is 0.39 cm/year. The "natural" rate of sedimentation, based on Carbon-14 analysis of sediment cores in Cardigan Bay has been 0.05 cm/year. A combination of natural and man-induced processes has apparently increased the rates of accumulation by approximately 10 times.

Souris Harbour

SEDIMENT DISTRIBUTION. The sediments in Souris Harbour (Fig. 9) range from silty clay to coarse sand and gravel. However, fine silt and clay sediments are concentrated in the main wharf areas, whereas fine- to medium-grained sand is dominant in Souris River and Colville Bay. Bedrock, gravel and boulders underlie the nearshore area djoining Souris Head. Whole and broken mollusc shells are present in most sediment samples.

The area extending from Swanton Point to Souris Head is underlain by fine to medium, quartz and feldspar sand, with abundant mica, scattered pebbles, cobbles, worm tubes and whole and broken shells. The sediments throughout the harbour are commonly reduced at levels of 1 cm to 5 cm below the sediment-water interface, except in the main wharf area. Here the sediments and overlying waters are commonly anaerobic and H_2S-emitting. The sediments in Souris River, Causeway Beach and Colville Bay are consistently 5YR 4/4 on the G.S.A. Munsell colour chart. Inside the main wharf area the sediments are black (N1 on the G.S.A. Munsell colour chart).

RATES OF SEDIMENTATION. The relative rates of sedimentation vary from 0.12 cm/year (Station 32) to 0.85 cm/year (Station 23). The average rate of sediment accumulation for the entire estuarine

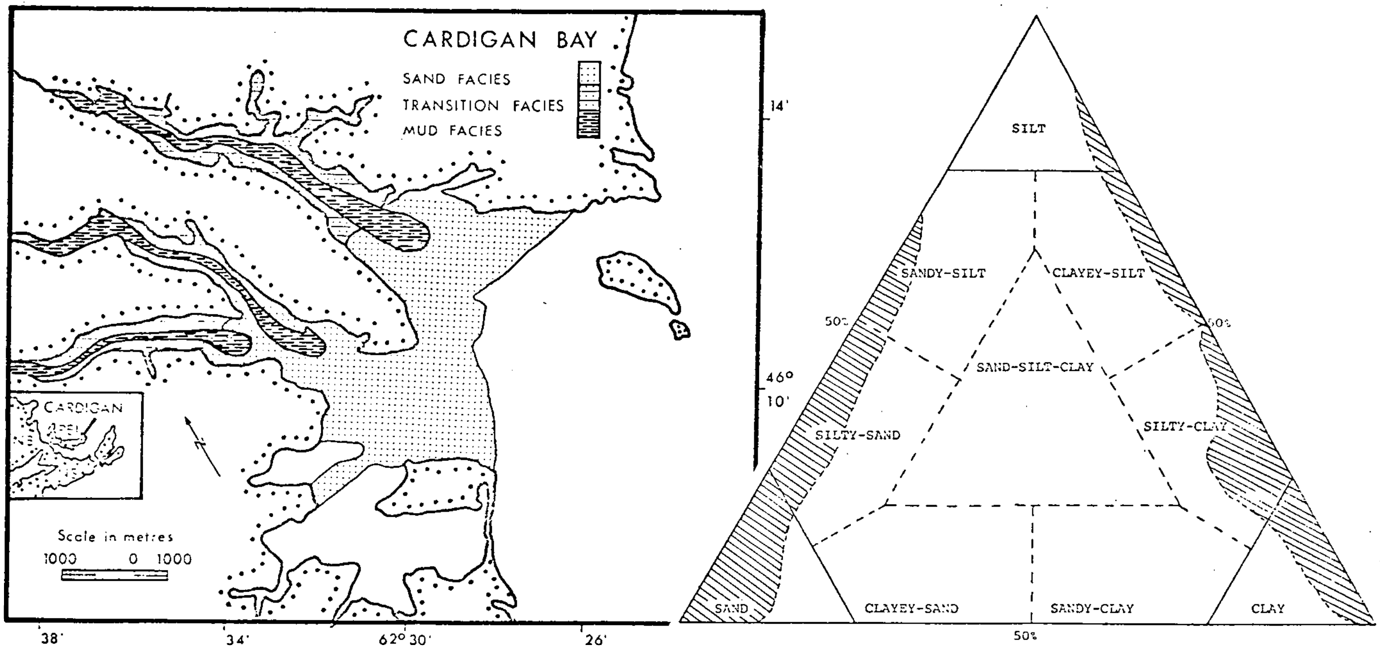
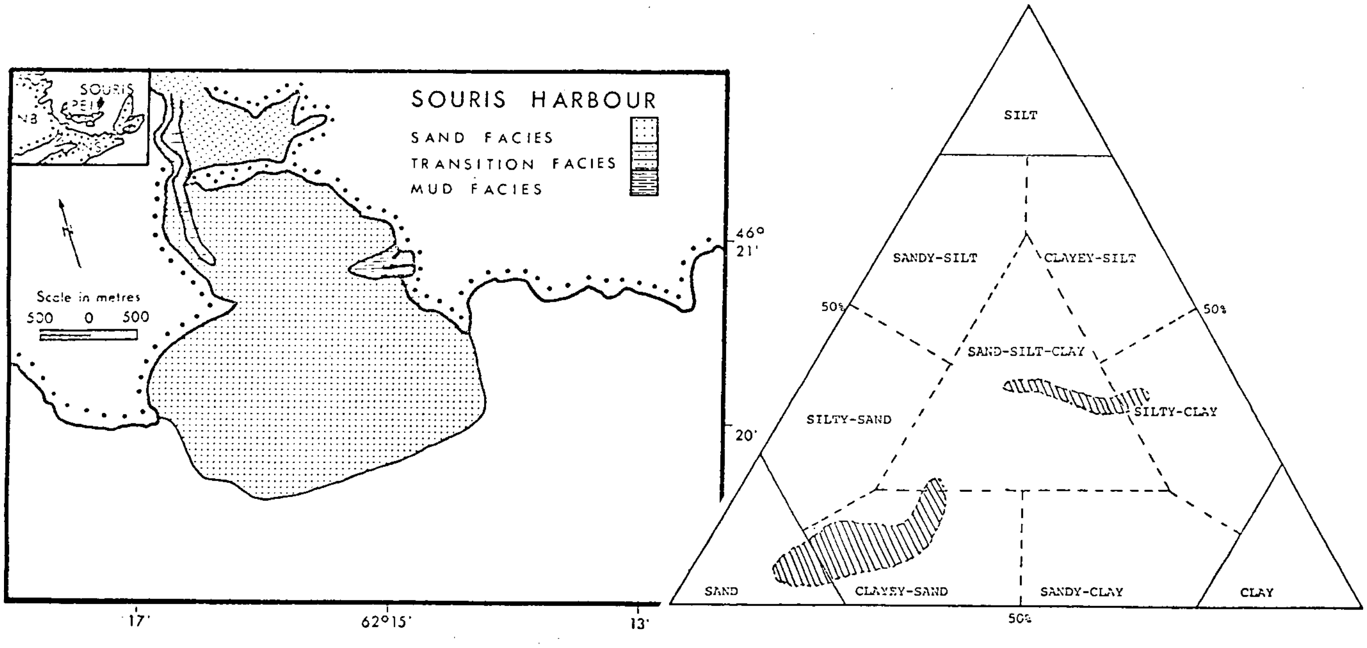


FIG. 8 Ternary plot and lateral distribution map of sediments in the Cardigan Bay estuaries. Note the distinct bimodal nature of the sediments. Fine-grained clay and silt are dominant in the rivers and adjoining wharves and outfalls; silty-sand and sand characterize the open bay.

FIG. 9 Ternary plot and lateral distribution map of sediments in Souris Harbour. Note the bimodal nature of the sediments. Sand and clayey-sand are dominant except adjoining the wharves and in the Souris River where silty-clay is more common.



complex is 0.53 cm/year.

The Souris River and the main channel leading into the harbour have relative average accumulation rates of 0.46 cm/year. Although significant amounts of fine sand and silt are transported by the Souris River, the channel is apparently swept clean by river flow and tidal currents. Silt and clay are accumulating up-river beyond the present sampling grid.

Colville Bay sediments are composed of fine- to coarse-grained sand and gravel. The average rate of accumulation is 0.67 cm/year. The main wharf area with high concentrations of organic suspensoids from the nearby fish-processing plants has an average rate of siltation of 0.38 cm/year. A large proportion of the fine flocculants are transported seaward and do not concentrate on, or affect the main beach adjoining the causeway area.

The "natural" rate of sediment accumulation in Colville Bay, based on Carbon-14 dating of sediment cores is 0.048 cm/year. Natural and man-induced processes have, on the average, increased this rate 10 times.

CLAY MINERALS

The clays in each harbour generally have a uniform composition. Dioctahedral illite is the most abundant mineral and is associated with lesser amounts of kaolinite, chlorite, quartz and feldspar. Such a composition might be expected for sediments from the land of Prince Edward Island, e.g. see Crowl and Frankel (1961), Prest (1972). Trace amounts of amphibole and talc were detected by Reid (1972) at a few stations in Summerside.

Sand-size quartz is the most abundant mineral in the bedrock and till of the Island. During weathering and erosion these grains are carried to the estuary but, because of short transport and because quartz is chemically resistant, the grains remain sand size. Therefore, quartz would not be expected to be the most abundant mineral in the clay fraction of the estuarine sediments. Feldspars are the next most abundant mineral on land and, as noted by Frankel and Crowl (1970), these grains are normally 'sericitized and kaolinized.' Thus when the feldspars break down during weathering and transportation, kaolinite and sericite (fine-grained muscovite) are formed. The dioctahedral illite of the sediment is consistent with a muscovite source. Small amounts of unaltered feldspar might also be expected to reach the harbour. Muscovite and biotite are the main accessory minerals in the bedrock, and commonly weather to produce illite and chlorite. Chlorite is also an accessory mineral of the sandstone and could be carried to the estuary by erosional processes. The clay minerals in each estuary seem fundamentally to be weathering and erosional products of the parent material on shore.

ORGANIC CARBON

GENERAL. Most marginal marine sediments contain several percent of organic matter (organic matter = 1.7 x organic carbon). This matter comprises a number of substances which include: humic acids, amino acids, bitumens, hydrocarbons, lipids, porphyrins and lignin. Organic matter in the coastal zone environment is extremely important because it exerts a strong control over the kind of diagenetic change occurring in marine sediments subsequent to their deposition. An understanding of the general relationship between the organic matter in marginal marine sediments and the environment of deposition is essential. The relationships in the four estuaries are as follows: (1) The organic matter content is highest in fine-grained sediments (Fig. 10), which are commonly olive green or dark grey to black, and decreases as sediments become more coarse. (2) The organic carbon content is commonly higher on tidal flats and in areas of restricted circulation, decaying plant material and sewer effluent, than in the main tidal channels. (3) The total content of organic matter decreases seaward. (4) The extent to which organic matter is preserved in a sediment depends largely on the rate of deposition of the total sediment components. (5) Decreases in organic matter are associated with decreases in both suspended load and bacteria. The type of organic matter varies from area to area and humic acids may constitute more than 50 percent of the total organic matter in most harbours.

All organic matter, both particulate and dissolved, plays a vital role in marine ecology because it provides part of the energy, food, vitamin and other requirements for bacteria, plants and animals. The high content of organic matter in estuaries of Prince Edward Island may cause rapid depletion of oxygen which permits the development of anoxic H_2S-emitting environments immediately below the surface (1 cm to 10 cm) "life zone". Factors which are dominant in causing the observed carbon distribution patterns appear to be the energy variations in the various environments and the inorganic oxidation of organic matter because of a plentiful supply of dissolved oxygen.

PERCENT DISTRIBUTION AT CHARLOTTETOWN. The organic carbon content (Fig. 11) in winter varies from lows of 0.12 percent at Station 81 and 0.83 at Station 3, to highs of 3.41 and 3.94 at Stations 30 and 51 respectively. The average value for the harbour during winter is 1.80 percent. In the spring the organic carbon content varies from lows of 0.13 at Station 81 and 0.80 at Station 3, to a high of 5 percent at Station 10. Stations with values above 3 percent are 22, 30, 51, 60 and 63. The average for the entire harbour environment is 2.1 percent, an increase of 0.3 percent from the winter value. The doubling of the organic carbon content at Station 10 and the continued high at Station 51 is worthy of note. There is a slight drop in the summer to an average of 1.8 percent. Low observations of 0.15, 0.56 and 0.64 percent were recorded at Stations 81, 28 and 34 respectively. The content at Station 3 doubled during this period, whereas a significant drop from 5 to 3.8 percent occurred at Station 10. The concentrations during autumn range from 0.16 percent at Station 81 to a high of 4.25 percent at Station 51. Values of over 3 percent are recorded at Stations 1, 22 and 60 during late summer and early autumn.

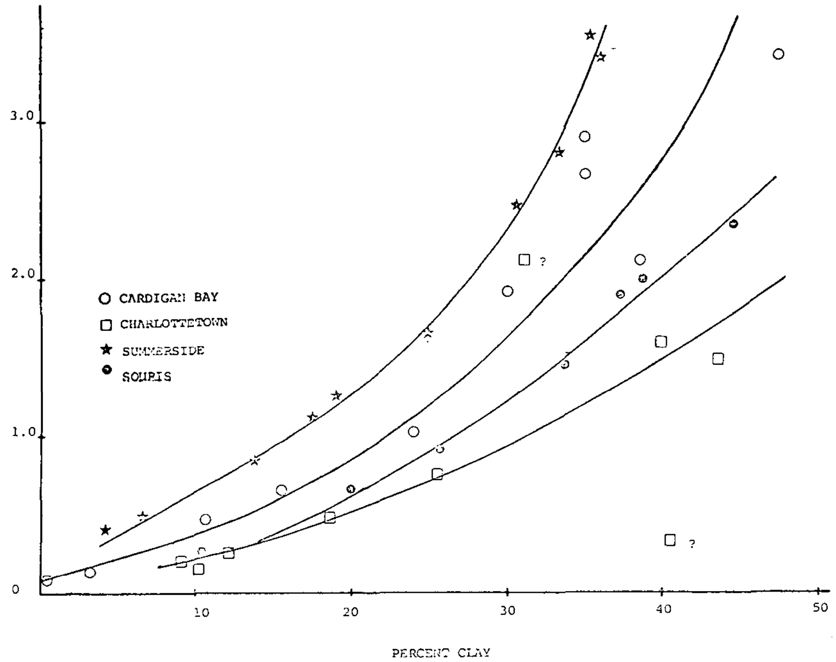
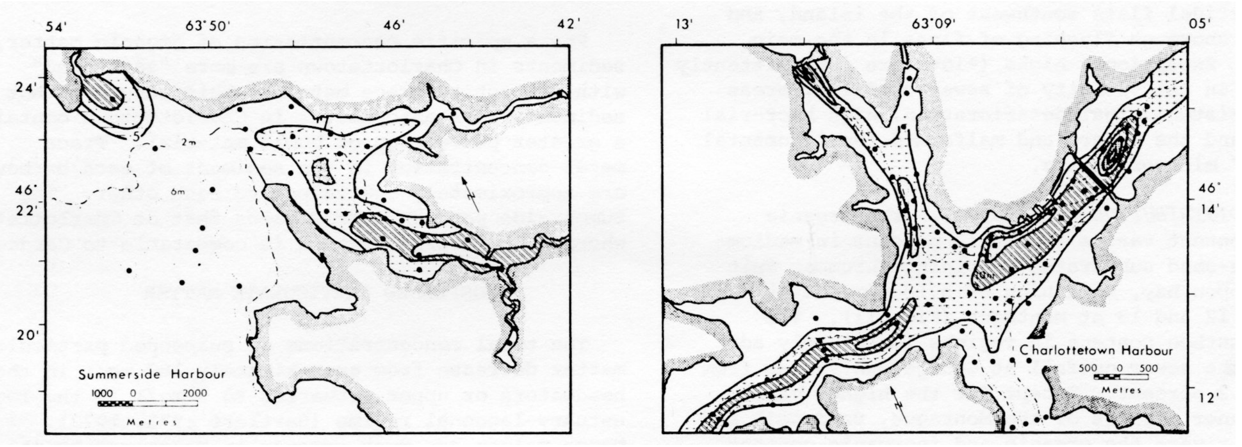


FIG. 10 Clay fraction - organic carbon relationship. An increase in organic carbon is reflected in a corresponding increase in clay size sediments. Note that sediments with the same organic carbon content contain approximately 10 percent more clay in Cardigan and Souris than in Charlottetown and Summerside. The higher organic carbon content per unit of fine sediment in Charlottetown and Summerside is attributed primarily to anthropogenic processes associated with sewage, agriculture and construction.



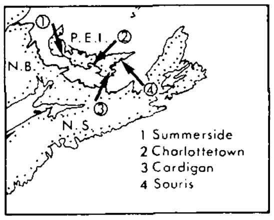
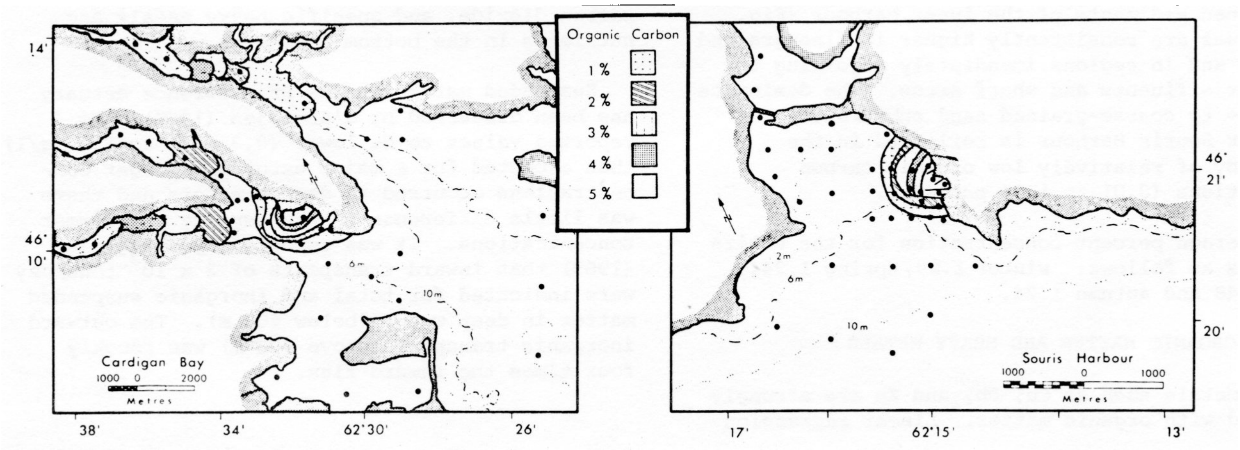


FIG. 11 Organic Carbon Distribution. Note that the higher concentrations are always associated with fine grained sediments of inner harbours and/or the inner reaches of most rivers.



PERCENT DISTRIBUTION AT SUMMERSIDE. The organic carbon content (Fig. 11) varies from a low of 0.01 percent at Station 1 during the winter to a high of 7.4 percent at Stations 12 and 15 in late spring and early summer. There is a general increase in organic carbon during the summer, with slight decreases at most stations in autumn. The average total organic carbon for the entire harbour varies as follows: winter 1.02, spring 1.55, summer 1.65 and autumn 1.24 percent. Consistently low values are recorded at Stations 2, 3, 5, 8 and 9, with highs at Stations 6, 12, 15, 16, 18, 22, 24, 26 and 28. In general the highest values (Fig. 10) are recorded in the transitional sediment facies. Highest values occur in the inner Dunk River at the entrance to the main harbour, and at Miscouche Cove. Much of the organic carbon in these localities is attributed to municipal sewage effluent, high fine-grained sediment influx, its concentration due to estuarine circulation and the associated degradation of both floral and faunal elements. An interesting aspect of the organic carbon distribution is the relatively higher values southwest of Holman Island, rather than in the main channel. This may be attributed to the high floral production on the shallow banks and intertidal flats southwest of the island, and the more thorough flushing of fines in the main channel. Exceptional highs (>10%) are intermittently recorded in the vicinity of sewer outfalls, areas with consistent algal deterioration, high bacterial counts, and the meagre and malformed "environmental specific" microorganisms.

PERCENT DISTRIBUTION AT CARDIGAN. The organic carbon content varies from 0.12 percent in medium- to coarse-sand substrates adjoining Thrumcap Spit and the open bay, to a high of 5.18 percent at Stations 12 and 13 at Montague (Fig. 11). The organic carbon content in regions immediately adjoining the sewer outfall at Georgetown varies from 3.3 to 3.2 percent. Except for the higher values in the inner regions of the Montague, Brudenell and Cardigan rivers the organic and inorganic content is highest in the sediments at Georgetown Harbour. The average percent concentration for the entire estuary is as follows: winter 1.76, spring 2.15, summer 1.80 and autumn 1.56.

PERCENT DISTRIBUTION AT SOURIS. The organic carbon content varies from less than 0.01 percent in medium- to coarse-sand substrates (Stations 12 to 16), to a high of 6.78 percent (Station 31) in the fine-grained sediments of the inner harbour (Fig. 10). Values are consistently higher in fine-grained sediments and in regions immediately adjoining the main sewer effluents and wharf areas. The dominance of medium- to coarse-grained sand substrates throughout Souris Harbour is reflected in the consistency of relatively low organic carbon determinations (0.01 to 1.84 percent).

The average percent concentration for the entire estuary is as follows: winter 1.00, spring 1.34, summer 1.48 and autumn 1.24.

ORGANIC MATTER AND HEAVY METALS

Heavy metals such as Cu, Pb, and Zn are strongly associated with organic matter. Linear regression analysis was completed for the organic matter-heavy metal system and good results were derived (Figs. 12 to 14).

Organic carbon was plotted against each metal for both Charlottetown and Cardigan. These two systems were chosen because they are at opposite ends of the "degraded environment" spectrum on Prince Edward Island; Charlottetown is in a state of degradation, whereas Cardigan is relatively pristine (Travers 1975).

Charlottetown generally contains higher metal concentrations than Cardigan. Although, Cardigan sediments are slightly higher in organic content, they maintain a lower proportion of bonded metal. Charlottetown sediments, in particular the clay-size fraction, are being used to a greater extent to fix Cu, Pb and Zn.

The direct relationship between organic carbon content and trace metal concentration is a result of the bonding properties of the humic material (50 to 80 percent of the organic material) with clay minerals and the trace metals. Simple mathematical expressions are recorded on each graph.

For a specific concentration of organic matter, sediments in Charlottetown are more "saturated" with respect to trace metals. This suggests that sedimentary organic matter in Charlottetown contains a greater percentage of humic material. Trace metal concentration in the sediment of each harbour are approximately equivalent to each other. The Summerside pattern approximates that at Charlottetown whereas the Souris pattern is comparable to Cardigan.

SUSPENDED PARTICULATE MATTER

The total concentrations of suspended particulate matter decrease from approximately 180 mg/l in the headwaters or upper estuaries to 3 mg/l in the lower estuary-lagoonal regime (Bartlett 1971, 1973). These values are much greater in March and April (accompanying spring freshet), and during periods with high rates of precipitation, especially when coincident with cultivation or construction. Concentrations of suspended material always increase from the air-sea surface to the sediment-water interface, (e.g. 4 mg/l to 80 mg/l) except at main-channel stations. The resultant turbidity plays an important role in limiting photosynthesis in the watermass and in the concentration of oxygen, carbon dioxide, and specific heavy metals and nutrients in the bottom sediments.

Suspended matter in the St. Lawrence estuary has been discussed by d'Anglejan (1969). He reported values to be lower (0.3 mg/l to 2.0 mg/l) than expected for a major estuary. Larger concentrations occurred in deeper waters and there was little difference between spring and summer concentrations. It was reported by d'Anglejan (1969) that inward transports of 2 x 10^3 tons/day were indicated for total and inorganic suspended matter in deep water (below 400 m). The outward inorganic transport (above 400 m) was roughly four times the inward flux.

Suspended sediment in the estuarine-lagoonal complexes of Prince Edward Island is contributed by rivers, shore processes, industrial effluents, sewer outfalls, marine processes, biological activity and resuspension during periods of excessive turbulence. Maximum concentrations of suspended sediments are present during spring freshet and periods of heavy rainfall with associated erosion. However, the common practice of dumping dredged material immediately outside (<1 km) the entrances to the estuaries increases suspended load concentrations in the lower estuary by 100 to 300 times the resident amount. It is thought that the present practice of dumping dredged material in regions immediately adjoining the mouths of estuaries has contributed significantly to the development of baymouth shoals, and has substantially increased siltation in the harbours.

The suspended load in most estuaries during the year varies from 1 mg/l in the surface waters to 180 mg/l in the bottom waters. Shoreward from the main harbours every sample has a concentration between 20 mg/l to 60 mg/l. Rivers adjoining the harbours have summer concentrations of 1 mg/l to 90 mg/l in surface waters, and 4 mg/l to 100 mg/l in bottom waters.

During late autumn sampling periods, the suspended load is considerably reduced. During flood tide, surface concentrations range from 1 mg/l to 12 mg/l, and bottom concentrations from 3 mg/l to 14 mg/l. Concentrations at intermediate depths (salt-water wedge surface) are variable. Suspended loads are greater within the outer estuary than immediately upstream.

During late autumn ebb tides, suspended load concentrations are also low with surface concentrations ranging from 4 mg/l to 8 mg/l, and bottom concentrations ranging from 2 mg/l to 10 mg/l. Suspended loads at intermediate depths are also lower (1 mg/l to 2 mg/l) at all stations.

According to Schubel (1971) flocculation cannot produce "turbidity maxima" in the lower reaches of estuaries. The zone with the highest suspended sediment concentration is produced by a combination of physical processes namely the periodic local resuspension of bottom sediments by tidal scour and sediment entrapment by the net non-tidal estuarine circulation. Areas adjacent to spits and shoals form effective zones of entrapment during both flood and ebb tide. Dredging and dumping of sediments and construction of wharves within estuarine harbours have contributed significantly to siltation and turbidity in these areas.

SEWAGE DISCHARGE AND SEDIMENTATION IN ESTUARINE ENVIRONMENTS

Industrial and municipal effluents daily contribute significant amounts of sediment to estuaries in Prince Edward Island (Fig. 11). It has been shown (Bridgeo 1966, Rambow and Hennessy 1965, Redfield and Walford 1951, Wheatland *et al* 1964) that the capacity of marginal marine waters to dilute this waste material depends upon waste volume flow, fresh water flow, tidal currents, wind conditions, temperature, basin size and shape to name only a few causes. Consequently, a study of the "record" preserved in the sediments as well as short-term monitoring is essential for proper analysis.

It has been shown by Bridgeo (1966) and other authors that sewage discharged into the marine environment is diluted in two stages: (1) the first occurs in the immediate vicinity of the outfall as the sewage rises to the surface in the form of a stream and its kinetic and potential energy is dissipated by turbulent mixing; (2) the second occurs as the sewage drifts from the outfall and is dispersed laterally and vertically by currents which are critical in the mixing of surface and deeper water layers. The second phase of sewage and seawater mixing in estuaries is limited to the upper two to five metres, and dilution rates are dependent upon volume flow, river flow, tidal cycle, wind velocity, wind direction and turbulence. Lower-layer circulation moves significant quantities of bedload material upstream.

The regions adjoining most sewer outfalls in Prince Edward Island contain highly organic oozes and high concentrations of white to grey-brown and black organic and inorganic suspensions. Human waste contribution to these environments is commonly calculated at 0.5 pounds/person/day. Major concentrations of both suspensions and coarse floating material are recorded during the daylight hours (8 a.m. to 5 p.m.) which apparently coincide with industrial operations and during the hours (7 a.m. to 11 p.m.) of maximum human waste output. Gulls remove most of the coarse floating material in many regions. However, the finely suspended material is transported into the adjoining salt marshes and intertidal areas, and onto and beyond bars and shoals and toward wharves and other structures in inner harbours.

GEOLOGIC IMPLICATIONS OF MODERN HYPOSALINE ESTUARY-LAGOON SEDIMENTATION

The estuary-lagoon systems of Prince Edward Island contain a variety of sediment types that were deposited at varying rates in water depths ranging from 0 to 30 m within changing chemical and dynamic regimes. An understanding of estuaries requires an understanding of the inherent sediment characteristics.

Modern hyposaline estuaries provide important "formative process" information for the "natural" interpretation of ancient marginal marine depositional environments. Important modern attributes that are significant for modelling these environments geologically are:

(1) Fine-grained silt and clay-size sediments are always indicative of middle and upper estuary regimes where salinities are commonly less than 20 o/oo.

(2) Coarse- to medium-grained quartz or quartz-feldspar sands are typical of lower estuary, beach, barrier and offshore bar environments.

(3) Total organic matter and organic carbon is highest in the fine-grained upper estuary environments (2% to 8%). In ancient environments this

realm should also have provided prime source material for the generation of petroleum. Associated mytiloid and ostreoid "reefs" and baymouth (shoestring) barriers should provide excellent reservoirs. Additionally and perhaps even more important is the direct relationship between organic carbon and heavy metal accumulations. These fine-grained sediment and high organic environments provide natural sinks for heavy metals such as Cu, Pb, Zn, Au and Ur. These metals may remain "in situ" or subsequently migrate into the associated reservoir rocks.

(4) Sedimentation rates seldom exceed 1 cm/year and generally average less than 0.4 cm/year for the entire coastal zone system. However, the finer-grained components are commonly accumulating 4 to 10 times more rapidly than the associated sand-size material.

(5) Atypical accumulations of sand (tens of centimetres to a few metres) are the result of major onshore storms. These erosional-depositional events (preserved in the stratigraphic record) are commonly of a few hours duration only. However, it is apparent that several tens of years are required for the system to regain a state of pseudo-equilibrium.

(6) Estuarine depositional environments always contain elongate and sinuous silt and clay deposits in the down-dip direction. These down-dip deposits abruptly grade into broad sheet-like clayey sand, silty sand or sand representing the lower estuary-lagoon and (or) barrier and offshore bar regime. The barrier deposits are elongate in the direction of strike and are one of the progenitors of shoestring sands.

(7) Upper estuarine deposits are chemically highly reactive whereas lower estuarine and barrier deposits are generally chemically inert.

(8) All areas of the coastal zone system are subjected to bioturbation but the highest activity and greatest preservation of structures occurs in the silty sand and sandy clay of the middle estuary or lagoon.

(9) Estuarine sediments have the following floral and faunal characteristics:

- (a) The upper estuary is characterized by abundant plant material, spores, pollen, diatom frustules and agglutinated, pseudotectinaceous or naked protozoans.
- (b) The middle estuary is characterized by abundant mollusc shells, in particular mussels (*Mytilus edulis*) and oysters (*Crassostrea virginica*) and a calcareous benthonic foraminiferal population dominated by species of *Elphidium*.
- (c) The lower estuary-barrier bar environment is dominated by bar molluscs *(Arctica islandica, Mya arenaria, Ensis directus)*, a mixed calcareous agglutinated benthonic foraminiferal assemblage with species of *Elphidium, Buccella, Islandiella* and *Eggerella*, and high concentrations (10 to 40%) of fragmented shell material.

(10) Geologically, coastal zone environments are short term, repetitive features. The sedimentary deposits are commonly rich in organics and are sinuous to sheet-like in appearance. Modern coastal zone environments in Prince Edward Island have existed in their present form for at least the past 3,000 to 6,500 years. The deposits seldom exceed 20 m in thickness and are commonly less than 5 m thick.

SUMMARY

The geology of southern and southeastern Prince Edward Island is remarkably uniform. Quartz is the predominant mineral supplied to the estuarine environment. Conglomerates, calcareous mudstone breccias, sandstone and siltstone are widespread. Glacial deposits in the form of ground moraine, lodgment or basal till, kames and kame terraces blanket the outcrop. These materials are easily eroded and, with the soils which are exposed by construction, ploughing and cultivation, provide several thousand cubic metres of sediment to the numerous coastal zone environments.

There is widespread evidence of submergence of much of the region to depths of 2 to 4 m below High High Water (HHW) during the past 1000 years. This submergence has played an important role in the development of beach ridges, spits, drowned river and bar-built estuaries, bars, and in the entrapment of fine-grained sediment within the estuarine-lagoonal complexes.

Although the sediment source material is similar, each of the estuaries and lagoons investigated is a specific entity with distinct basin configuration and volume flow characteristics. Consequently, areal distribution of bottom sediments in each environment and variations in sedimentation patterns are directly related to the dynamic processes associated with watermass circulation.

River flow, tidal flux and basin configuration are the principal factors determining the salinity distribution in each estuary. These parameters are also primarily responsible for the horizontal and vertical changes in the physical characteristics of the estuary. Changes in any of these factors produce variations in the estuarine circulation pattern, the suspended particulate matter, and bedload, and alter the resulting sedimentation pattern.

Estuarine sediments range from fine silty clay to coarse sand and gravel. Sand is dominant in the main channels and shallows of outer estuarine-lagoonal environments. Transition facies of silt and silty, fine-grained sand flank the main channels. Medium- to very fine-grained silt and clay are dominant in all inner estuaries where salinities are commonly less than 20 o/oo. Quartz is the main mineral in the sand fraction, which reflects its abundance in the bedrock and till. Feldspars are also common, but most break down upon weathering to kaolin and sericite. The principal accessory minerals, biotite and muscovite, weather to produce illite and chlorite.

Heavy minerals decrease in concentration downstream, indicating an upstream source. Their distribution pattern is understandably similar to that of sediment size, with higher concentrations in areas where sediment size is greatest.

Organic matter content is highest in finer-grained sediments, which are dark grey to black in colour. Highest concentrations occur near sewer outfalls, wharves and inner estuaries. The total content decreases seaward and in coarser sediments.

Continuous tidal movement constantly affects sediment distribution and many sediments are frequently deposited and resuspended several times before final deposition. Flood tides transport marine-derived sediments into the lower and middle estuary, and cause upstream transport of suspended sediment which has settled into the lower more saline salt-wedge layer from the seaward-flowing fresher water layer above.

The total concentration of suspended particulate matter decreases from approximately 180 mg/l in the headwaters (salinities <4 o/oo) of inner estuaries to less than 3 mg/l in the outer estuarine-lagoonal environment. The concentrations are highest in March and April (accompanying spring freshet), or during periods when high rates of precipitation are coincident with ploughing and highway construction. A variable bottom-sediment distributional pattern reflects this situation. In summer most of the suspended load settles and accumulates on the bottom and the pattern becomes more stable as runoff and turbulence of the water-mass are decreased and cultivated crop-cover holds the soil.

During the past 30 years, and in particular the past 15 years, siltation in estuaries has increased by 10 to 400 times due to increased human activity. Agriculture, deforestation, construction and the use of earth fill in harbours have made large quantities of sediment available to the estuarine environment. Man-made features such as wharves and causeways have altered the basin configuration and the natural circulation patterns, and caused entrapment areas in most estuaries.

Bedload and suspended load are difficult to distinguish in the estuarine environment. Material may alternatively be bedload or suspended depending upon the tidal cycle. The bedload is normally composed of discrete sand-size quartz grains, whereas the suspended load is commonly composed of highly organic aggregates of various clay-size minerals.

Suspended particulate matter (SPM) is the intermediate phase between water and sediment, and accounts for the optical (turbidity) and acoustical properties of estuarine waters. SPM levels are highly variable, however, their concentration is much less than that of the total dissolved constituents. Sea water contains 30 to 40 gms/l of various salts, whereas the SPM level is approximately 1 mg/l. Estuarine levels commonly range from 2 mg/l to 50 mg/l but approach 180 mg/l during periods of excessive surface runoff. Most of the SPM settles out and is eventually incorporated as bottom sediment.

SPM is composed of both organic and inorganic fractions. The inorganic fraction is mainly composed of resuspended sediment. The composition of the organic fraction is variable but includes phytoplankton and zooplankton exoskeleton fragments, faecal pellets, seaweed, pollen grains, plastic fragments (evidence of man's activities) and a significant amount of "humic-like" material.

Upland discharge is generally the prime source (at least 75%) of sediment for coastal zone environments, in particular the upper and middle estuarine regimes. This material is highly organic and predominantly medium- to fine-grained silt and clay. The volume, grain size and mineralogy of the material depends primarily on:

(a) The flow of the river - temporal variations in the flow rate result in a sudden influx of runoff material into the system.

(b) The geology of the drainage basin - friable bedrock and unconsolidated overburden are easily eroded by runoff and added to the system.

(c) The climate of the drainage basin - high rates of precipitation dramatically increase runoff and sediment loads.

(d) The extent of man's activities - when the land in the drainage basin is utilized for agriculture or construction there is a substantial increase in sediment supply to the system.

The ability of various sediment components to retain and absorb trace metals is not clearly understood. However, there is a strong correlation between trace metal concentration and organic carbon. The ability of organic matter to form metal ion complexes is in part attributable to the fulvic and humic acid components.

The depositional environments identified are associated with distinct morphological elements and energy regimes. Further study is required to document the latter association quantitatively.

Because of the interaction of physical, chemical and biological factors in the estuary and lagoon system, changes in flow characteristics will be expressed through a number of different parameters. Primary among these because of changes in the energy regime is the alteration of sediment distribution patterns, however, other repercussions follow. Decreases in current velocities, because of man-made and natural barriers, in addition to increasing the rate of sedimentation of suspended particulate matter, may result in the elevation of water temperature, the trapping of nutrients and eutrophication. Reduced mixing of fresh and saline waters results in either reduced salinities, through exclusion of the normal tidal influx, or increased salinity through entrapment of tidal water.

Since the concentration of SPM, heavy metals and major ions in both river and marine water varies with both temperature and salinity (primarily), the alteration of these two factors alone could result in serious ecological alterations through the availability of reactive and nutrient ions. This in turn will have an effect on the geochemistry of the sediments, the buffering capacity of the water, pH, Eh, and ultimately on the suitability of the environment to its original floral and faunal constituents. The last stage in this chain of effects is man's use of the environment either economically or esthetically.

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