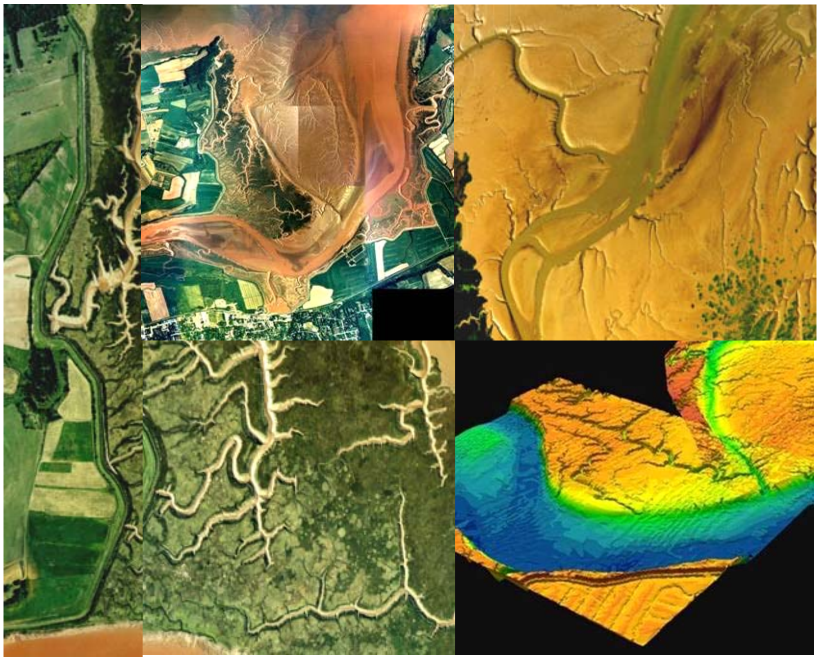
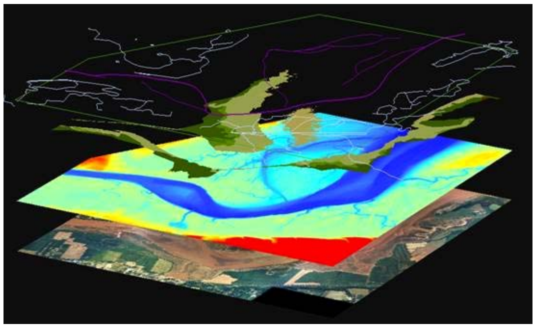
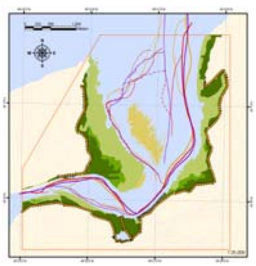
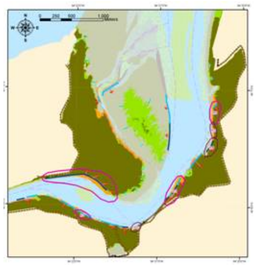
Thirty Year Assessment of the Cornwallis Estuary Evolution









Aerial Photograph and GIS analysis

Internship project for the MBWG
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In the Acadian land, on the shores of the Basin of Minas,
Distant, secluded, still, the little village of Grand-Pre
Lay in the fruitful valley. Vast meadows stretched to the eastward,
Giving the village his name, and pasture to flocks without number.
Dikes, that the hands of the farmers had raised with labour incessant,
Shut out the turbulent tides.

"Evangeline", Henry Wadsworth Longfellow

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ABSTRACT

The Cornwallis River Estuary lies in the Southern Bight of the Minas Basin. Erosion occurs on the banks of this macrotidal estuary and could threaten the old Acadian dykes. This represents a concern for the Nova Scotia Department of Agriculture and Fisheries. This study offers an assessment of the evolution at the mouth of the estuary between 1977 and 2002. Mainly based on aerial photographs and bibliography of the area, the use of GIS technology, by digitizing the data allows multiple analyses of vegetation dynamics, sedimentary changes, and area and volume computing. The most important observed phenomena were the rapid erosion of 11 meter high salt marsh cliffs which can lead, in a medium time scale, to erosion of the nearshore dykes, and the colonization and exponential growth of a salt marsh on a central mudflat. More monitoring is recommended to validate the forecast of this study as well as to avoid dramatic erosion of the old dykes

L'estuaire de la rivière Cornwallis débouche dans la baie septentrionale du Bassin des Mines. L'érosion qui sévit sur les berges de cet estuaire macrotidal est susceptible de menacer les vieilles digues acadiennes, ce qui inquiète le Ministère de l'Agriculture et des Pêches de Nouvelle-écosse. Cette étude propose donc une évaluation de l'évolution de l'estuaire marin entre 1977 et 2002. Principalement basée sur des photographies aériennes et la bibliographie existante sur la zone, l'utilisation de la technologie SIG, par le biais de la numérisation des données permet de multiples analyses comme la dynamique de la végétation, les modifications sédimentaires et les calculs informatiques de surfaces ou de volumes. Les phénomènes qui retiennent l'attention concernent l'érosion rapide des falaises du marais salé, hautes de 11 mètres, qui peut a moyen terme menacer les digues toutes proches, et la colonisation et la croissance exponentielle des herbus sur la vasière centrale. Un suivi plus précis est préconise pour valider les prévisions issues de l'étude ainsi que pour éviter une dramatique érosion des digues.

ACKNOWLEDGEMENTS

Firstly, I would like to thank Maxine Westhead who was a fantastic supervisor and was here each time I needed her and without who this internship would not have been possible. Thanks also to Mike Brylinsky the coordinator of the Minas Basin Working Group and the whole participants of the MBWG. Many thanks to Hank Kolstee who provided me the idea and the materials for this study as well as Danika Van Proosdij for her good tips and the aerial photograph mosaics and Tim Webster who provided me the very useful LIDAR DEM.

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Je ne peux évidemment pas oublier, non plus, les étudiants IBIS éparpillés aux quatre coins du monde, mais toujours solidaires.

1. INTRODUCTION

In the Minas Basin, one of the inner branches of the Bay of Fundy, lies the Cornwallis River Estuary. Even if this estuary does not suffer from physical disturbances by human activities, a majority of its banks were dyked more than three centuries ago by the first Acadian settlers. Here occur natural movements of sediments which includes a complex erosion/transport/sedimentation pattern. Unfortunately this shifting of the natural system can meet the surrounding dykes and threaten them by erosion.

In order to understand better the evolution of the estuary* and to avoid dramatic consequences of an eroded dyke, a study of the historical changes could bring answers and solutions. There is nothing better than aerial photographs to travel in time and follow the natural changes of the estuary until today.

Geographic Information System* (GIS) technology seems to be the best tool to assess this evolution by extracting and digitizing* data from the photographs, by comparing them, analysing them and finally by interpreting the results.

This project offers analysis of the changes in the tidal channels, in the salt marsh vegetation, in the sedimentology of intertidal* zones as well as area and volume computing for a better illustration of the phenomenon.

Because the approach of this study was focussed on aerial photos, no monitoring and no thorough measurements were done. That would be the subject of further projects to validate the conclusions of this project.

1.1. The Minas Basin Working Group and the Nova Scotia Department of Agriculture

Born under the impulsion of the Gulf of Maine Council on the Marine Environment (GOMC), and following two similar pilot projects in Great Bay, New Hampshire, and Passamaquoddy Bay, New Brunswick, the Minas Basin Project was created in 1998. In 2000, it became a Working Group (MBWG) of the Bay of Fundy Ecosystem Partnership and began to formally articulate and expand its purpose, mission, and objectives.

The Working Group mission is to maintain and enhance environmental quality in the Minas Basin and its watershed, and to allow for sustainable resource use by existing and future generations. Indeed, its objectives are:

- to engage the public in identifying issues and actions pertaining to the sustainability of the Basin's resources and its coastal communities;
- to facilitate partnerships, collaboration and new funding opportunities among researchers, policy makers, resource managers and community groups pertaining to any aspect of the sustainable use and management of the Minas Basin.
- to work towards a multistakeholder-supported, management plan for the Minas Basin, taking into account its natural resources (living and non-living), the needs for conservation and protection, and Canada's long-term commitment to sustainable development;
- to facilitate coordination of efforts to identify critical habitats and living resources of the Minas Basin (i.e. encourage conservation of the Basin's biodiversity);
- to identify habitats and species issues for future scientific investigation and research;
- to enhance access to and interpretation of information on the Minas Basin and its natural resources.

1.2. Minas Basin Area characteristics

Located between the two Provinces of New Brunswick and Nova Scotia, on the East coast of Canada, the Bay of Fundy is a funnel-shaped and elongated structurally controlled bay (maps 1 and 2). It is widely known for its very large tidal range, which increases from 4 m near the mouth, to an average of 12 m in the upper bays where extreme values around 16 m have been recorded.

The Minas Basin is a large, triangular and shallow estuarine embayment located at the head of the Bay of Fundy, in the central region of Nova Scotia. It is comprised of four distinct parts: The Minas Channel, Central Minas Basin, The Southern Bight and Cobequid Bay (Willcocks-Musselman, 2003). The Minas Basin is generally considered an estuarine environment because of the changeable salinity, the vigorous movement of tidal water, and the close interaction between the water and the surrounding land (Daborn *et al.*, 2004) (maps 3 and 4)

The energy of the extreme tidal flows that occur in the area is dissipated in sediment transport, scour and coastline erosion. Therefore, geomorphology is affected, which is the main terrestrial cause of the extreme tidal range. Thus, macrotidal* environments stay a wink in the geological scale time.

1.2.1. A tidal dominated environment

The semidiurnal constituent of the tidal cycle in the Bay of Fundy is by far the dominant engine of the hydrodynamics of the area. This constituent is partly of shallow water origin and partly of astronomical origin. (Godin, 1968)

In the Minas Basin, the average semidiurnal tidal range is 11.5 m, ranging up to 15 to 16 m in the Cobequid Bay. The surface of Minas Channel and Minas Basin covers about 1,630 km^2 and the volume of water necessary to raise the level by about 9.15 m equals $14.9x10^9$ m^3, so that around 15 km^3 of water enter twice a day in the area (Godin, 1968). Also, the extreme tidal range and shallow bathymetric gradients produce an extensive intertidal zone that averages 1-2 km in width. Approximately 358 km^2 of intertidal flats are exposed at low tide in Minas Basin, close to 32 % of the total area of the "estuary*". (Amos and Joice, 1977; Yeo and Risk, 1981)

Major flood and ebb currents trend East and West, respectively, with minor variations due to bedrock, or local sediment accumulations. Current velocities vary from 1 to 1.5 m/s in channels, to 0.5 to 1.0 $m.s^{-1}$ over bars, and decrease shoreward (Dalrymple, 1977; Knight, 1977; Yeo and Risk, 1981). These currents resuspend large quantities of fine sediment.

The main rivers of the Minas Basin watershed (map 4), the Cornwallis, Avon, Shubenacadie and Salmon, bring a small amount of fresh water compared with the volume of tidal water, but this is sufficient to lower the salinity of the Minas Basin to 26 to 30 ‰, instead of 35 ‰ in the ocean. (Amos *et al.*, 1976; Daborn *et al.*, 2004)

1.2.2. Geology, sedimentology

In the outer Bay of Fundy, strong tidal currents induce a non-depositional or erosional sedimentary environment, whereas accumulation of sediment, derived from shoreline erosion, mainly occurs in the two major bays at the head (Chignecto Bay and Minas Basin). Indeed, the Minas Basin experiences rapid accumulation of Triassic-red-sandstones-derived sediments, which gives a particular red color to the basin.

Sedimentology (transport, suspension, sedimentation) in the Minas Basin is based on its hydrodynamic characteristics (tides, currents, waves) which are themselves induced by the geomorphology of the Bay. In fact, sedimentological, hydrological and geomorphological components interact between themselves, in the endless quest for balance.

1.2.2.1. Geology of the Minas Basin (map 5)

The Bay of Fundy is underlain by the Fundian Lowlands formation of Carboniferous-Triassic sedimentary rocks. The bottom contours largely follow the coastline and reflect its origin as a former drainage system originating in the Minas Basin area. This basin is underlain by the Precambrian-Devonian metamorphic basement rock.

Figure 1. Triassic rocks and red sediment of the Minas Basin at Economy.

The first Triassic red beds (fig. 1) were deposited under arid conditions in a narrow, hill-fringed basin while Nova Scotia was still part of Pangaea. The early deposits washed down from South Mountain and the Cobequids were coarse sands that were later consolidated into crumbly sandstone (Wolfville Formation). Much of the basin was then flooded with lava as volcanoes became active in the

Fundy region. Then the basin has been stretched by the proto-Atlantic ocean opening. This gave birth to a half-graben structure in which the continental Triassic sandstones, shales, and extrusives basalts (as Cape Split) dip at 5-10° towards the centre line of the Minas Basin. This trough is now largely occupied by the sea.

Rapid erosion then ensued as a river system developed in the trough followed by glacial scouring and, finally, invasion of marine waters. Much of the Triassic Lowlands Region is now covered by water. The largest area still above the sea level is the eastern part of the Annapolis-Cornwallis Valley, our study area. (NSMNH, 1997)

1.2.2.2. Origin of the sediments

During the Quaternary period, glacial downwasting and sea level changes were at the origin of glacial till and outwash accumulations, then of a silt, sand and gravel sequence, coming from both marine and fluvial margins. Glacially derived sediments comprise much of the seabed of the Inner Bay. Since the last glaciation and maximum lowering of sea level (20,000 BP), the world wide Holocene sea level rose and was superimposed by the effect of increasing tidal amplitude, which began 6,300 BP. Therefore, this is also the age of the first intertidal deposits in the Minas Basin.

Modern sediment dynamics in the Minas Basin are directly related to tidal and wave dynamics. The present origin of sediments are derived from cliff recession and erosion (40%), from the Bay of Fundy through the Minas Channel (21%), from stripping and resuspension from wave-cut platforms of the Basin itself (38%), and from surrounding fluvial sources (1%).

The total annual sediment influx for the Minas Basin (all sources, but the waves-cut platform resuspension) amounts to $4.8*10^6$ $m^3.y^{-1}$. (Amos and Joice, 1977)

1.2.2.3. Seabed Morphology

Sediments in Minas Basin are principally sands and gravels, but intertidal and sheltered environments have muddy bottoms. The sand mainly comes from the wave erosion of sandstone cliffs along the shoreline and from glacial outwash deposits.

In some intertidal areas of the Minas Basin, lies a complex series of sand waves, megaripples, and sandbars that reflect the locally strong tidal flows.

1.2.2.4. Sediment dynamic

The regional tidal circulation in the Bay of Fundy is counter clockwise, but geometry and bottom features of the Minas Basin complicate the circulation, dividing it into flow and ebb dominant channels.

Modern sediment dynamics in the Minas Basin are directly related to this tidal dynamic, and also to wave dynamics. Generally speaking, the Bay of Fundy, and the Minas Basin know a transgressive phenomenon reworking or eroding material subtidally* and redistributing it intertidally. Thus, much of the subtidal area of the Bay of Fundy is relict.

Intertidally, tracts of migrated sand flats cover much of the wave-cut platform. And the mud eroded in subtidal areas is deposited in sheltered regions, such as Windsor Bay or the Cornwallis estuary, to form mudflats.

The global Minas Basin sedimentary environment knows endless readjustment in the balance between erosive forces of the rising sea level as well as the increasing tidal amplitude and the constructive forces of sediment progradation. This balance has globally been disrupted by the human hand, which has artificially increased the sediment accumulation by building dykelands and which has disturbed the water circulation and the sediment dynamic with numerous tidal barriers. (NSMNH, 1997)

1.3. Dykeland history

1.3.1. Acadian period

The first European settlers in Canada were French, known in the Maritimes as Acadians. On good terms with the earliest inhabitants of these lands, the Mi'kmaq people, they first constructed the maritime dykelands in the 1700s, inspired by the techniques used in the North-Western France (fig. 2). From an agricultural perspective, it was found easier to build dykes around the fertile tidal marshes of the Bay of Fundy than to clear the upland of trees. Indeed, the tidal flooding that inundates twice daily, deposits silt-sized particles and induces exchange between the saltwater and the coastal grassland. These exchanges form soils ideal for farming.

Figure 2: "Acadians building a dyke at Grand Pré" by Lewis Picard, Commissioned by Canadian heritage (Parks Canada), Atlantic Region.

Traditionally, dykes were built with wood posts, firmly packed mud, and grass sod cut from the marsh. A dyke is an earthen structure that prevents tidal flooding of the land it protects. During low tide, the land behind the dyke is drained through an aboiteau sluice, which is a culvert under the dyke with a gate on the tidal side of a dyke. This structure allows fresh water to flow out during times of low tide and prevents salt water from flooding the land during high tides. Elevations of dykes are maintained so that their height is around 0.5 m above predicted maximum tide elevations. Most dykes measure between 1 and 2.5 m in height. (NSDAF, 2001; Ross, 2002; Robinson *et al.*, 2004)

1.3.2. Post-acadian period

Five years after the Acadian deportation in 1755, the government of Nova Scotia passed the first Act relating to dykeland. The Act provided for a group of owners to appoint commissions who would decide what work was required to arrange for labour and the raising of all costs associated with keeping the dykes in repair. For many years the dyke system in Nova Scotia was maintained in this manner.

By the late 1930s all dykeland areas were suffering from the effects of the world-wide depression. Drainage ditches clogged up, dykes leaked and aboiteaux sagged. On some marsh bodies the protective works failed completely, sending acres of long-dyked soil out to sea. Thousands more hectares of the region's best farmland threatened to disappear.

In 1943, the Experimental Farms branch of the Federal Department of Agriculture set up an emergency program to meet the situation. The cost of dykeland repairs in New Brunswick and Nova Scotia would be shared equally by the owners, their provincial governments and the Federal Government.

At this moment, came the first wide use of modern machinery in dykeland construction. Although long thought too heavy for slippery marsh mud, bull-dozers and draglines did the bulk of the work on several major projects. Even with the help of this break-through, however, it became obvious that the scope of the emergency program was too small. Dykes and aboiteaux were failing faster than the owners and the program's tiny staff could patch them up, and only a massive reconstruction effort would save the day. (NSDAF, 2001; Robinson *et al.*, 2004)

1.3.3. Maritime Marshland Rehabilitation Act

In 1948 the Federal Government created the Maritime Marshland Rehabilitation Act to mount a comprehensive long-term program for preserving the region's dykelands. Under the Act the Federal Government would build and maintain dykes and aboiteaux, and the three Maritime Provinces would provide liaison with landowners to look after the main drains and promote land-use programs.

Based in Ahmerst, Nova Scotia, the Maritime Marshland Rehabilitation Administration (MMRA) staff began applying modern engineering techniques to the traditional problems of dykeland construction and maintenance. It ensured the protection of 18,000 hectares of tidal farmland in Nova Scotia and 15,000 hectares in New Brunswick, building 373 kilometres of dyke in the process.

A major accomplishment of the Administration was the construction of large tidal dams near the mouths of the Shepody, Annapolis, Avon, Tantramar, Petitcodiac and Memramcook rivers, all bound by saltmarsh and dykeland. These giant concrete and steel aboiteaux now keep the tides off all lands upstream and eliminate the need for many kilometres of dyke and many smaller aboiteaux.

In 1970 the individual provinces took over all government responsibilities for the dykelands. Since then one of the major aims of the Nova Scotia and New Brunswick governments has been to increase the amount of dykeland that can be farmed with modern machinery.

At the present time, the landowners are responsible for maintenance of internal dyke roads and also the acquisition of land required for the reconstruction of dykes and aboiteaux. The NSDAF manages the dykelands and maintains the good state of dykes and aboiteaux. (NSDAM, 1987; NSDAF, 2001)

2. STUDY AREA: THE CORNWALLIS RIVER ESTUARY

Located in the upper reaches of the Bay of Fundy within the Southern Bight, which is a very sheltered area of the Minas Basin, the study area was determined at the south of the Starrs Point mudflat as the Cornwallis River Estuary. It could appear strange to qualify the study area as an estuary. Indeed, previously it was said that the whole Minas Basin is considered as an estuary, but at a large scale. In a geomorphological view, the area could be considered as the mouth of the Cornwallis estuary. However by considering the salinity and the tidal influence, which define an estuary, the study area could be considered as a tiny part of the huge Minas Basin estuary. This is the endless discussion about where estuaries start and end.

The Cornwallis Estuary is also located at the extreme east of the 128 km long Annapolis Valley, where the Cornwallis river flows on sandstone bed, between the South Mountain granite and the North Mountain basalt. (NSMNH, 1997)

The Cornwallis Estuary covers an area of approximately 23 km^2 of which about 80% is intertidal (Brylinsky and Daborn, 1987), whereas the Cornwallis river watershed cover about 361 km^2 (map 6). The study area, the mouth of the estuary, was chosen as the area to be covered by aerial photographs. It covers approximately 15 km^2 in which around 9 km^2 correspond to the estuary (channels, tidal flats and salt marshes).

Since the construction of the dykes in the 17th century, the estuary is well preserved, unlike many tributaries of the Minas Basin which are hindered by tidal barriers. Nevertheless, since the second half of the 20th century, human activities (wastewater and farmlands runoff) affect water quality of the river with nitrogen, phosphorus and fecal coliform inputs, like most of rural area. (Timmer, 2003)

2.1. Around the Cornwallis Estuary

2.1.1. Climate

Protected from the cold Labrador Current by the surrounded Nova Scotia land, the Minas Basin knows a temperate marine climate.

2.1.1.1. Temperatures

Winter is cold but not severe. The January mean daily temperature is -6°C, compared to -8°C in northern Nova Scotia, and -5°C in southern Nova Scotia. Mean daily temperatures rise above freezing in late March. Spring temperatures are warm, and by July the mean daily temperature is 18°C. Mean daily temperatures fall below freezing during the first week of December (fig. 3). (NSMNH, 1997; National Climate Archive, 2002)

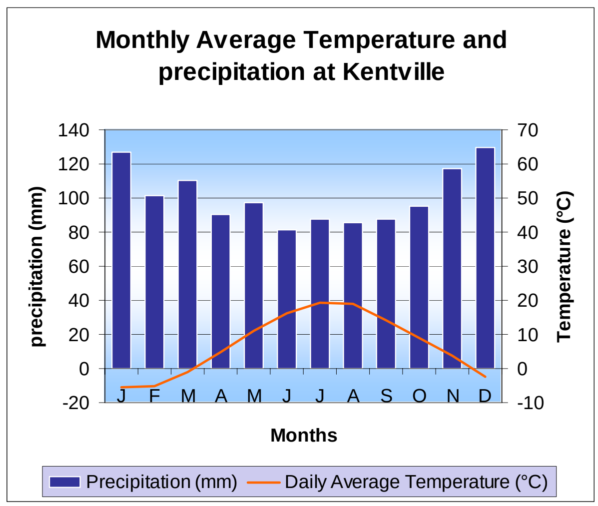


Figure 3: Precipitation-temperature diagram for one average year at Kentville. (Source: National climate archive, Environment Canada)

2.1.1.2. Precipitation

A majority of the precipitation in the Annapolis Valley falls during the fall and early winter, with precipitation levels peaking in December and January. High accumulations of snow during the winter, combined with soils that drain quickly make April the most likely time for floods in the Valley. However, flooding is not considered to be a high risk in the area. Flooding in the Valley typically occurs when the dykes along the Minas Basin are exceeded by high waters. This is most likely to occur when high tides, storms, and snowmelt all combine to create abnormally high tides that overwhelm the dykes. (Timmer, 2003)

Summer precipitation on the Cornwallis River drainage basin is lower than elsewhere, and this, combined with the prevalence of coarse sandy soils, can lead to drought conditions in some years. The warm temperatures and low elevations create a high potential for evapotranspiration and a mesothermal climate. (NSMNH, 1997)

Total annual precipitation at the eastern end of the region is less than 1200 mm. Compared to the rest of the region, snowfall is moderate, being more than 250 cm annually. (National Climate Archive, 2002)

Winter ice accumulations in Minas Basin are significant. Shorefast ice thicknesses of 3-4 m are common. Winds and tidal currents cause grounding of pack-ice within the intertidal zone, which in turn causes ice gouging and sediment erosion. Transport and melting of this debris-laden ice is an important process in sediment redistribution.

2.1.1.3. Wind

Dominant wind direction is south-westerly throughout the year, which coincides with the direction of maximum wave fetch. Late winter storms occasionally occur and hurricane force gales are common once or twice per year.

2.1.2. Geology

The Cornwallis Estuary lies at the south-western corner of the Minas Basin, and is the focus of drainage from the eastern part of the Annapolis Valley. The Annapolis Valley is bounded on the north by the North Mountain cuesta* that is capped by Triassic-Jurassic basalt, and on the south by a highland area called the South Mountain that is underlain by Palaeozoic metasedimentary and granitic rocks. The Valley floor is underlain by weakly cemented and easily eroded red fluvial sandstones of the Triassic Wolfville Formation, and by the conformably overlying fluvial and lacustrine mudstones of the Blomidon Formation. The Wolfville sandstone is exposed in low cliffs along the shore of the Cornwallis River estuary. (Daborn *et al.*, 2004)

2.1.3. Fauna

Due to the strong currents, high turbidity, low average salinity, and variable temperature within the inner estuary, very few organisms live in the estuarine water, in marked contrast to the high biological productivity of the salt marshes and tidal flats. (Daborn *et al.*, 2004)

The mudflats, salt marshes, dykelands, and estuaries are important breeding and staging areas for waterfowl and migratory shorebirds such as the Semipalmated Sandpiper. Together with wet meadows, the salt marshes and dykelands are among the largest areas of suitable habitat in Nova Scotia for Arctic Shrew. Typical freshwater fishes include Atlantic Salmon, Brook Trout, and Creek Chub. (NSMNH, 1997)

2.2. The Cornwallis Estuary

The Cornwallis River estuary is a convergent (trumpet-shaped) tidal dominated estuary (map 10). Its mouth lies between Starrs Point and Long Island-Evangeline Beach (or between Kingsport and Evangeline Beach if we include in the system the Canard River and Habitant River estuaries), while the head of tide is about half a kilometre above Kentville.

2.2.1. Study area in figures

Further GIS calculations allowed characterizing the area with figures. These calculations were done with the 3D analyst and XTools Pro tools of ArcView 8.3 on the aerial photographs and the LIDAR DEM. More details about the data will be given further in the Methodology chapter.

Thus in the study area (15km^2) located at the mouth of the Cornwallis estuary, the estuarine system (salt marshes, intertidal zones and channels) covers 9 km^2. Salt marshes compose about 35% of the estuary, intertidal flats (between salt marsh and Mean Low Water Level) cover around 55% and water covers only around 10% permanently.

A tidal oscillatory volume of about 138x10^6 m^3 was assessed with bathymetry in the LISP 89 (Yeo *in* Daborn, 1991), but this figure includes the Starrs Point mudflats. Thus, a calculation was made only on the study area (with the LIDAR DEM) giving a result of about 49x10^6 m^3. The volume at mean high tide was calculated at 51.5x10^6 m^3 and at mean low tide at 2.5x10^6 m^3 (5% of the high tide volume).

The total dyke length is around 9,800 m whereas the coastline length is around 12,360 m. Thus 80% of the estuary has been dyked: 64% on the left bank (2,430 m of 3,800 m) and 84% on the right bank (7,370 m of 8,570 m). The left bank dyke (Starrs Point) is 7 m high (above the MSL) and protects around 760 m^2 of land from flooding. The right bank (Grand Pré) is 8 to 9 m high and protects, with western dykes, around 7,500 m^2 of agricultural land.

2.2.2. Hydrology

Good tidal or current data for the Cornwallis estuary do not exist, but, because of the exceptional nature of the tide, different numeric tide or current models were experimented in the Bay of Fundy, in the Minas Basin and more particularly in the Southern Bight (Godin, 1968; DeWolfe, 1981; Milne, 2003). In order to have an idea of the tidal cycle and an idea of the current velocities in the vicinity of Starrs Point, the WebTide computing model can be used (fig. 4) (Oakey *et al.*, 2004), with the appropriate 'regional' solutions of the Scotian shelf, Gulf of Maine, Bay of Fundy, which were developed with focus data near the study

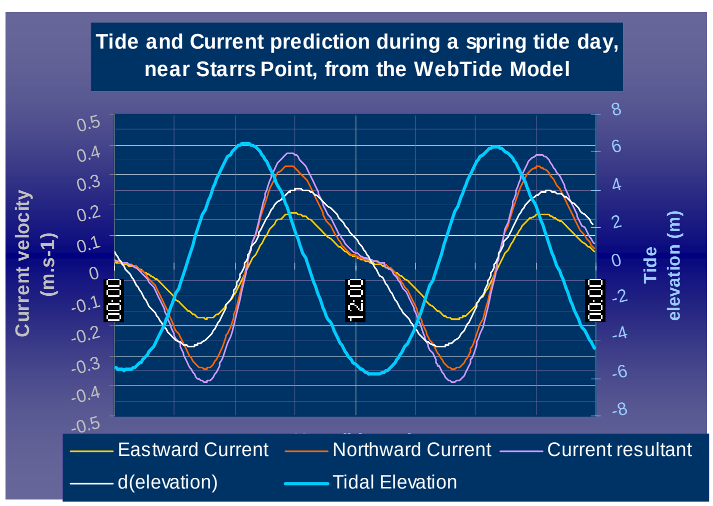


Figure 4. Tidal predictions for a spring tide day with the WebTide model.

area(Milne, 2003). We should notice that the error is nearly 10% for the tidal amplitude (Dupont *et al.*, 2005), and approximately a 5 minute error in the Minas Basin.

The WebTide model gives tidal amplitudes of 8 to 13 m, for neap and spring tides, in the outer estuary, which amplitudes seem to be close to reality. The average tidal amplitude is 11.5 m with a period of oscillation of 6.29 hours (approximating a semidiurnal period). The estuary is well sheltered from the strong currents or waves of the open body of the Minas Basin.

According to Daborn and Pennachetti (1979), this macrotidal estuary has an extreme spring tide range in the outer estuary of 15-16 m, and a neap tide range about 9 m. Average salinity decreases headward, from ~29‰ at the mouth to less than 0.1‰ at the Kentville Bridge, 15 km upstream from the mouth of the estuary, where the tidal influence ends. In the middle estuary, lighter salinities are observed along the south shore, where the flood tide is strongest there (Daborn and Pennachetti, 1979). It seems that there is no vertical stratification concerning temperature and salinity in the water body of the estuary, according to the Brylinsky's study on community structure and productivity, led between late may and mid October of 1985. (Brylinsky and Daborn, 1987)

The tidal currents in the estuary are maximal during the ebbing and the flooding tide, and there is a momentary minimum during the slacks. Moreover, these currents are mainly alternative which means that their spectrum is composed of 2 opposite directions, even if a light rotational pattern was observe on the northern mudflats.

The mixing index (the volumetric ratio of fresh water input during a half-tidal period to marine water entering during a flood tide) is estimated to be 0.004 (Dickinson, 1991). This is well within the range for well-mixed, Type C estuaries (table 1) (Neilson and Cronin, 1981). Tidal mixing is efficient, and no stratification of temperature or salinity occurs within the sample area. (Daborn *et al.*, 2004)

Table 1. General drowned river valley estuarine characteristics (Neilson and Cronin, 1981)

Estuarine type[a]	Dominant mixing force	Mixing energy	Width/depth ratio	Salinity gradient	Mixing index[b]	Turbidity	Bottom stability	Biological productivity	Example
A	River flow	Low	Low	Longitudinal vertical	≥ 1	V. high	Poor	Low	Southwest Pass Mississippi River
B	River flow, tide	Moderate	Moderate	Longitudinal vertical	<1/10	Moderate	Good	V. high	Chesapeake Bay
C	Tide, wind	High	High	Longitudinal lateral	<1/20	High	Fair	High	Delaware Bay
D	Tide, wind	V. high	V. High	Longitudinal	?	High	Poor	Moderate	?

[a]Follows Pritchard's advection-diffusion classification scheme.
[b]Follows Schubel's definition: MI = equation here▸ (vol. freshwater discharge on ½ tidal period) / (vol. tidal prism).
Source: Neilson and Cronin, 1981.

The large tidal amplitude results in current velocities often exceeding 1 $m.s^{-1}$. On the Starrs Point mudflat, the main axis orientation of the tidal currents is approximately NE-SW. Local variations are obviously associated with their position in relation to the ridge and also to the length of the inundation time. During the flood tide, the main channel formed by the Cornwallis River fills before the adjacent tidal flat. This necessarily creates a pressure gradient directed to the flat giving rise to a flow component perpendicular to the main axis of the flat. (Perillo *et al.*, 1993)

Flow measurements have been taken at the Wolfville harbour, where the tide is influential, between 1984 and 1994. A minimum flow of 0.4 m^3/s, a maximum discharge of 35.6 m^3/s and a mean flow of 8.6 m^3/s was recorded (Timmer, 2003). These values do not reflect the river flow, but the strong tidal influence on the Wolfville shore. By regarding the salinity in the area, the fresh water input from the river seems to be negligible compared to the water volume moved by the tide.

Other measurements were taken during the LISP 89. On the Starrs Point mudflats, average currents amount to 17 $cm.s^{-1}$ in both ebb and flood directions with peak velocities always less than 45 cm/s. Current velocity profiles were often homogeneous, with occasionally a significant negative difference between surface and bottom during the flood, and positive during the ebb.

2.2.3. Sediments

In the estuary, the sediment characteristics can be divided in relation to areas of very different hydrodynamics. Generally speaking, coarse unconsolidated sediment, such as sand and gravel, occur mainly in the river/tidal channel. Fine unconsolidated sediment, such as mud and fine sand, occur on the tidal flats. On the tidal flats, mainly unconsolidated and surficial sediments are found including red silty till, outwash sands and mud, and the recent tidal deposits. Finally, recently consolidated sediment, as mud (silt and clay), occur mainly in the mature salt marsh area. In the young salt marsh area, sediment is still unconsolidated, but with time and without disturbance, organic matter from biological activity and vegetation degradation will increase within the sediment deposition, active to increase cohesive strength. Moreover, elevation increase, sediment compaction and natural drainage will also increase the sediment consolidation.

2.2.3.1. Conceptual Model of a tide-dominated estuary (Ryan et al., 2003)

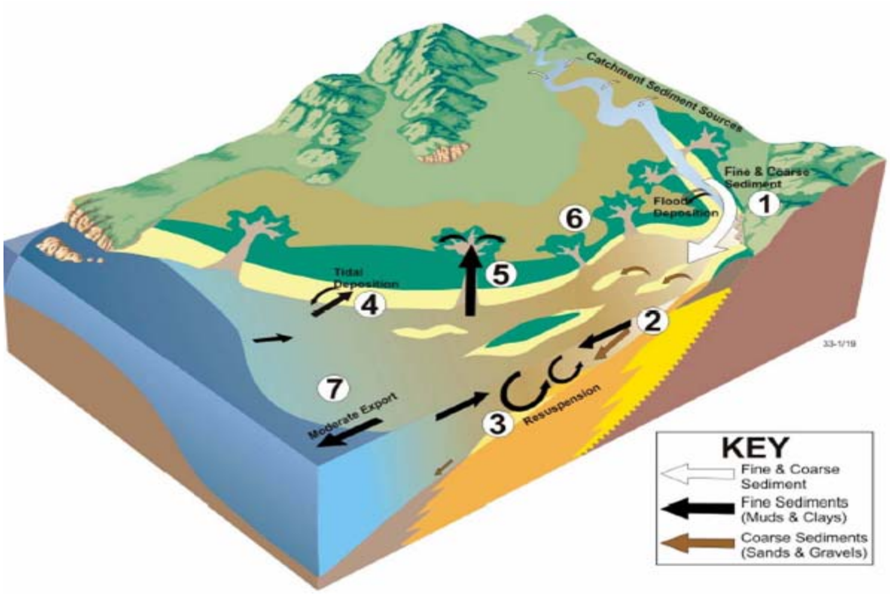


Figure 5. Conceptual model of major sediment dynamic in a tide-dominated estuary *(Ryan et al., 2003)*.

The overview of an Australian conceptual model concerning the sediment dynamic in a tide-dominated estuary could help us to understand better the circulation of material in the Cornwallis estuary (fig. 5)

1. Fine and coarse sediment enters the estuary from the catchment.

2. Sediment is deposited at the point where the river flow and tidal currents meet and cancel each other out. As a result of this rapid decrease in the capacity of the river to transport sediment, most of the coarse material (such as gravels and sands) is deposited. Reworking and redeposition of material by tidal currents occurs.

3. Large quantities of suspended sediment are characteristic of tide-dominated estuaries. Strong tidal currents continually resuspend and rework fine sediment in the channels, so that the water

column is naturally highly turbid (Wells, 1995). Quantities of fine and coarse sediment can pool temporarily within the channel, forming tidal sand banks. A zone of abnormally high suspended sediment can occur in many tide-dominated estuaries, known as the ‘turbidity maximum’ (Wells, 1995). This typically transient feature develops as a result of trapping and resuspension of particles, and contributes to the deposition of material in the tidal sand banks. High suspended sediment loads can also lead to a phenomenon known as 'fluid mud', a gel-like accumulation of low density muddy sediment which may be stationary, or mobilised by tidal currents (Wells, 1995). Turbidity is especially marked during spring tides, and the location of the turbidity maximum depends on the tidal cycle (spring to neap) and river flow velocity. Ebb and flood tides can follow mutually evasive channels (which periodically migrate), and currents may be powerful enough to cause scouring at the channel base, leaving gravel and bioclastic debris at the base. (Harris, 1988; Green *et al.*, 2000)

4. Fine sediment undergoes both deposition and erosion on the extensive intertidal flats. Deposition is aided by biological activity such as burrowing and improved cohesiveness, whereas erosion is typically related to storms and tides. Coarser material is also deposited on flanking environments by tidal currents and flood events. Over time, intertidal flats tend to expand seawards.

5. Salt marsh environments, with interspersed tidal drainage channels, commonly flank tide-dominated estuaries, and serve as a depocentre for fine sediment, and rapid deposition of fine sediment and organic material is increase by vegetation. Over time, salt marsh tends to expand onto, and replace intertidal flats.

6. This feature typically does not exist anymore in the Cornwallis estuary since it was dyked. The salt flat in the Australian model can therefore be assimilated with the very high marsh. It normally experiences inundation only during very high tides, during which some deposition of fine sediment occurs. Sediment in supra-tidal regions (including the floodplain) is mostly mud, which is deposited during high tides or river floods. Ebb tide waters often flow back to the main estuarine channel through tidal drainage channels.

7. The sediment trapping efficiency of tide-dominated estuaries is moderate. Coarse sediment tends to be redistributed by tides, and results in the seaward expansion of intertidal habitats and infilling of the main channels with tidal sand banks. Net sediment export is more significant during floods, when large quantities of sediment are moved offshore.

Finally the following schema (fig. 6), modified from Eisma (1997), could sum up the sedimentary processes and exchanges in the Cornwallis River estuarine system.

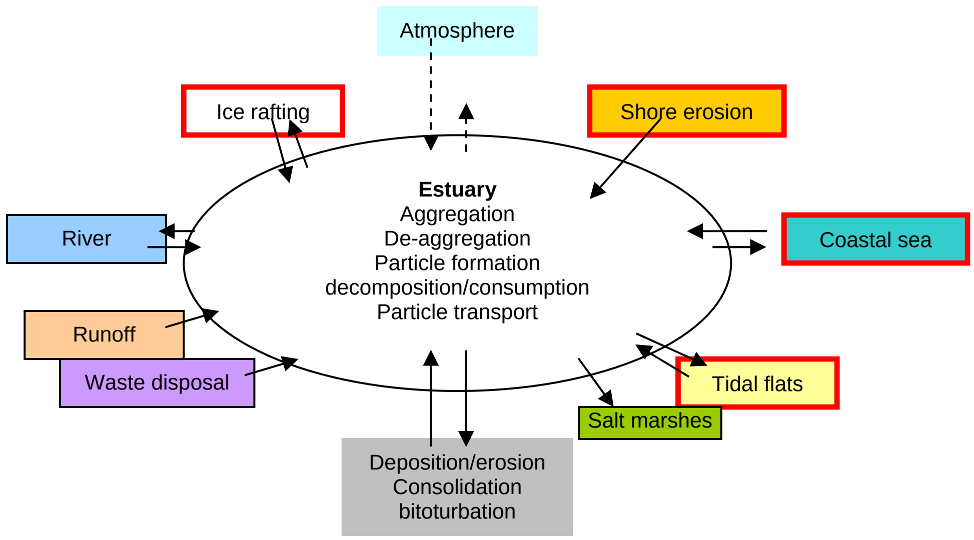


Figure 6. Diagram of supply and removal of suspended matter and principal particle processes in the Cornwallis estuary, modified from (Eisma, 1997)

2.2.3.2. The Daborn and Pennachetti study (1979)

In the summer 1978, Daborn and Pennachetti (1979) studied the oceanography and the sedimentology of the Southern Bight. Measurements taken at the Mouth of the Cornwallis River showed a salinity decrease from 29‰ at the entrance of the Southern Bight to <25 ‰ at the mouth of the river, whereas surface suspended sediment concentration (SSC) increased from <10 mg/L to >100 mg/L. They also showed that the particle size frequency distributions varied according to locality and stage of tide: in the main channel of the estuary, the particle size distribution is heterogeneous upstream and a peak for sizes between 10 to 20 µm increases toward the downstream waters.

In the estuary, during a tidal cycle, vertical temperature and salinity data indicate that the water column is generally moderately to well mixed. But great vertical heterogeneity occurs in the SSC. Horizontally, during the ebbing tide, mean SSC increases from 30 to 170 $mg.L^{-1}$, whereas decreases from 200 to 30 mg/L occur during the flooding tide. The decline in concentration near high tide was attributable to dilution by clearer water from the open part of the Basin, and also might be the result of gravity settling of larger suspended particles.

Also, within salt marshes in the area, mean SSC values are different and generally higher than in the channels. SSC could range from 20 mg/L to 550 mg/L (Daborn *et al.*, 2004; van Proosdij and Townsend, 2004).

A study of the Cornwallis river upstream showed a continuous decrease of salinity and a large increase of SSC from 50 to >4,500 mg/L, >5,000 mg/L (Brylinsky and Daborn, 1987). This turbidity maximum is located in the vicinity of the town of New Minas and could be identified as a "fluid mud" phenomenon. This could locate the nodal point* of the estuary, far upstream in the estuary because of the low river flow. This study occasionally observed lateral stratification with higher salinities along the southern shore where stronger flood waters occur and lower salinity along the northern shore where river outflow is more important.

Finally, it was shown that the suspended sediments present in the river mouth at high tide, are not transported out into the Southern Bight in any quantities on the ebb tide. At all stages of the tide, the water in the southern Bight is considerably less turbid than in the river mouth. Residual water oscillates back and forth over the mudflats and into the river mouth. Accumulation on mudflats is very low which suggests that the sediments are almost in dynamic balance with fluvial supply (Daborn and Pennachetti, 1979). This study was conducted only on calm days, whereas Yeo and Risk have demonstrated that the major causes of erosion and translocation of deposited sediments are storms or strong wind activity in the Minas Basin (Yeo and Risk, 1979).

(Daborn and Pennachetti, 1979)

2.2.3.3. LISP 89

In the summer of 1989, an intensive study of sediment distribution, properties, and environmental factors influencing their behaviour was conducted on the Starrs Point tidal flat at the north of the study area. This study, coordinated by the Acadian Center for Estuarine Research, could bring some sedimentary data in the estuary.

In 1985, a mineralogy study on similar low plasticity and non-cohesive sediments was conducted at the Evangeline Beach, on the North shore of Long Island. The fine fraction is dominated by quartz (24%) and feldspar (18%), with illite (18%) and chlorite (12%) dominating the clay assemblage.

It was showed during the LISP 89 that the sediment grain size increases seaward and toward the bounding channels from 0.44 mm to 0.125 mm, with coarser sediment near Long Island Head in megaripples (1.3 mm).

Sediment distribution within the Cornwallis Estuary could be similar to that described for the nearby Avon Estuary, i.e. there is an inverse relationship between particle size and current velocity, with the latter increasing up in the estuary. This phenomenon, “tidal pumping”, is due to the flood dominance which tracks the fine particles in the estuary. Also the coarse sediment at the mouth of this estuary can be transported (it is not lag), and the transport is not the same for each sediment size class. By this hydraulic sorting, coarse sediment is excluded from the estuary head creating the inverse relationship.

Sampling in the bed of the estuary during ebb tide indicates that significant bedload transport occurs, resulting in ebb-oriented bedforms (sandwaves and dunes), particularly around the inside bank of meanders. Numerous mud pebbles were found in the troughs with fluid mud (around 0.022 mm median diameter) draped over the sandbars and accumulating in depressions and in quiet water embayments between the bar and the shore. Fluid mud deposits appeared to occur with greater frequency upstream from the estuary mouth near Wolfville.

The SSC or suspended particle matter (SPM) measurements gave the same results than the previous studies.

2.2.4. Tidal flats

The outer estuary (i.e. the study area) is characterized by broad mudflats where they are sheltered from strong currents or waves, or complex bedforms including sand waves and megaripples in more exposed areas.

The disposition of the tidal channel in the estuary isolates a large mudflat area between the main channel of the estuary, which flows along the Grand Pré Dykeland and a western secondary channel, which is only momentary filled of water during high tide and which drains the majority of the tidal creeks of the left bank salt marsh. This area will be called "Middle bank".

On the Starrs Point mudflat, only a few creeks dissect the external borders, each up to 3 m deep. Nevertheless, the creeks seem to have little influence on the dynamics of the flat (Perillo *et al.*, 1993). The large creeks of the middle mudflat of the estuary seem to be very similar.

The texture of surficial sediments decreases from sand at the lowest reach of the low tide, to silty mud at the tidal marsh level (Perillo *et al.*, 1993).

Life on these apparently sterile extents exists, but mudflats have many ecological functions. Their surfaces can be very productive (organic matter and benthic macrofauna) and can feed juvenile fish, birds and crustaceans. The crustaceans are well represented by the small *Corophium volutator* which is an important species for the feeding of migratory birds such as sandpipers. Numerous worms such as *Nereis sp*. are also present.

2.2.5. Salt marsh

Figure 7. Low marsh edge in the Cornwallis Estuary.

An extensive salt marsh is present all around the estuary and borders the 17th-century Acadian dykes. On this tidal salt marsh grows particular vegetation distributed along salinity and inundation gradients, which usually depends on the marsh elevation. On the low part of the marsh, which is subjected to the daily tidal flooding, and around the mean high water level (MHWL), occurs the low marsh dominated by *Spartina alterniflora* (fig. 7). Beyond these peripheral salt marshes, the salinity is lower but still high and the inundation is less frequent (extreme tides with storms). There and until the foot of the dykes, occurs the high marsh, where vegetation consists primarily of *Spartina patens*. Between low and high marshes exists a transition area: the middle marsh, where *Juncus sp.*(rushes) and *Spartina sp.* (cordgrass) dominate the Cornwallis estuary marsh.

In the estuary, salt marshes on the left and right banks have a different morphology. If on the left bank the surface of the ground is roughly flat, clifflets occur in the low marsh of the right bank. According to Allen, terrace-like features (ramps and clifflets) record medium-term (10 to 100 years) episodes of erosion followed by accretion in the high intertidal zone and erosion seems chiefly depend on the texture of the sediment deposited on the salt marsh. (Allen, 1989)

In the salt marsh water is oxygenated and the dissolve oxygen cycle is regulated because of shallow waters, turbulence resulting from tidal movement, vegetation, and photosynthesis. That permits the development of phytoplankton and then of larger fauna composed of worms, molluscs, insect larvae, juvenile fish, etc. Also, by the tidal creeks, salt marshes offer important shelter for many species of fish.

2.3. Erosion and sedimentary controls

2.3.1. Sediment characteristics

There are considerable divergences of opinion on the factors that control bed erosion: the macroscopic cohesive strength, sediment compaction, non-uniformity of the sediment, mineralogy, interstitial water, organic matter content, effects of sediment desiccation, vegetation cover, bioturbation and biological activity. The settling of suspended particles is a function of the SSC, settling velocity, probability of particle resuspension, and effects of temperature, salinity and also, effects of flocculation. This explains the difficulty to forecast erosion or sedimentation, especially in rapidly changing environments such as a macrotidal estuary.

In 1985, Amos and Mosher leaded a study on the erosion and deposition of fine-grained sediments at Evangeline Beach and near the Windsor Causeway.

Accretion measurements made on the Windsor Mudflat, which shares similar aspects with the study area, especially the middle flat, showed a systematic accumulation throughout the spring and the summer period. The maximum accretion occurred on the seaward side of the mudflat in the lowest lying part. The spatial deposition appeared to be independent of the water depth during peak tidal inundation, but highly dependent on the mean concentration of sediment. The net deposition thus decreased from the spring through the summer.

Initial results showed that the resistance to erosion of intertidal fine-grained sediment is controlled largely by the degree of subaerial exposure and the consequent dehydration and compaction: more compaction from subaerial exposure. The sediment shear stress (resistance to erosion) was high (4 kPa), but generally decreased seawards across the intertidal zone. The resistance to erosion of newly deposited intertidal mud can be 80 times greater than subtidal counterparts. But the rate of sediment erosion varied as a complex function of the applied bottom shear stress. The depletion of suspended matter due to increased intertidal deposition means less deposition in the subtidal zone and generally clearer waters. All these elements show the link between high SSC and deposition, and the existence of the spatial equilibrium between erosion and accretion (Amos and Mosher, 1985).

We must be cautious with an extrapolation of these results to our area, because of the particular sedimentological behaviour due to the Windsor Causeway disturbances. And we should note that the results are related only to mudflats, and not to salt marshes or channel sedimentology.

2.3.2. Hydrology (tides, waves, river flow, currents)

In the framework of the LISP 89, a study of the tidal circulation pattern on Starrs Point was conducted. We should note that the southern part of the Starrs Point mudflats are located at the north of the study area and are much more exposed to wave activity, so the conditions are a bit different.

Wave activity on tidal flats is very important in resuspending the bottom material and by providing vertical fluctuations, so the sediments are maintained in suspension, whereas tidal currents are the major dynamic element that control evolution of these environments. The observed circulation was the result of the interaction of the reversible tidal currents, the general morphology of the intertidal flat and the local coastal topography. On the Starrs Point mudflat, the main axis orientation of the tidal currents is approximately NE-SW (Perillo *et al.*, 1993). This axis is modified when entering in the estuary shared between the main tidal channel (N-S) and the secondary channels around the middle flat (NE-SW).

Wind waves in tidal basins are due either to incoming waves from the adjacent shelf or are generated locally by the wind. Surface waves are dampened because bottom friction is relatively high on the shallow tidal flats. However, these short waves have the ability to resuspend bottom sediment especially in shallow water, because of the higher magnitude of the near bottom orbital velocity. (Eisma, 1997)

In our area, the flats are, generally, protected from strong winds that may produce storm surges and strong stirring of the surface sediments. Because of its location at the head of the basin, the flat is also protected from large waves generated on the main body of the Bay of Fundy. Only local waves may be active when the wind blows from the northeast, which is statistically quite rare. Moreover, the estuary is partly sheltered from these winds by Long Island, and in winter the ice cover protects the flat. (Perillo *et al.*, 1993)

The sediment transport and deposition are majority due to the cyclic tidal flow characteristics. In our area, the tidal cycle is marked by periods of low current velocities around slack tide that favours sediment deposition around high or low tide. In this layout, sediment transport and erosion in and near the tidal channel are important during the ebbing and the flooding tide. Cohesive and non-cohesive sediments localized along tidal channels are eroded by this particularly active form of erosion. The large scale reworking of material by tidal and river flows, which induces meandering of tidal channels and lateral erosion, whereas waves erode the tidal flats vertically.

Concerning the mudflats, their formation and sedimentation/erosion dynamics are related to the high SSC plume. Thus these phenomena depend, in a short term on tidal stages, and in medium term, on weather and seasons.

Moreover, mudflats have a wave dissipation capacity, which means that landward of the flat or when the flat altitude increases, hydrodynamics decreases, giving a more depositional environment. In time, with a positive sedimentary balance, a transgressive environment and without great disturbance events, sedimentation will occur, followed by vegetation colonization by the low marsh.

2.3.3. Vegetation

The distribution of intertidal plant species shows a zonation related to the frequency of flooding or to the elevation above mean sea level. Flooding can be the result of a temporary rise in the sea level because of a storm as well as of the high spring tides.

Generally, the pioneer vegetation of the salt marsh settles near the mean high tide level and also between mean high tide and mean sea level where the coast is flat and sheltered against waves and where the degree of consolidation of the sediment is already firm enough.

The salt marsh vegetation strongly influences the accumulation of sediment. Indeed, it creates favourable conditions for sedimentation: reduction of the flow when the marsh is submerged so that suspended matter is deposited, and protection of the sediment against erosion both by dampening and reduction near the bottom of waves, and by consolidating the sediment with roots. (Eisma, 1997)

The type of vegetation can also have a decisive influence on sediment deposition: for example, *Spartina alterniflora* collect suspended matter as a film on stems and leaves, whereas at *Juncus* sp. such films are absent. (Leonard *et al.*, 1995)

2.3.4. Intertidal fauna

Activities of organisms influence sedimentation and erosion as well as the physical and chemical nature of sediments. Benthic organisms usually occur in high densities. Indeed estuaries are among the most productive regions in the sea because of the high primary production due to the important nutrient inputs. But in our area, because of a high salinity (>> 5‰), few species survive and colonize the area in great numbers.

Biota affect intertidal sediments and sedimentation in a number ways: Biodeposition (fecal and pseudofecal materials), bioturbation, surface traces, shear strength of the sediment increased by mucus, disturbance of the water velocity by the structures, increase of the sediment permeability by burrowing organisms (exchange sediment/water), and biogenic particles (siliceous or carbonate exoskeletons). (Eisma, 1997)

In our area, it was shown that the tubiculous amphipod *Corophium volutator*, and the foraging activities of birds and fish, may increase roughness of the surface, and thereby increase its susceptibility to erosion. In addition, by controlling the growth of diatoms, *Corophium* probably decreases the enhancement of cohesion related to mucus secreted by the diatoms. The combined effect is to increase sediment erodability.

It seems probable that the arrival of the migratory shorebirds during summer, which are benthic predators, produces an effect that 'cascades' down the food chain to: affect *Corophium* behaviour, decrease grazing pressure on diatoms, increase mucus production, increase surficial cohesion, increase water content, and decrease erodability (Daborn, 1991).

2.3.5. Ice destructive and protective action

The salt marsh and the upper flat are covered by ice in winter. The scouring and compaction effects of ice are some potentially important factors in determining the degree of consolidation of the mudflat. Although this ice cover protects the intertidal flats against wave action, the ice is continuously fragmented and mobilized by tidal action, and can heavily scour tidal flats by disturbing the sediment surface and subsequent resuspension, as well as by ice-rafting. In the latter process, all sediment sizes, even up to boulders, can be transported and redeposited on the tidal flats or on the salt marsh. This explains why sediments of all sizes are dispersed on the flat. Carried by tidal currents, ice cakes up to several meters wide can move large amounts of all sediment size across the area. Sedimentation rates during the summer are high; therefore, scarves produced by ice rafting are not preserved.(Knight and Dalrymple, 1976; Daborn, 1991; Perillo *et al.*, 1993; Eisma, 1997)

2.3.6. Storms and Hurricanes

Waves resulting from hurricane force gales cause extensive erosion of salt marsh and intertidal sediments. Induced erosion does not affect the morphology of the main channels, more than during calm days. In the Minas Basin, after a hurricane and storm events in the summer 1975, with a wind direction parallel to the maximum stretch of the basin, consequences on tidal flats were observed. Maximum erosion occurred lower in the intertidal zone where wave activity was higher, due to the slope of the flat. In some cases, up to tens of centimetres of surface material was removed. The result of this erosion was to leave behind a residual veneer of fine sand, significantly coarser than the material originally present on the flats.

Also, resulting of this drastic erosion, the mortality in shallow-burrowing organisms (*Corophium volutator*, *Macoma balthica*) was high and the whole population was affected for the next two years (Yeo and Risk, 1979; Yeo and Risk, 1981).

2.3.7. Sea Level Rise

The increase of mean sea level modifies the system by inducing a relative decrease of the altitude of terrestrial surfaces. But a study led by Danika van Proosdij in the Cumberland Basin (North upper Bay of Fundy) showed that the vertical accretion of the salt marsh was greater than the forecasted sea level rise. And even if the vertical salt marsh accretion is partly controlled by this sea level rise, it seems that the marsh also responds through horizontal translations of its edge. (van Proosdij *et al.*, 2003)

2.4. Dyke management and shore protection history

The first French settlers moved on the area around 1682 and began to build the dykes of Grand Pré and the Canard River and certainly around the Cornwallis Estuary (called "Rivière Saint-Antoine" whereas Starrs Point was called "Côte de Boudreau"). The dykes were built on former salt marshes, so numerous salt marshes were lost. At the beginning of the 1700's, the dyke on the left bank seems to already exist. Small ferries also enabled the Acadians to travel between Starrs Point and Grand Pré or to go down the Cornwallis River to New Minas. (Surette-Draper, 2004)

Historically, all of the Southern Bight coastal watersheds had more or less extensive salt marshes. A 1724 map by Morris shows that the Canard watershed (northern shore of Starrs Point) was tidal for almost all its area, and represented a large fraction of all of the salt marsh in the region. The Morris map holds particular interest because it does not indicate any marsh in the area of Grand Pre: presumably this had been largely recaptured by dyking by that time. (Daborn *et al.*, 2004)

History tells us that the left bank of the estuary is also one of the points of embarkation for the Acadians living on this side of the Cornwallis River at the time of the Deportation. In those days, Starrs Point was the largest hamlet in the area.

After the Acadian expulsion, the fertile lands lay empty, New England settlers, known as planters, invited by Nova Scotia, came and designated a town site to be known as Town Plot, which was never developed. At this period dykes were still here (*cf.* Planters cairn at Town Plot).

Until the Maritime Marshland Rehabilitation Act (1948), landowners had maintained the good state of the dykes by themselves. And then during MMRA, during the 1960's, works on the elevation of the dyke and on the aboiteaux were done (project No NS8 for the Grand-Pré's dyke and NS80 for the Starrs Point's dyke).

Since the NSDAF manages the dykelands, Starrs Point has had very little changes in dykes or protections over the last 30 years, although the salt marsh has changed considerably. The bridge at Port Williams was replaced about 25 years ago, although it certainly had no effect on channel changes next to Starrs Point marsh. The bridge was replaced at basically the same location with no major changes in cross sectional area.

Finally, rocks and riprap* protection have been added to 725 m along the right bank dyke downstream of Wolfville Harbour, over the last 20 years. Local erosion near the southern extremity of the Starrs Point dyke obliged the NSDAF to put rocky protection on different spots several years ago (photo 1).

3. METHODOLOGY

3.1. Data

3.1.1. Aerial photographs

This study is based on the use of aerial photographs. Different sets were furnished by Hank Kolstee from the Nova Scotia Department of Agriculture and Fisheries. The choice of the aerial photograph campaign dates was based on the stage of the tide. Indeed, only the photographs taken during a low tide and the summer time were of interest to have a good view of the whole area. The July 1977, September 1992 and September and July 2002 sets were used because they were the most relevant (maps 7, 8 and 9).

These aerial photographs were scanned with a 600 dpi resolution which gives a 0.5 meter ground resolution, which is a good deal between resolution and the file sizes. During and after scanning, an adjustment on the levels and contrasts of each photographs with Adobe Photoshop 5.5 permitted a larger range of pixel colors in the estuary area and easier distinguishing of features by texture. These raster files were saved uncompressed under the TIF format to keep an optimal quality.

3.1.2. Other data

GIS data from the NTS map sheets were used to orthorectify and georeference the aerial photographs. These data of 1996 consist on 1:10,000 maps based on the North American Datum* 1983 (NAD83) geographic coordinate system and georeferenced with the Universal Transverse Mercator projection (zone 20N). Many different vector data, in point, polyline and polygon shapes, are included such as roads, river streams, railways, dykes, coastline, marsh outlines, buildings, wood areas, topographic contour lines, and many others. The section 021H01, which includes the Cornwallis estuary, was used for this study.

GIS data provided by Danika van Proosdij, from the Maritime Provinces Spatial Analysis Research Center of Saint Mary's University, have completed these data. These GIS vector shapes included roads, streams and coastline, which were a bit more detailed than the NTS sheets.

A 2 m resolution Digital Elevation Model* (DEM) derived from a LIDAR campaign conducted on May 2003 was used (map14). LIDAR* is an acronym for “LIght Detection And Ranging” which is a Laser Radar technology using a plane to obtain topographic data. This DEM was generously provided by Timothy Webster from the Applied Geomatic Research Group (AGRG). The referenced Datum of the DEM was the Canadian Geodetic Vertical Datum 1928 (CGVD28) which is different from the NAD83, because the datum is the mean sea level (MSL) for the CGVD28 and the datum is a geocentric ellipsoid for the NAD83.

LISP 89 data as sediment data and bathymetric map (1989) (map 16), and data from the one day field trip (July 2005) as erosion/accretion and currents observations were also used.

3.2. Field work (observations, measurements)

Work on aerial photographs need field ground truthing to have a good idea of the area, and to do correlations between reality and photographs. Thus, a whole day field trip was scheduled on Wednesday, July 27th, 2005 in the Cornwallis estuary. This day was chosen for the spring tide in order to observe much of the sedimentology of the estuary as possible.

Numerous pictures of our observations were taken and some of them have been joined with Adobe Photoshop 5.5 to build panoramic view of the banks (*cf.* “Photographs” chapter).

3.2.1. Vegetation

Particular attention was taken for the vegetation areas. The recognition of tidal marsh plants and their distribution within the marsh zonation gave us a good idea of the zonation of the salt marsh. Thus, by comparison between the field observations and the most recent aerial photographs, an extrapolation on the whole area was done.

Vegetation is a good indicator of the dynamism of the channel river edges. Tidal marsh vegetation grows in restricted areas and meets constraining conditions: high salinity and tidal levels and flooding. Each tidal marsh species requires specific growth demands and, thus, reflects typical conditions of the system: elevation and tidal inundation period and frequency.

Plants are producers of organic material, which in turn becomes food for other species or decomposes into nutrients. Once the salt water cord grass establishes itself in a salt marsh, other salt-loving plants follow. These plants are termed halophytic and have the unique ability to excrete excess salt and/or retain water.

Larger salt marshes can be divided into two sections, the high and the low marsh. Each has a distinct plant community.

During our field trip day we could recognize the following areas of the salt marsh and the associated plants:

- **Low marsh**
  - ***Spartina alterniflora*** (Smooth Cordgrass) is a salt-water cord-grass which is a tough grass that forms dense stands (up to 2 m tall) in saline areas close to the water and can withstand being submerged. This cord grass is found primarily in the low marsh and forms the majority of the Cornwallis Estuary low marsh. It can occur intermixed with *Juncus sp.* (as Black Rush) in brackish areas.
  - ***Juncus sp.*** (rush) occurs in shallow ponds in salt marshes that are created by poor drainage, uneven distribution of sediment, or ice scouring. Rushes are often found mixed in with the cord-grasses or alone forming stands in the mud in our study area.
- **Middle marsh**

  The middle marsh is an intermediary area where growth a pattern of the low and high marshes intermixed.
- **High marsh**
  - ***Spartina patens*** (Salt-Meadow Cordgrass) is generally found abundantly in dense stands on higher elevations of saline marsh, especially near upland areas. In the

Cornwallis Estuary, Salt-meadow Grass forms large meadows further away from the tide line in the high marsh. It is also found intermixed with *Juncus* sp. (as Black Rush) in brackish marshes.

- ***Juncus sp***. as above.
- ***Limonium carolinianum*** (Sea Lavender) has mauve flowers in summer, but during our field trip, the flowering was just beginning. It grows generally in saline marshes and sandy salt flat. In the area, the Sea Lavender distribution is spotty.
- ***Salicornia sp.*** (Glasswort) is an annual plant to 60 cm tall. Pale green to green it is succulent and stout, often turning red or reddish at maturity (fall). Very few plants were observed.
- ***Triglochin sp***. (Arrow-grass) is a perennial plant to 60 cm tall. It is infrequent and, dependant on species, it can occur in brackish marshes near small sources of fresh water from upland drainage. We observed few Arrow-grass high on the high marsh.

(Eleuterius, 1990; NSMNH, 1997)

3.2.2. Sedimentology

The formation of physical sedimentary structures is basically subject to hydrodynamic processes. However, the intertidal environments distinguished from other environments as current strength varies greatly, and current reversals occur twice a day, while depth varies with the tidal amplitude (Eisma, 1997). Thus, sedimentary structures could indicate the main current direction, the flood or ebb dominance, or the current velocity and a good picture of mean hydrodynamics.

Accurate observations of the bedforms in the river channel should have been made if we had the opportunity, but the short low tide and the instability of mudflats were not favourable. Rough observations of these bedforms (essentially sediment type: mud, sand, etc) from the banks and the salt marshes were made as well as observations of the erosion/accretion structures along the tidal channels was possible. Thus erosional structures such as cliffs and landslides in cohesive sediments, could be observed on both the flood and ebb channels, and they are due to both or one of theses dominating currents. The accretion structures form smooth and soft mud accumulations, gently inclined, and occur where hydrodynamics is quieter, as in the internal part of meanders (point bar*) (map 11).

In association of these observations, care was exercised to the tidal flow pattern during the whole tidal cycle in order to localize the diverse current intensities in the channel, as well as the preferred channels during the ebbing and flooding tides.

We also attempted to sample sediment (8 samples) in several locations to have an idea of the hydrodynamics along the channels.

After coming back to the Bedford Institute of Oceanography (BIO), unconsolidated bottom sediment samples were analysed with a TAII Coulter Counter, which is an electroresistance particle size analyser. This device is suitable for grain size analysis of sediment in the size range 0.5 – 1000 μm. It determines the number and volume of particles held in an electrolyte suspension. Particles, in a dilute suspension, drawn through a constant current kept between two electrodes, displaces its equivalent volume of electrolyte. This induces fluctuations in impedance which are detected as voltage pulses proportional to the volume particle. The output is a graph of the grain size distribution of the sediment sample (Milligan and Kranck, 1991).

3.3. GIS preparation (georeferencing*, orthorectification* and mosaics)

The Environmental Systems Research Institute (ESRI) Geographic Information System* (GIS) software ArcView 8.3 has been used for all the GIS work. This software includes the ArcMap, ArcCatalog, ArcToolbox and ArcScene moduls. Specific tools like Spatial Analyst, 3D analyst and XTools pro 3.0 were used.

During the GIS process, when you wish to analyse data, preliminary steps must be taken to prepare the data.

Concerning the raster files (scanned aerial photographs or paper maps), we had to orthorectify and georeference them. These operations waere done with the georeferencing* tool by choosing numerous control points referenced on a already georeferenced referential layer. Statistical error (RMS error) is reduced by the multiplication of the control points. The referential layer chosen was the National Topographic System map sheet (roads) (map 10).

Each aerial photograph covers an area of about 2.4 by 2.4 kms, so several were needed to cover the estuary area. This results in several large size files, and the use of a mosaic of the georeferenced photographs was proved to be more practical. The Maritime Provinces Spatial Analysis Research Center of Saint Mary's University has already worked on salt marsh evolution in the Minas Basin based on aerial photographs. They used a customized Arc Macro Language to create the mosaics. Having done the mosaics of the Cornwallis Estuary area, the 1977, 1992 and 2002 mosaics were generously provided.

Each mosaic was based on the NAD83 geographic coordinate system, georeferenced with the UTM projection (zone 20N) and had a 1 m resolution. Unfortunately to do an assessment of the estuary accurate photographs are needed, and in some areas of the 1977 and 2002 mosaics, where georeferencing knows significant errors because of the lack of reference points in the mudflats, showed disturbing overlaps. The 1977 and 2002 scanned photos were kept, as well as the 1992 mosaic and the southern part of the 2002 mosaic that were lacking on our aerial photo set (maps 7, 8 and 9).

Because of the evolutionary assessment of the estuary, we chose a reference year for the georeferencing. Indeed, the 1:10,000 NTS sheets are not accurate enough to do an accurate georeferencing. Georeferencing the aerial photos on a unique set with much more control features permitted the most exact overlapping of each photo. We chose the 1992 mosaic because of the central position in time. This mosaic was georeferenced on the NTS sheets in the NAD83 geographic coordinate system and with the UTM projection (zone 20N). The other mosaics and aerial photographs were adjusted on the 1992 mosaic and few local corrections were made with the NTS sheet, when needed. All the other georeferencings and orthorectifications were made on the reference 1992 mosaic.

The large sizes of some mosaics were reduced by using the ECW compression technique (Enhance Compression Wavelet).

Based on the area covered by the aerial photos, the study area was precisely defined. As the 1977 photos did not cover the whole area (south parts of the main channel were cut), two study areas were used: the 1977 study area, which covers 11 km^2, and the general study area which is the extent of all interesting areas of the estuary. The general study area covers 15 km^2.

3.4. GIS analysis (feature choice, digitization and computing)

3.4.1. Field data analysis

The field data were only qualitative observations and not quantitative measurements. Thus they were mainly used to corroborate the aerial photograph feature observations (vegetation, sedimentary structures and hydrodynamics), by comparison with the most recent photographs (2002 set).

Vegetation observations allowed highlighting of the visual differences between the high, middle and low marshes on the aerial photograph sets.

Sediment samples were plotted in the GIS and compared to grain size distributions found in other studies.

Accretion and erosion dominance observed and photographed along the banks of the estuary were transferred under GIS. They allowed a better identification of the sedimentation/erosion and hydrodynamics along the tidal channels on the aerial photos.

Sedimentary features observed and photographed in the channels from the banks gave ideas of sediment grain sizes and hydrodynamics. This was particularly true for the sandbar located in the river channel at the south of Willow Point.

Finally observations of the flood and ebb currents and channels were partly used to build preferential tidal flows.

3.4.2. Aerial photograph data extraction and digitization

Extraction of data from aerial photographs requires field observations or measurements, general knowledge of the system and the area, and also requires to intersect others data. But unfortunately visual extraction is guided by the operator and is therefore potentially subjective.

3.4.2.1. Dykes

Polyline shape files the dykes, aboiteaux and embankments were drawn from the reference 1992 mosaic. From pictures taken in the field, the 2002 photographs and the 1992 mosaic were digitized and the ripraps added during the last few decades by the NSDAF. GIS Calculations with XTools Pro have been done to obtain the total length of the dykes and of the banks of the estuary in our study area.

3.4.2.2. Salt marsh area (map 12)

On the different sets of aerial photos, vegetation color changes because of the different ages, height and stages of growth of the vegetation, the sun height and shade, and finally because of the photograph quality. Thus, it was not always easy to differentiate the low marsh from the high marsh. After going in the field, however, vegetation differentiation in the aerial photographs was quite clear.

We digitzed the different zonation of the marsh in polygone vector layers, associating a visual density index number depending on the density of the marsh. So that light density is often a good indicator for recent low marsh colonization.

The set comparison permitted visualization of the evolution of the salt marsh and the river channels, and gives a good indication of the accretion areas and salt marsh cliff erosion.

GIS calculations with the XTools Pro and 3D Analyst modules were done to obtain surfaces of the salt marsh (high and low marshes) and evolution of its extent.

As well differential maps showing gain and loss of vegetation between 1977, 1992 and 2002, have been obtained by intersecting the layers with the Geoprocessing tools of ArcMap.

3.4.2.3. Intertidal area (map 13)

The aerial photographs were taken at low tide, so they give an overview of the bottom sedimentation in the tidal channels. In these channels occur sedimentation, transport and erosion depending essentially on hyrdodynamism and sediment characteristics as shown in the Hjulstrom diagram (fig. 8). The distribution of the sedimentary features (mudflats, sand flats, sandbars, cliffs) and sediment grain sizes (mud, sand) will occur depending on the particle sizes and the tidal currents. However, we must exercise extreme care because of the combined action of the flooding and ebbing tide, which give a complex hydrodynamic pattern. Moreover, observation on the photographs has not been precisely verified on the field: on the photos, color and texture of the sediment can drastically change because of the water content, the mineralogy and the sun illumination.

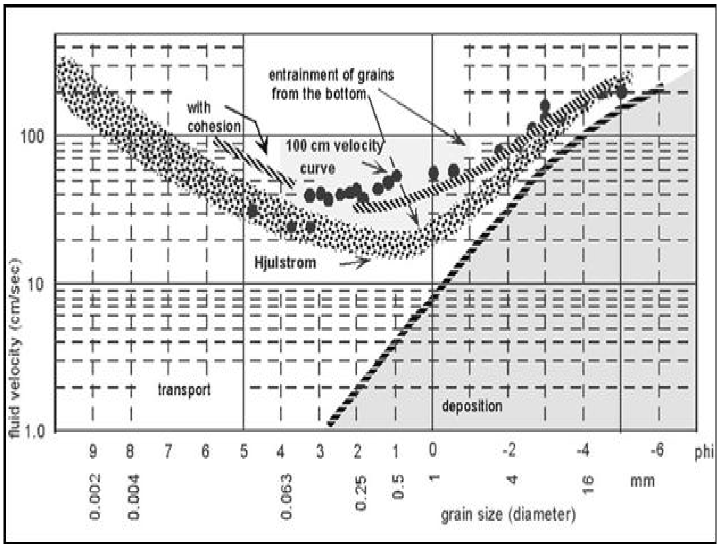


Figure 8. Hjulstom diagram.

This digitization* will give only a possible picture of the hydrosedimentary processes* (transport, erosion, deposition and flow characteristics) in the estuary and should be confronted with all the other data to confirm the results.

Thus, based on a study of Yeo and Risk (1981) on the sedimentology and stratigraphy of the intertidal deposits in the Minas Basin system, representative sedimentary structures were chosen. Yeo and Risk defined a classification of six major depositional facies* related to the intertidal zone sediments in the Minas Basin (Yeo and Risk, 1981). By observing the aerial photographs, and the definitions of these depositional facies, those could be kept to define the different features that could be easily distinguished.

An ideal vertical section of a preserved stratigraphy for the upper intertidal zone is illustrated in Yeo and Risk's study. It is a reflection of the evolution in time of the intertidal estuarine zone, and thus it is an ideal cross section of this zone. In our area, the sedimentary facies succession is as follow: Salt Marsh, Upper Mudflat, Lower Mudflat, Mixed Flat, Sand Flat, Channel Lag, Sandbar. Sedimentary structure would reflect a transition from suspension processes in the upper mudflat to mixed suspension-bed load transport in the lower mudflat to traction-deposition in the mixed mudflat-sand flat.

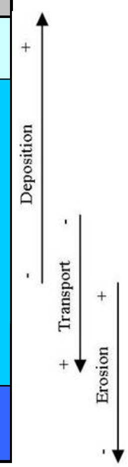
Also for the GIS analysis, an empirical index number was defined related with the hydrosedimentary processes. This index number was based on the Hjulstrom diagram and flow velocity observations in our area. The index number is approximatively equal to the logarithm of the mean current velocity found around the sediment feature (table 2).

During the digitization in polygon vector layers, the index number will be associated with the sedimentary feature chosen. Unfortunately, objectivity can not be guaranteed in the shapes of the features as in the choice of the index.

Also the different maps were converted to raster, then converted to point shape files, which were interpolated under an analysis mask of the whole estuary in order to give homogeneity to the hydrosedimentary process. The interest of these manipulations is only to see the evolution of the sedimentary processes in the estuary by subtraction of the obtained maps.

Table 2. Classification of the different sedimentary features with the associated empirical index number.

Sedimentary features	***Dominant sediment size***	***Mean flow velocity (cm.s-1)***	***Logarythm of mean flow velocity***	***Index Number***	***Tide exposure***
Salt marsh	Clay and silt	around 0	0.00	**0**	extreme high tide
Mudflat (upper to lower)	Silt	< 1.5	< 0.20	**1 to 3**	Low tide ---> High tide
Mixed mudflat	Silt and fine sand	1 to 8	0 to 0.9	**3 to 5**	
Sand flat	Sand	1 to 15	0.70 to 1.20	**5,6**	
Sandbar	Sand and gravel	10 to 35	1 to 1.50	**5 to 8**	
Channel lag	Sand and gravel	> 20	> 1.3	**6 to 9**	
Cliffs	Consolidated clay, silt or sand	> 40	> 1.6	**9, 10**	low tide to high tide



a. Upper and Lower Mudflat Facies (Yeo and Risk, 1981)

This facies consists of a continuum of progressively coarser sediments across the intertidal zone toward low tide. Because wave and/or current energy decreases shoreward in the intertidal zone, mud deposition occurs near high tide while sands lie closer to low water levels.

Mudflat is composed of more 20 % of silt and clay by weight with a mean grain size <0.125 mm. The mudflat-sandflat boundary is usually an abrupt change from cohesive sediment to non-cohesive, coarse, rippled and megarippled sand. The mudflat is also marked by the lowest occurrence of *Corophium* and the bivalve *Macoma balthica*.

Two subfacies can also be distinguished:

- Upper mudflat where sediment is a poorly sorted sandy and clayey silts (2-31 µm). Small and abundant channels occur with usually a lack of basal lag deposit.
- Lower mudflat where sediment consists of 50-80 % of very fine sand (31 – 125 µm). We could notice the presence of interference and current ripples and at low tide mud cracks could be observed. *Corophium* and *Macoma* populations are 2-3 times higher than in the upper mudflat. This subfacies is cut by deeper channels which display lateral migration features similar to point bar deposits.

b. Mixed Mudflat Facies (Yeo and Risk, 1981)

This minor facies between the lower mudflats and sandflats is composed of gravelly sands with 10-15% silt. Small populations of *Corophium* and *Mya arenaria* occur. Wavy bedding, flashers, lenticular sands, rippled cross bedding, gravel filled scours could be observed. Sand-gravel lag, approximately 10 cm depth, from meandering and laterally aggrading tidal channels rich in shell material could be observed.

c. Sandflat Facies (Yeo and Risk, 1981)

This occurs seaward of the mudflat zone. Sediment is very well sorted with fine to coarse sands and <15% mud (0.2-1 mm). Grain size increases seaward due to increasing tidal current energies. Wave and current ripple cross lamination, plane bed lamination and flashers could be observed. Tubiculous polychaetes are abundant but patchy in distribution.

d. Channel Lag Facies (Yeo and Risk, 1981)

This is a transitional facies from the upper intertidal zone to the lower or outer intertidal zone, and it can extend to the subtidal zone. Flood tide channels are opposed to ebb channels. Coarse sands, gravels, cobbles, boulders and even exposures of bedrock compose the bottom. Much of the sand found at low tide is derived from nearby sand bodies and deposited during late stages of tidal ebb. Concentration of shell debris could be observed. Except for current rippled-sands, sedimentary structures are rare.

e. Sandbar Facies (Yeo and Risk, 1981)

Differentiated from the sand flat facies by the sedimentary structures and by the position in the intertidal zone, sandbars occur furthest seaward and are separated from the sand flats by a tidal channel. They are generally parallel to the shore, and the sediment is composed of sand to granule-size material (0.1-4 mm). Large scale of bedforms distinguished this facies from the sand flats: megaripples (sinuous or straight crested, ebb or flood dominated) and large ripple forms. Occurrence of smaller features on larger bedforms could be observed.

3.4.2.4. *Channels (map 17)*

The line of lowest points along the tidal channels, which is always submerged, is not located in the middle of the channels because they are not symmetric. Thus for each channel, lines were deduced from the sinuosity of the river and the morphology of the channel. A digitization in a polyline layer was also use, which has allowed a preliminary description of the evolution of the tidal channels.

To sum up the different features digtlized the following cross section (fig. 9) shows an ideal picture of the vegetation and sedimentology perpendicular to the main channel.

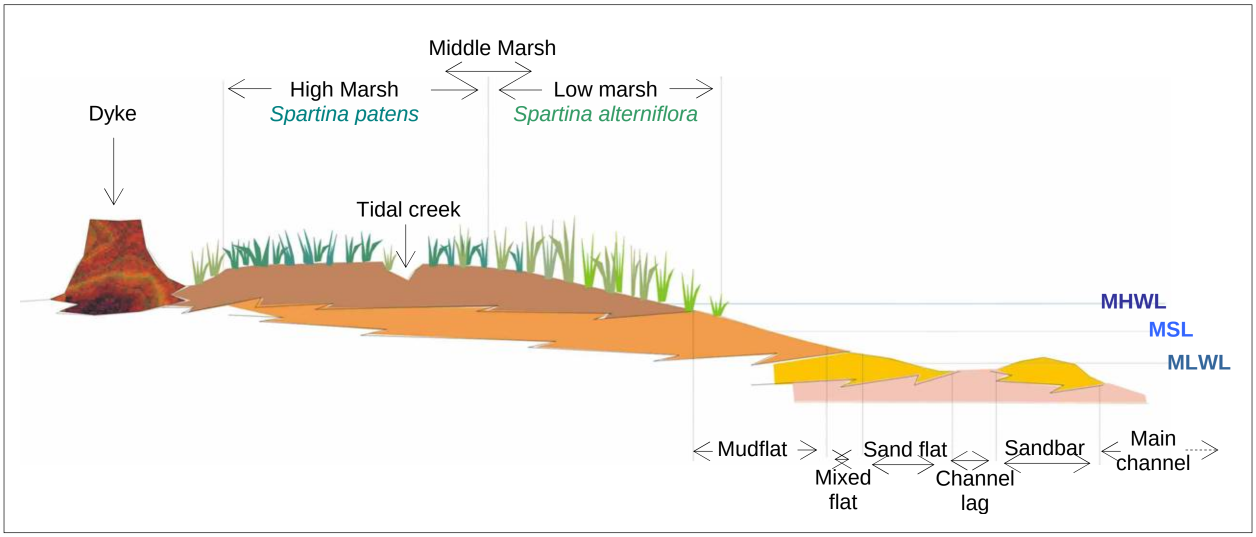


Figure 9. Ideal cross section of theCornwallis estuary bank.

3.4.3. LIDAR DEM analysis (map 14 and 15)

Two meter resolution DEM was firstly used to calculate the volume of the middle bank and the oscillating volume of the tide with the 3D Analyst tool (fig. 10). Then a calculation of the slopes was operated in order to visualize the high slope areas, which are usually associated with erosion. Also, surface calculations of the marsh were done from the topography, with the 3D analyst module, to give confirmation to the XTools Pro results. And finally, much topographic and bathymetric information were extracted for this useful DEM.

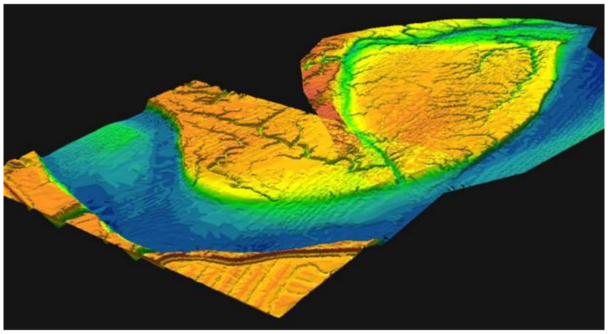


Figure 10. 3D view of the Cornwallis Estuary, TIN of the LIDAR DEM using ArcScene (vertical exaggeration).

3.4.4. LISP data analysis (map 16)

A LISP 89 bathymetric map was produced by echo-sounder profiles measured in August 1989. Its datum matches approximately with the mean low water level. Thus the mean tidal amplitude being around 11.5 m and symmetric around the mean sea level (MSL), a correction of about -5.75 m was done to fit altitude with the MSL datum.

The paper map was scanned and the isohypses* have been digitized into polylines. A DEM was then created by using the Triangulated Irregular Network method (TIN) with hardlines (fig. 11). From this TIN, slope calculations and comparison with the LIDAR DEM have been done.

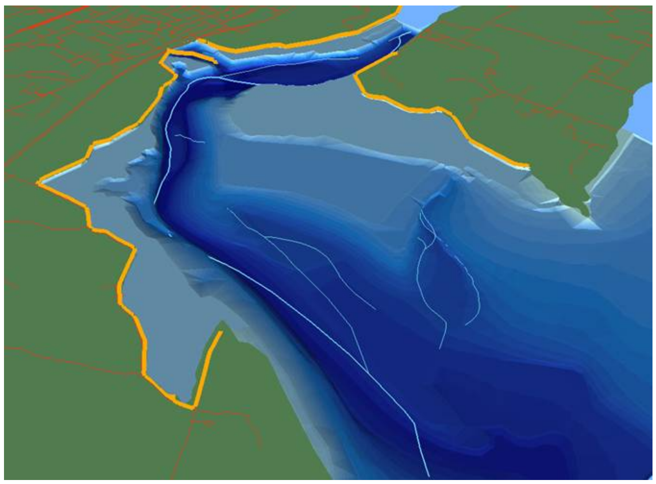


Figure 11. TIN of the LISP 89 digitized bathymetric data (ArcScene 3D view with vertical exaggeration)

4. RESULTS AND INTERPRETATION

4.1. Data set comparison and calculation

4.1.1. Channels (map 17)

4.1.1.1. Main channel

Looking at the main channel evolution, it was concluded that evolution occurs mostly in the concave parts of the curves, and the trend is an increase in curvature. These channel modifications have a strong relationship with the areas of cliff erosion. Along the south shore which was strengthened by riprap during the last decades, the main channel has not changed for 30 years.

4.1.1.2. Sandbars

The largest sandbars are limited by the tidal channels, and it was observed that sandbars at the mouth seem to change a lot over time. From this it was concluded that the sediment at the mouth is not lag, and that transport and erosion is very active.

These phenomena may be more active than around the sandbar at the head of the study area, likely a result of the more restricted river bed. The large sandbar underwent evolutions in its shape by changes in small transversal channels, but generally it stayed surrounded by the main tidal channel, ebb dominated at the north and a secondary tidal channel, flood dominated, at the south.

4.1.1.3. Tidal channel between the middle mudflat and the left bank salt marsh

This secondary channel is the final output for the drainage creeks of the left bank salt marsh. Between 1977 and 1992 a light westward migration was observed, maybe related to an increase of sedimentation on the middle mudflat, but after 1992 no significant changes occurred.

4.1.1.4. Northern middle mudflat channels

During the last decades, these channels seem to change a lot as did the sandbars at the mouth, with possible shoreward stabilization induced by a sediment elevation. The moving nature of these channels is possibly due to wave and transport dominated processes related to the open body of the Minas Basin, but nothing allows us to say if these changes occur only after storm events. The shifting nature of the channels shows that the sediments of the area are unconsolidated and subject to active transportation.

4.1.2. Salt Marsh Vegetation (map 18)

The surface of salt marshes covered in the study area occupies 30 to 35% of the estuary depending on the year. However this study did not take into account the tidal creeks and guzzles, which account for around 15% of the surface salt marsh calculation. This estimation was obtained by surface computing with 3D Analyst, based on the LIDAR DEM. Also in the study area, the mean altitude of the transitional limit mudflat-low marsh is around 3 m and the transitional limit of low marsh to high marsh is around 6 m (MSL datum).

4.1.2.1. Low marsh/High marsh dynamic

Differentiation between low marsh and high marsh is not an easy task using the aerial photographs, and digitization of the middle marsh is not objective enough to make conclusions on this part of the marsh.

In general, though, we can observe a trend of high marsh gain on the left bank, which could indicate slow elevation of the marsh (fig. 12). On the right bank the dynamic between the two main areas of the marsh seem to be stable, with only local changes.

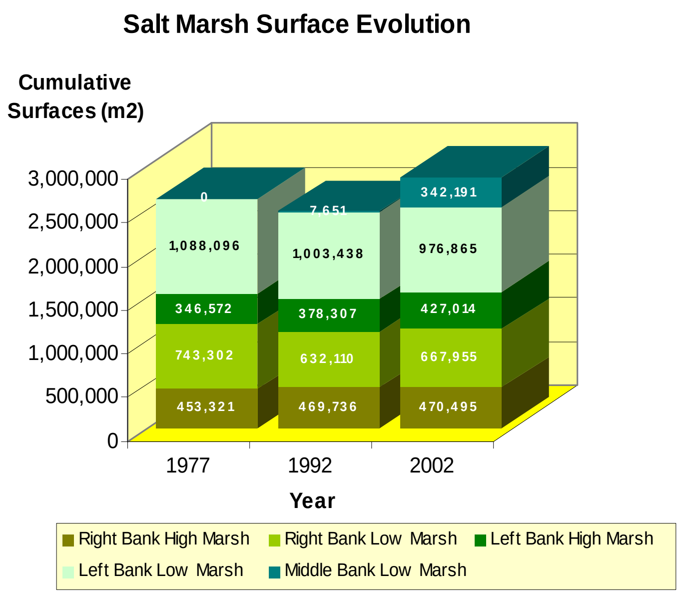


Figure 12. Surace evolution of the Cornwallis estuary salt marsh (Study area of 1977).

On the middle mudflat, the colonization by the low marsh is quite impressive with an exponential surficial growth. From small patches in 1992, it grows up to more than 340,000 m^2 in 10 years. This exponential growth is comparable to the salt marsh growth at the Windsor causeway. On this quiet mudflat, it shows that elevation became sufficient to induce low marsh settlement, indicating accretion in this area of the estuary.

Sediments could come from erosion in the main channel or reworking of sediments of the mudflats. Indeed the northern mudflats (Starrs Point) could be a huge source of fine sediments if only erosion occurs there.

4.1.2.2. Salt marsh edge dynamic

The comparative map of the evolution of the salt marsh extension shows the loss and gain of vegetation in the estuary. Loss is almost always due to erosion on the tidal channel banks, by cliff regression, or mudflat erosion. Gain of vegetation is induced by sufficient accumulation of fine sediment in sheltered and hydrodynamically favorable areas.

An error of 5 meters on the length measurements should be applied in the major part of the study area. This error is mainly due to the fact that the overlapping of the three aerial photo sets is not perfect because of georeferencing error. In the western part, only covered by the 1992 and 2002 photos sets, no conclusions could be made because the error reached a maximum of 10 m.

a. Left bank

The left bank edge is portrayed in 4 erosion/sedimentation sets:

1. On the South part of the salt marsh, the cliffs are 11 meter high and erosion occurs. This erosion is of concern because it could threaten the dykes directly upstream. In fact, erosion pressure is mainly concentrated on the concavity of the bank, but with regressive

erosion and local turbulences, the bank at the foot of the dyke is eroded (photo 2). Calculations with the 3D analyst module have been done by intersecting the LIDAR bathymetric map with the loss of salt marsh. The results are given in the following table (table 3).

Table 3. Withdrawal of the salt marsh cliffs of the left bank (3D analyst calculations).

Period	Lost area (m^2)	surficial erosion speed (m^2/year)	Maximal cliff withdrawal (m)	Maximal withdrawal speed (m/year)	Lost volume (m^3)	Lost volume speed (m^3/year)
1977-1992	26900	1793	55	3.66	-	-
1992-2002	20900	2090	40	4	-	-
1977-2002	47800	1912	95	3.8	387,000	15176

Using these figures, nearly a maximum of 100 meters of salt marsh between 1977 and 2002 were lost. The eroded volume of the marsh (calculated in only this section), reaches 390,000 m^3 in 25 years or around 15,000 m^3 each year. Unfortunately, the error of these results (+/- 5 m) is too high to conclude on a real increase. The phenomenon seems to have constancy in a medium time scale, but according to previous observations, maximal erosion could occur during high energy events such as spring tides or the transport of ice blocks.

2. On the southeastern part of the salt marsh, the low marsh colonized new areas of mudflats with a southeastward stretch, resulting from the aggradation* of the point bar, a convex area of the meander (photo 3). A maximal extension of 100 meters toward the channel was measured and calculations give a total area of 40,600 m^2 colonized since 1977. First, colonization was patchy, and then, between 1992 and 2002, extensive colonization of the whole area occurred.
3. Along the channel between the salt marsh and the middle bank, there is slight erosion between 1977 and 2002 with a slowing down in the 1990's: a mean loss of 15 meters until 1992 and of 7 meters until 2002.
4. Finally at the north end of the marsh, near Starrs Point, slow colonization with little local loss has occurred during the last 30 years. With vegetation spreading into the muddy spaces between the newly colonized patches, the vegetation density increased.

b. Middle Bank

Here, a spectacular exponential growth was seen between 1992 and 2002, and seems to continue. Salt marsh grew to more than 340,000 m^2 in 10 years, and a crown of *Spartina alterniflora* patches settled around the new salt marsh. Without any strong disturbances, the empty silty spaces between them will be filled by the low marsh vegetation, following the typical colonization strategy.

c. Right Bank

After the first curve, along the sandbar and just across the channel from the left bank cliffs occurs more and more erosion going downstream. Vegetation loss rate seems to have been constant between 1977 and 2002 and a mean withdrawal of 30 to 35 meters was calculated (more than 1 m per year). In the concavity of the meander, we have only data for the 1992 and 2002 periods, and the mean withdrawal rate of 1 meter per year still appears correct.

Further, where riprap was put, loss of vegetation is minimal, around 3 to 4 meters since 1992. But these figures are smaller than the error, so direct conclusions cannot be made; moreover it appears that riprap has totally stopped erosion.

Further, where the salt marsh is wider and where riprap is further from the bank edge, 11 m high cliffs compose the edge of the salt marsh, and withdrawal of vegetation is almost as intense as on the left bank cliffs. A maximum of 70 meters of withdrawal is measured (45 m between 1977 and 1992, 25 m between 1992 and 2002), a total marsh surface of 33,300 m^2 has been lost since 1977. On this central part of the marsh near the mouths of the main tidal creeks vegetation progresses, but between them vegetation regresses.

In the rest of the marsh, a 900 m long band on the north-south oriented bank, constant loss of vegetation about 25 meters since 1977, occurred, a reflection of slow erosion. Near the Long Island side, at the estuary mouth, salt marsh seems to be in balance during the last 3 decades.

4.1.3. Intertidal flats and hydrosedimentary processes (map 19)

a. Sedimentological facies distribution

Comparison of the sedimentary facies distribution in time does not tell us more about sedimentary movement than the previous observations. However, we can more precisely see the modifications in the sandbar shapes, especially in the mouth of the estuary: in the main channel, hydrodynamics did not change along the years, but migration of the tidal channel leads to changes in the sandbar location. This confirms the observations made on the channel comparisons.

We also observed that the tidal channels that limit the northern side of the middle bank are highly reshaped. Channels changed, such as sandbars. Between 1997 and 2002, the middle mudflat had lost area at the north; the northern limit in 2002 was 150 m less than in 1977. It seems also that the channels began more stable after 1992, especially near the marsh. This observation must certainly be verified with long term monitoring, as comparisons were made with only 3 static photo sets.

Finally, the channel that separates the middle bank from the left bank seems to have been filled in during the last 25 years.

The interpolation by kriging* of the hydrodynamics deduced from the sedimentological facies distribution gives no new information, but a probable picture of the mean hydrodynamics in the channel and on the intertidal zones.

b. Hydrosedimentary changes

Two sorts of maps were created to view the changes in the hydrosedimentary processes: subtraction of the interpolated hydrosedimentary Index maps, which give a homogeneous picture of the changes, and direct subtraction of the rasterized map of the Index number.

The goal is the same for both maps: to highlight the sedimentary evolution of the channels and intertidal zones.

Observations of these maps confirm the previous notes.

Constant erosion of the cliff areas has occurred where the salt marsh regression has been severe during the last 3 decades. The sedimentation on the southeast side of the left bank salt marsh seems to have increased more between 1977 and 1992 than during the 1990's. Concerning the tidal channel between the left and middle banks, these maps highlight the fact that between 1977 and 1992, the channel has moved westward, which explains the loss of salt marsh on the left bank at this point. After 1992, the channel began to be filled by sedimentation. It was also observed that an erosion pressure exists on the north and the west sides of the middle bank. The dynamically unstable area of the south Starrs Point mudflats is highlighted by a mosaic of numerous sedimentary changes.

Concerning the right bank, after an erosional trend between 1977 and 1992, the hydrosedimentary processes seems to be better distributed with more accretion along the less exposed areas in recent years.

The map showing changes between 1977 and 2002 shows a trend on a longer time scale:

- Erosion, or more energetic hydrosedimentary processes on the right bank, in the concave meander of the left bank and on the north and west sides of the middle bank,
- sedimentation or less energetic sedimentary processes on the southern part of the Starrs Point mudflats, in the tidal channel between the left and middle banks and along the convexity of the left bank salt marsh.

4.1.4. Bathymetry and other observations

4.1.4.1. Bathymetric maps (maps 14, 15 and 16)

The bathymetric map established from the LIDAR data of 2003 was very useful to build a central channel line and to confirm what it could not be seen under the low tide water level. Numerous calculations have been made from this DEM and calculations were confirmed with the 3D Analyst tool.

A map of the bank slopes was also created. Thus areas could be defined as steep slope (in particular cliffs) which is often a result of erosion. Erosion of the concavity of the left bank, with high cliffs, as well as the high cliff area on the right bank, was obvious. The area on the right bank just after the curve, near the first large sandbar showed high slopes also. There, vegetation withdrawal was detected. Finally, an area along the east side of the middle bank showed a linear zone of slopes around 20 degrees. This slope rupture highlights the erosion pressure previously discussed.

The bathymetry TIN map obtained from the LISP 89 and the slope map induced were not accurate enough to conclude changes in 1989.

4.1.4.2. Calculations

Table 4. Middle mudflat volume calculation (3D analyst calculations).

Middle Bank calculations	**Above -1.5m**	**Above Mean Sea Level**
Surface of the bank (m^2)	$1,27*10^6$	$1,13*10^6$
Volume of the bank (m^3)	$4,28*10^6$	$2,48*10^6$

Calculations of the sedimentary volume of the middle bank were done using the LIDAR DEM (table 4). Two volumes were calculated: the volume above the Mean Sea Level and the volume above the altitude -1.5 m (Mean Sea Level Datum) which is an arbitrary reference point chosen because it better isolates the middle bank from the surrounding channels. Both sediments and interstitial water is included in these volume estimates.

A brief comparison of the creeks in the salt marshes show that on the left bank, the heads of tidal creeks (where the muddy bottom is not anymore visible on the aerial photographs) change in location. The heads moved seaward about 15 m between 1977 and 1992 and about 5 m between 1992 and 2002. On the right bank, salt marshes are too narrow and the development of the creeks is blocked by the dykes, but a decrease in the width of the tidal creeks was seen between 1977 and 2002. This is a clue of the long term sedimentation around and in the salt marshes. Seaward migration of the tidal creek heads is certainly induced by a readjustment of the drainage slope by accretion and decrease of hydrodynamics in the inner part of the creeks.

4.1.4.3. Sediment samples conclusions

Table 5. Sediment sample analysis.

μm units	CE5	CE7	CE8H	CE8L	CE9H	CE9L	CE10H	CE12
f84	3	3	8	3	4	4	3	3
f16	29	36	49	36	41	41	35	37
mean grain size	16	20	29	20	23	22	19	20
sorting	13	16	21	17	19	18	16	17
median	11	14	28	13	17	18	15	15
%clay	25	19	8	21	15	16	21	20
%silt	75	81	92	79	85	84	79	80
%sand	1	2	6	1	4	2	1	2
Estimated Elevation (MSL datum) in m	2.5	2.5	0.5	0.0	1.0	-0.5	0.0	2.0

The sediment samples were not very conclusive for our study because of the sampling locations and the low number of samples. Indeed, sampling was done in accessible locations during our field trip, i.e. on the mudflats near the salt marsh (table 5 and appendixes 1 and 2). Thus the following conclusion shows a very restricted and site specific picture of the hydrosedimentary processes and no extrapolation can be done.

The sediment of the intertidal mudflats is, in general, composed of 25% of clay and 75% of silts with very fine sands. It is characteristic sediment of salt marshes or upper mudflats. Comparatively, sediment near the Windsor causeway is composed of about 60% silt and 40% clay (Amos and Mosher, 1985). Grain size distribution of the samples has a peak around 25 μm.

The CE7, CE10 and CE12 samples seem to be typical of areas sheltered from tidal currents, and are high depositional mudflat areas

The CE5 sample is a little bit different. It is more homogeneous, likely because of the proximity to more active currents (erosion/transport) that promotes good sorting.

The CE9 sediment samples are coarser than the others, likely because of the proximity to the sandbars and the large tidal channel, and therefore stronger currents.

The CE8 samples were taken in the secondary channel between the middle bank and the left bank. Here the channel is submerged only during high tide because of its elevation. CE8L was taken in the middle of the channel, and CE8H was taken higher on the bank, with the former being coarser than the latter. This could be explained by weaker currents and settling of fluid mud more important specify at CE8L during the ebb tide, when the water level is low in the channel and SSC higher, than at high tide at CE8H.

4.2. Estuarine evolution

4.2.1. Conceptual model

A rapid model of the principal hydrosedimentary process was applied to the study area, using factors of location and season. It was inspired by several previous studies and knowledge of the estuarine systems. (Yeo and Risk, 1979; Yeo and Risk, 1981; Allen, 1989; Daborn, 1991; Lesueur and Lesourd, 1999; Ryan *et al.*, 2003; van Proosdij *et al.*, 2003; Daborn *et al.*, 2004)

The majority of the hydrosedimentary process (deposition, transportation and erosion) have a larger impact during spring tides than neap tides, essentially because of a more powerful hydrodynamics and larger tides. Thus, the impact of the following described phenomena is more important during spring tide. Moreover, in the study area, water level is not greatly influenced by the river flow.

During calm days, in the main tidal channels, sediments are transported longitudinally back and fro. Waters are calm and SSC is high, fine sediments and bed load oscillate between the inner estuary at high tide (dilution) and the extreme estuary mouth at ebb tide. Temporary deposition also occurs. Cliffs and abrupt banks are eroded and traction processes add sediments to the SSC load. From the lower flats to the salt marsh, deposition of finer and finer sediment occurs, depending essentially on the SSC. High deposition in the salt marsh occurs during spring tides. Between high and low tide there is also a lateral transportation on the intertidal flats.

The fall and the winter months experienced storms and high precipitation events. Even though our area is well sheltered from wave action, the northern part of the study area could be impacted by it. Wave energy in that area could cause an increase of the SSC in the whole water body by resuspension and erosion of the intertidal zone and the salt marsh margin. Material is reintroduced and deposited into the marsh at high tide and exported into the estuary at low tide.

River overflow due to high precipitation events have no strong impact during high tide in the study area. That may possibly increase the SSC, but although the sediment input by the Cornwallis river catchment has not been calculated, it is likely not high because of the small catchment area (361 km^2). At low tide erosion along the main channel (cliff and lower mudflats) and deposition on the upper mudflats are certainly more important than during calm days. Moreover, the increase of river flow would translate the sediment load (silt plug) seaward and expulsion of sediment could probably occur at low tide. Previous studies showed that the sedimentary balance is maintained in the estuary with few inputs and no net sediment loss.

Winter and spring experience ice cover and ice melting. In winter, high precipitation (rain and snow) induces high SSC. Ice formations create a mosaic of erosion/deposition. Ice protects the salt marsh and the mudflat, and despite a decrease of vegetation, sedimentation by settling of SSC occurs around the Mean High Water Level and ice rafting can erode and transport particles.

During the spring, ice and ice blocks melt, leaving sediments of all sizes, up to boulders. Ice melting induces high SSC and an increase of the mean river flow, but waters are calmer and calmer with the arrival of summer. Transportation is active in the main channels with high deposition occurring on the intertidal flats and salt marshes. Ice melting also favours erosion in the tidal creeks.

4.2.2. Summary

According to Amos and Joice (1977), the only nearby sources of sediment is the active cliff erosion at high tide at Kingsport, however this material is moved away from the Southern Bight and does not cause further accretion in the Cornwallis estuary (Amos and Joice, 1977; Daborn and Pennachetti, 1979). Also, the sediment input from the catchment basin in the estuary seems to be low. Maybe only a small amount of fine material from runoff in the catchment basin is brought.

Thus, exchanges of sediment in and out of the study area do not seem very important. However, we can suppose exchanges of sediments from the Starrs Point mudflats, which could have fed the middle mudflat, during the last decades.

The sedimentary evolution could show, in a medium term, light accretion on the mudflats (with associated salt marsh expansion) and few paroxysmal events of erosion (storms) which would result in a redistribution of the sediment. Added to that, evolution of the main channel moves toward equilibrium: flood and ebb currents cause erosion and resuspension that will be deposited in low hydrodynamic areas (map 20).

4.2.2.1. Main Channel

Erosion dominates along the bank of the main channel, and if the material is not removed from the estuary, it will be redistributed the coarsest fraction on the shifting sandbars and the finest fraction on the mudflats and salt marshes.

During the last thirty years at the head of the study area, the concave curves of the estuary where the banks are high, salt marsh cliff areas have known continuous and active erosion. The combined action of ebb and flood current increases the destructive potential of the hydrodynamics, by inducing successive but opposite eroding pressures.

On the left bank, the ebb currents dominate erosion and seem to induce a slow regressive erosion westward, which threaten the dyke, whereas the salt marsh is eroded northeastwardly. The eroded material is certainly a mix of silt and clay from the upper part of the cliff, and perhaps coarser sediments which would come from the deeper layers of the salt marsh cliff. Erosion takes diverse forms from, pulling out particles to inducing landslides. These particles are certainly transported back and fro in the estuary and deposited in areas based on their size.

On the right bank, where the cliffs threatened the dykes, measures have been taken and rip rap was added to strengthen the bank, approximately 20 years ago.

In the other parts of the main channel erosion is occuring but at a slower rate. Patches of sedimentation also exist, generally at the convexity of the banks, where both ebb and flood currents dominate near the opposite bank. On the left bank, just following the salt marsh cliffs, the convexity of the channel allows high deposition. The sediments likely come from the nearby erosion with finer sediments deposited higher. The marsh colonization may also indicate active sedimentation.

4.2.2.2. Middle bank

The middle mudflat of the 1970’s and 1980’s was colonized by the salt marsh after an increase of the flat elevation by sedimentation. There is no clue on the source of material, but it might have come from fluvial supply, estuary bank erosion or from erosion of the northern mudflat. As there is no measurement of the rate of mudflat accretion, the supply of sediment could be relatively light (i.e., just enough to allow *Spartina alterniflora* colonization).

Newly deposited intertidal sediment is much more resistant to erosion than marine sediment from other areas, as it compacted by drying and solar heating. The resistance to erosion increases shoreward as exposure time increases, and when the elevation is high enough, vegetation will colonized the intertidal flat. Thus on the middle bank, we can hypothesize that after long term deposition without any large erosion events, vegetation began to colonize the middle bank at the beginning of the 90's. A cascade effect then led to more sedimentation because of vegetation, more resistance to erosion, more compaction, and more available and suitable space for low marsh colonization.

The same type of colonization associated with deposition was seen with the exponential growth of the Windsor Causeway salt marsh, although any disturbances by any tidal barrier occur here. This comparison concerns only the surficial vegetation growth and the speed for *Spartina alterniflora* to colonize new suitable areas. The impressive sediment accretion, which occurred after the Windsor causeway building,, is not comparable in the Cornwallis estuary.

Moreover, it seems that sedimentation in the tidal channel between the middle bank and the left bank occurred during the last ten years. This infilling could be linked with the growth of the nearby mudflat/salt marsh.

4.3. Future evolution (map 21)

A climate change forecast concerning the Valley was done by Timmer (2003). It is expected that under climate change conditions, the frequency and severity of storms will increase; sea level will rise amplifying the potential for floods, coastal erosion, and dyke overtopping; thaws will either come early and be extended or the will come late and be paired with early frosts; and reductions in sea and river ice will accompany shifts in rainfall patterns that will alter growing seasons. The Annapolis Valley was found to be vulnerable to sea level rise, which would affect the dykes that protect the dykeland farms (Timmer, 2003). Thus in the long term, the main factors that could induce changes on the sedimentary processes are sea level rise, the reduction of ice, the rainfall pattern, and storms could be more frequent and more powerful.

Based on the main trends found in this GIS study, the following forecast can be hypothesized.

Firstly, it seems that the salt marsh on the middle bank will keep growing because its shape shows that new, patchy colonization occurs all around it. This will certainly increase sedimentation and the elevation of the middle bank. The tidal channel between the middle bank and the left bank could experience infilling until it becomes a larger tidal channel, unless the tidal currents are enough to keep the morphology of the cannel and avoid expansion of the salt marsh. The middle salt marsh has already begun to be eroded with clifflets on its western edge.

The northern channels will likely keep switching and no trend could be observed but it seems that during the last 30 years, erosion of the channels has moved southward by eroding the northern limit of the middle bank.

Concerning the main channel, the erosion trend makes it wider in many locations, without taking into account the dykes. Sediment is redistributed in the whole estuary, particularly the flats and the sandbars.

On the left bank, the active salt marsh cliff erosion will likely continue northeastward with trending westward (regressive erosion). This shows no signs of stopping in the next few years. With an annual mean withdrawal rate of 4 m, it changes the channel morphology by giving more space for the sandbar. The sedimentation area at the point bar, downstream, could see its evolution modified by the riprap protection on the opposite bank. As the channel could not shift anymore, a lateral balance might occur in the future.

On the right bank many areas experience erosion with spots of deposition. A forecast is difficult there but it is possible that the major erosion areas will keep experiencing erosion, especially in the area where both ebb and flood currents are the cause. Around the riprap protection, erosion will likely continue especially at the northern extremity where high withdrawal has been seen. On the northern part of this bank, slow accretion may still occur along the North Island shore.

5. DISCUSSION

5.1. Study validity

This study was mostly based on aerial photographs. Thus, measurements carried out do not include vertical assessment, so no vertical erosion or accretion of the tidal flat has been measured. Moreover, a horizontal error exists because of the georefencing errors, which can reach more than 5 meters, because of the lack of reference points in the estuarine zone.

Also, forecasting is not easy because of the dynamically unstable character of a macro-tidal estuary: many components with different time scale effects shape the estuary, such as sediment characteristics, tidal currents, SSC, storms, ice, vegetation, waves, stage of the tide, spring or neap tides, etc. Current measurement and sedimentary balance in the system could not be assessed from aerial photographs, and no thorough study has been done on these factors.

This study shows the medium time scale trends well, and that GIS technology is an efficient method to assess spatial evolution. The historical changes were assessed, and GIS cartography is certainly an excellent medium for this. The results help to better understand the Cornwallis Estuary system. However, association of long term hydrodynamic and sedimentary field measurements could lead to better forecasting.

Finally, aerial photo and GIS analysis can only be validated by monitoring of the estuary. A project that includes monitoring of sediment elevation on the intertidal and marsh zones, cliff withdrawal, sediment budget of the estuary and current measurements for a minimum of one year, could give a more complete picture of the whole system.

5.2. Shore protection

Dykeland areas always experience erosion or flooding threats because land was gained while sacrificing the natural buffers against these threats: wetlands and salt marshes. Thus in a macrotidal estuary, where channels endlessly try to reach a dynamic balance, an encounter between the dykes and channels is practically unavoidable.

Until now, the only bank protection technique used in the Cornwallis Estuary was riprap armour. It strengthens the bank and avoids erosion, efficient in stabilizing the slope. Potentially problems include changes in local streams, sediment transportation (the protected bank is not a further sediment source, and roughness of the new material induces transportation changes), and therefore changes in the channel dynamic (Fischenich, 2003; Timmer, 2003). Thus during a short time scale, effects around the protection could be seen. In a river, concentrated erosion could occur downstream from the protection by accelerating the water flow, but in our estuarine system, erosion could be observed on the upstream or downstream extremity, depending on the dominant current. Therefore an extension of the riprap protection is generally needed. Thus, erosional areas could be created over a period of time, requiring new riprap thereby causing a loss of the estuary's natural character.

In the Cornwallis estuary, riprap was used only near the most threatened dykes, where protection was greatly needed. In the future, if more precise studies on currents and sedimentary dynamic in the estuary are combined with this study, highlighting the most threatened areas, an impact assessment of the protections could bring long term solutions against erosion. Thus, optimum protection could be found with minimum impacts on hydrodynamics, sedimentary processes and surrounding habitats (by preserving sedimentary, chemical or biological exchanges between the estuary and its banks).

In this way, the use of alternative techniques like bio-engineering* (named also soft-engineering) is advised, which use live material (sometimes associated with classic protection) to strengthen the bank (Polster Environmental Services Ltd., 2003). This respects the natural ecological processes of the area with a practical approach, given that macrotidal environments are complex to grasp and forecast, especially with the salinity variations and the tidal conditions. Moreover, the semidiurnal tides would not facilitate the use of Bio-engineering. However, these techniques have several advantages:

- Technical advantages including surface erosion protection; root reinforcement and soil drainage.
- Ecological advantages such as the provision of habitat and improved soil conditions due to plant growth.
- Economic advantages due to reduced construction and maintenance costs and the employment of semi-skilled workers.
- Aesthetic advantages associated with the use of natural materials in natural settings.

In order to not see the Cornwallis estuary damaged or restricted by rocky banks, alternative engineering techniques could bring innovative, environmentally friendly and sustainable solutions to erosion issues. We should remind that the Acadians used vegetation to strengthen their dykes, an early use of Bio-engineering. However, because the most important focus is the protection of the dykeland, specialized studies should be carry out for an optimum application of this kind of engineering adapted to macrotidal environment.

GLOSSARY

Aggradation: Filling in or leveling by deposition (of fluvial or marine deposits).

Bio-engineering: Branch of engineering in which live and dead plant materials are utilized to stabilize hillslopes or stream banks. It often involves fascines, bundles, logs, root wads and other "hard" structures such as rock revetments or wooden crib structures in conjunction with plant materials.

Cuesta: In geology, a ridge with a gentle slope on one side and a cliff on the other.

Digital Elevation Model (DEM): Topographic surface arranged in a data file as a set of regularly spaced x, y, z coordinates where z represents elevation.

Datum: Agreed and known value, such as the elevation of a benchmark or sea level, to which other measurements are corrected. Surface on which a mapping and coordinate system is based.

Digitization: Transfer of information into a digital form.

Estuary: Regions of interaction between rivers and nearshore ocean waters, where tidal action and river flow create a mixing of fresh water and saltwater. These areas may include bays, mouths of rivers, salt marshes, and lagoons. These brackish water ecosystems shelter and feed marine life, birds, and wildlife.

Facies: Sedimentary body distinguished from others by its appearance or composition.

Geographic Information system (GIS): Computer-based mapping and modelling systems based on software designed to handle complex spatial information. The strength of GIS as decision-support tools is that they enable data from a variety of sources to be mapped in layers and then selected, transformed, analysed, combined, displayed and distributed. GIS help managers and decision makers to make use of diverse data in ways that are unique to their specific application or need.

Georeferencing: Refers to the location of an image or vector file in space as defined by a known coordinate system. Action of referring a file in a coordinate system.

Hydrosedimentary processes: Sedimentary processes (erosion, transportation and deposition) directly controlled by the hydrodynamics of and within a water body.

Intertidal: Portion of the sea bottom that is submerged at high tide and exposed at low tide.

Isohypse: synonym of contour line.

Kriging: Geostatistical interpolation technique that considers both the distance and the degree of variation between known data points when estimating values in unknown areas.

LIDAR: Acronym for 'Light Detection and Ranging,' a sort of radar using LASER technique for performing accurate remote measurements, like altimetry or bathymetry.

Macrotidal: Tides with a vertical tidal range greater than four meters.

MSL: Mean Sea Level, Average sea level for a particular geographical location, obtained from numerous observations, at regular intervals, over a long period of time.

Nodal point: Point on the bed of the estuary where the residual currents (tide and river) converge and cancel each other out.

Orthorectification: In photogrammetry, the process of removing geometric distortions in an image caused by sensor tilt and terrain relief, and projecting the resulting image onto a map projection system.

Point bar: Deposit of sediments located on the inside of, and extending into the curve of, a meander. It is an active area of deposition.

Riprap: Layer of broken stone on the earth surface for protection against erosion by water; extensively used on irrigation channels and river improvement works.

Subtidal: Said of that part of the "littoral" zone that is between low tide and a depth of about 100m.

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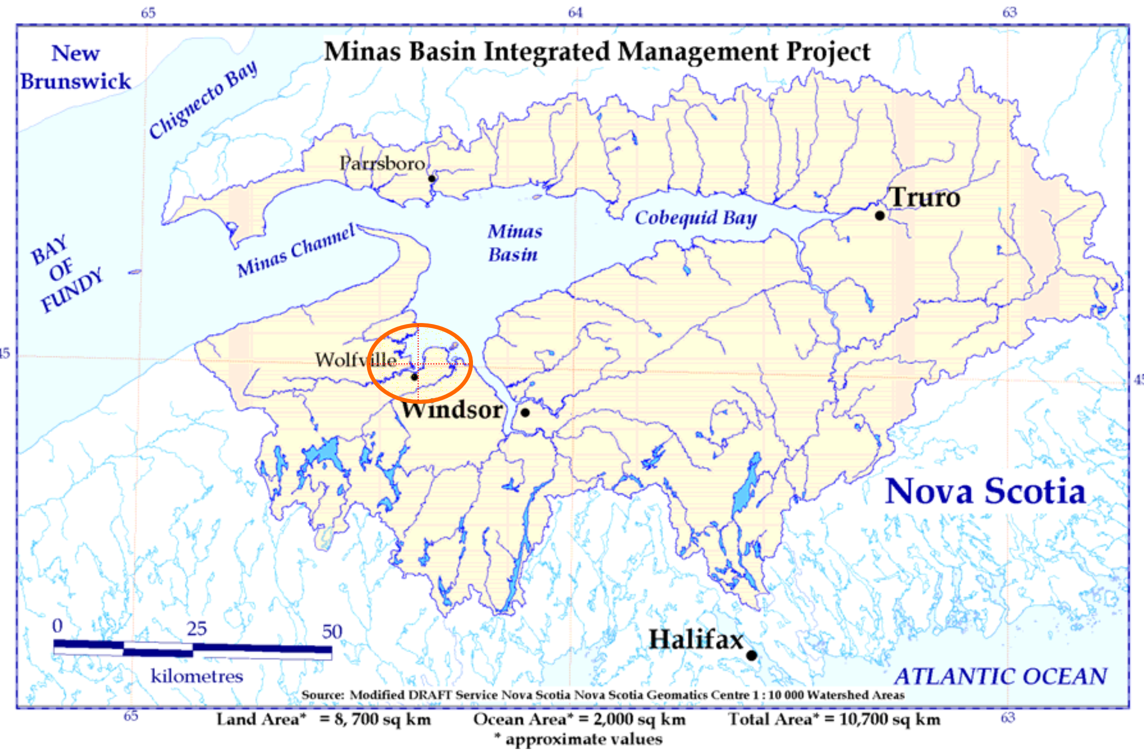
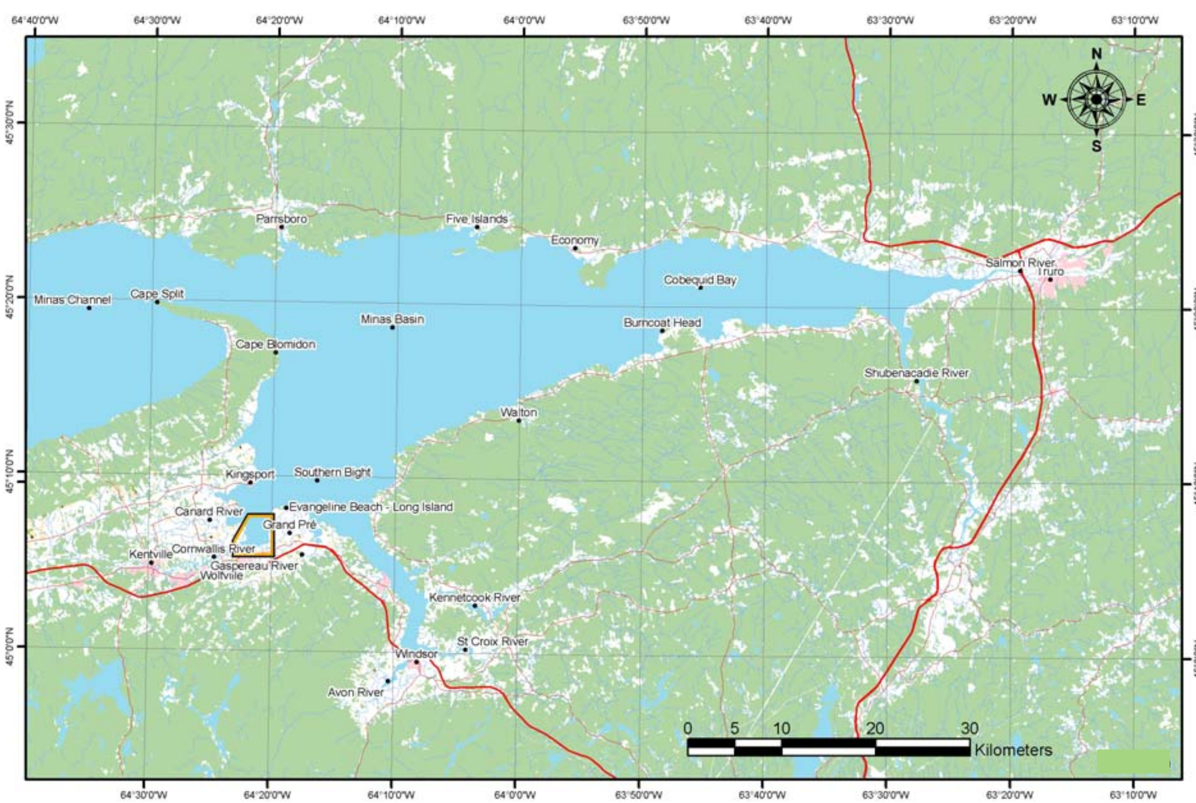
MAPS

Map 1. Location of the Bay of Fundy, Minas Basin (source Atlas Canada, http://atlas.gc.ca)

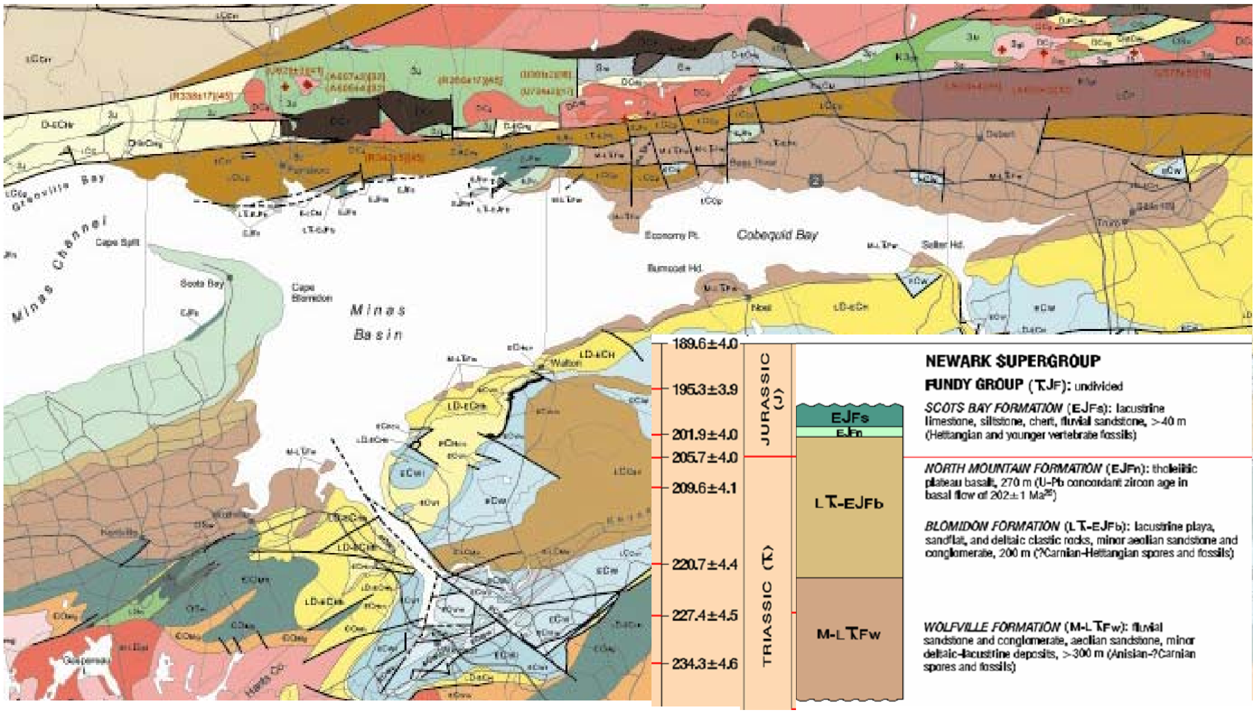
Map 2. Maritime Provinces (source Atlas Canada, http://atlas.gc.ca/)



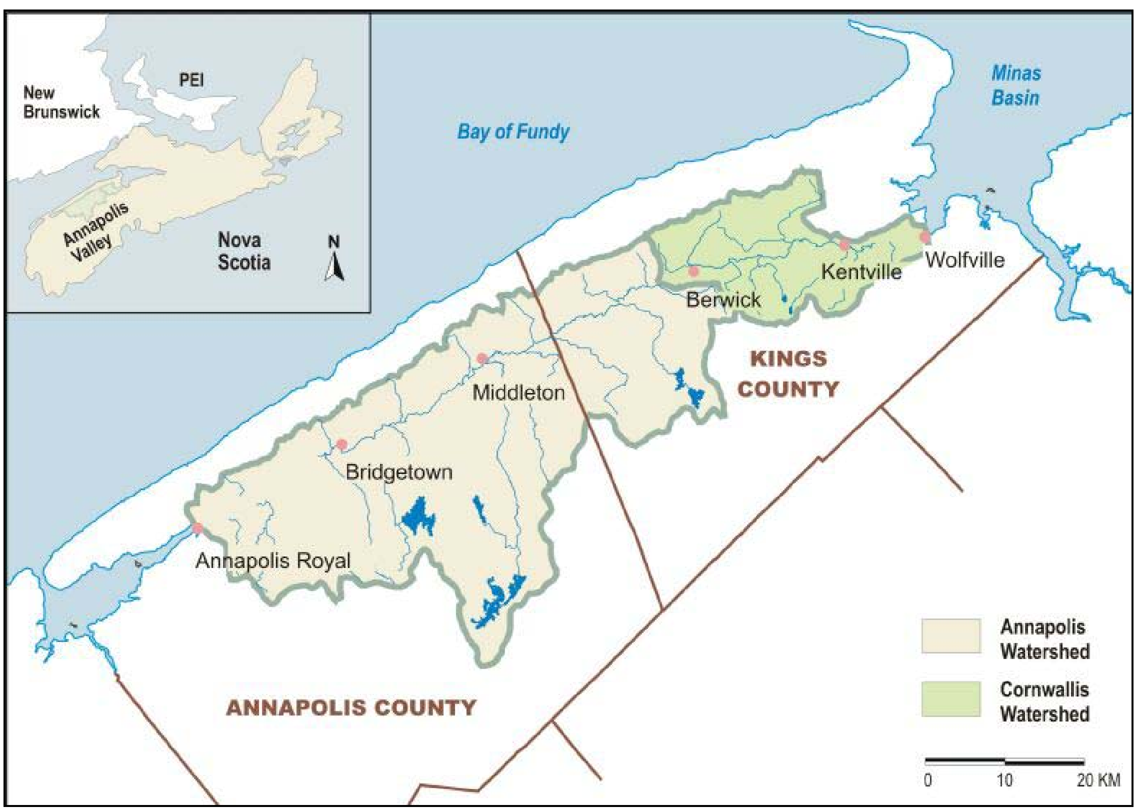
Map 3. Minas Basin watershed.



Map 4. Minas Basin General Map (NTS map sheets).



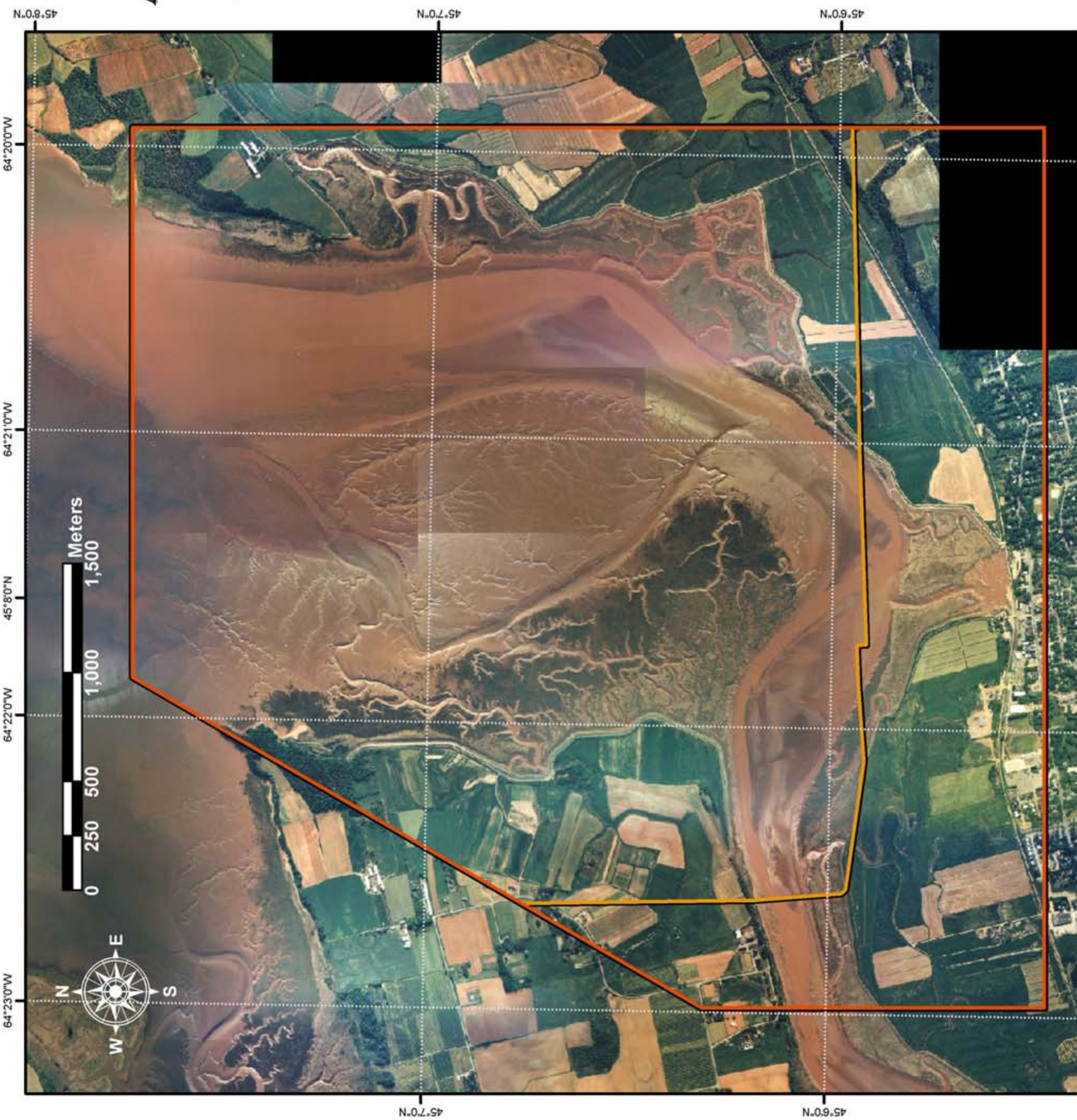
Map 5. Geological map of the Minas Basin.

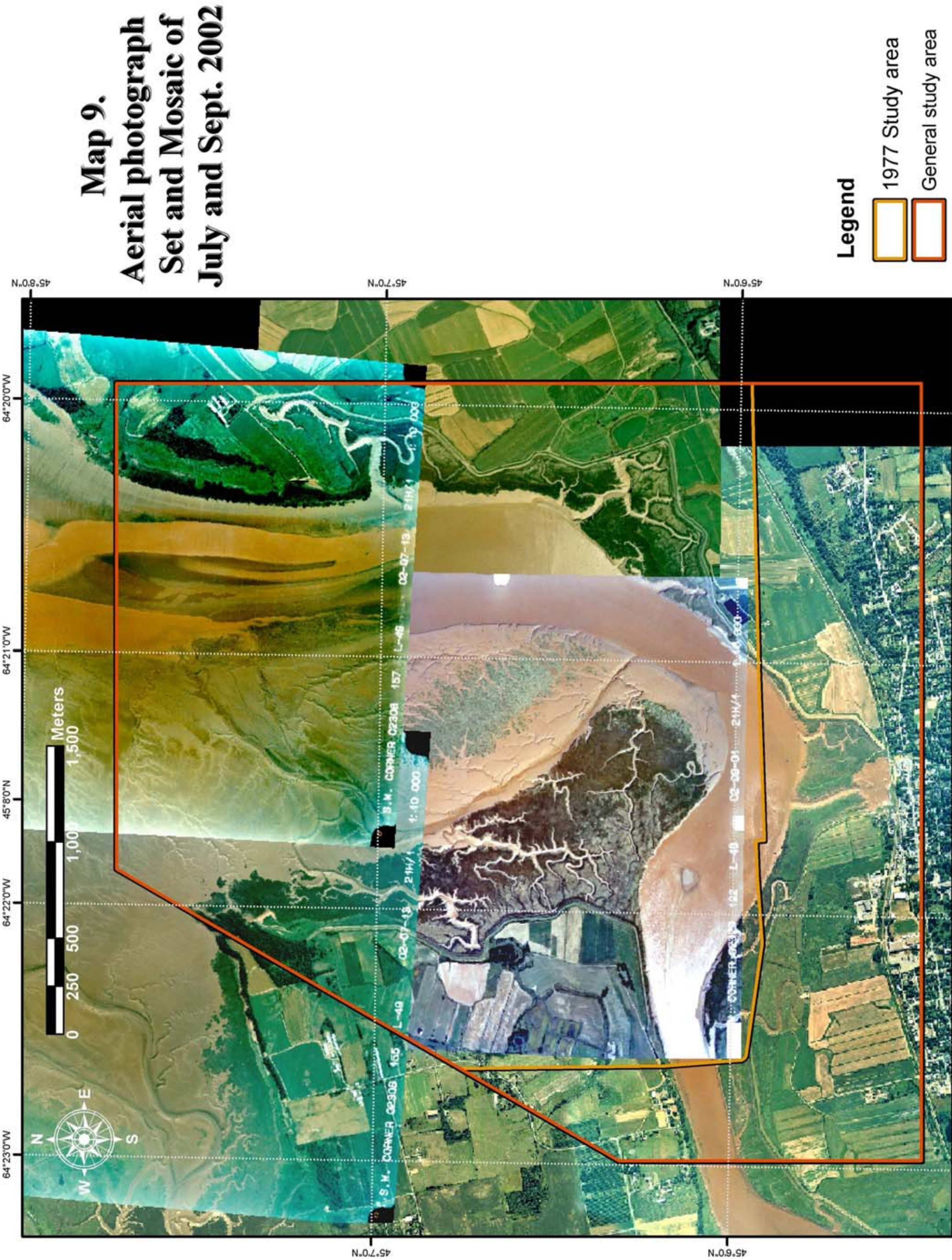


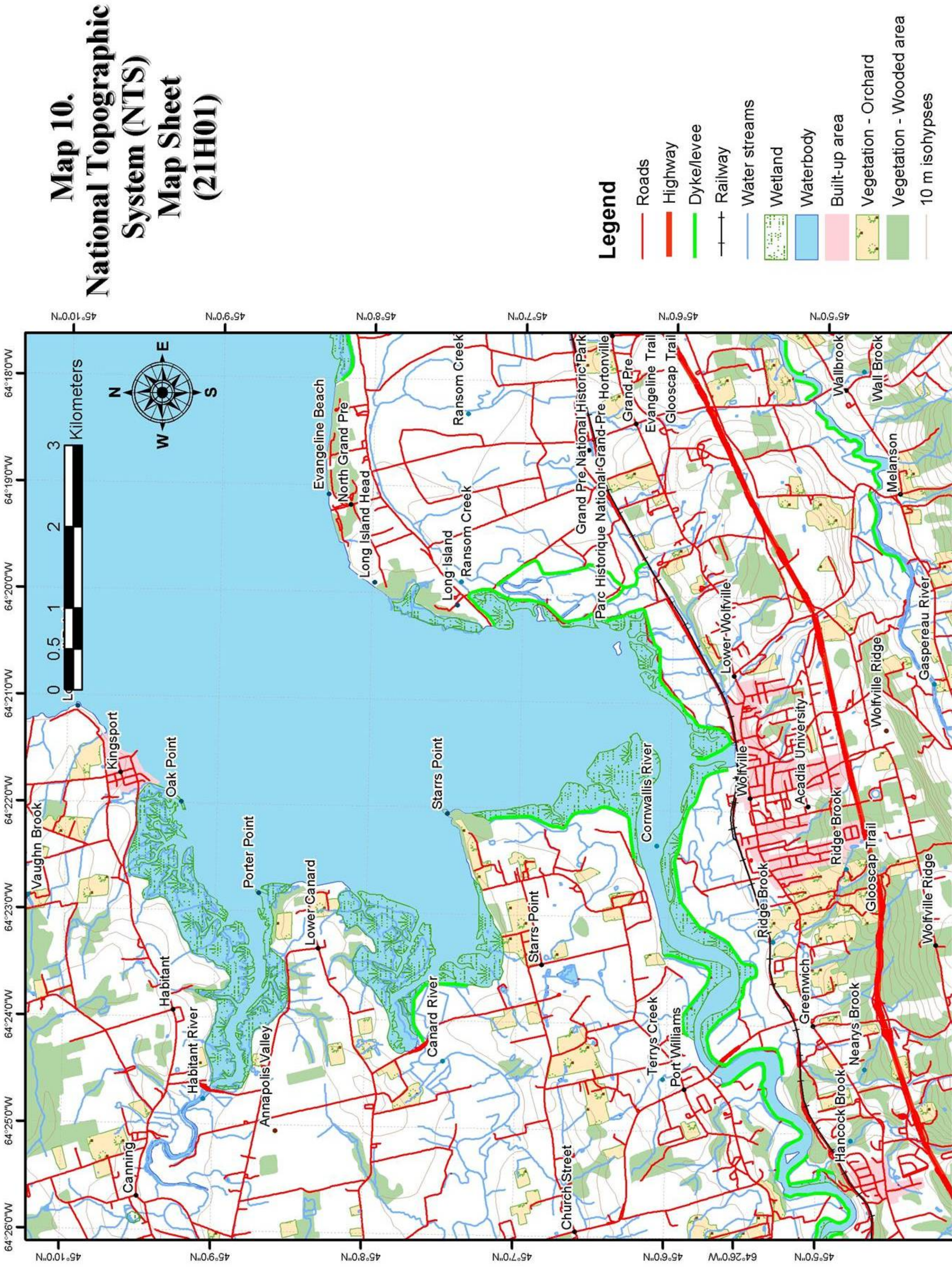
Map 6. Annapolis and Cornwallis Watersheds (Timmer, 2003)


Map 7.
Aerial photograph
Set of july 1977
Legend
1997 Study area
Meters
0
250
500
1,000
1,500
N
E
S
W
64°20'0"W
64°21'0"W
64°22'0"W
45°7'0"N
45°6'0"N

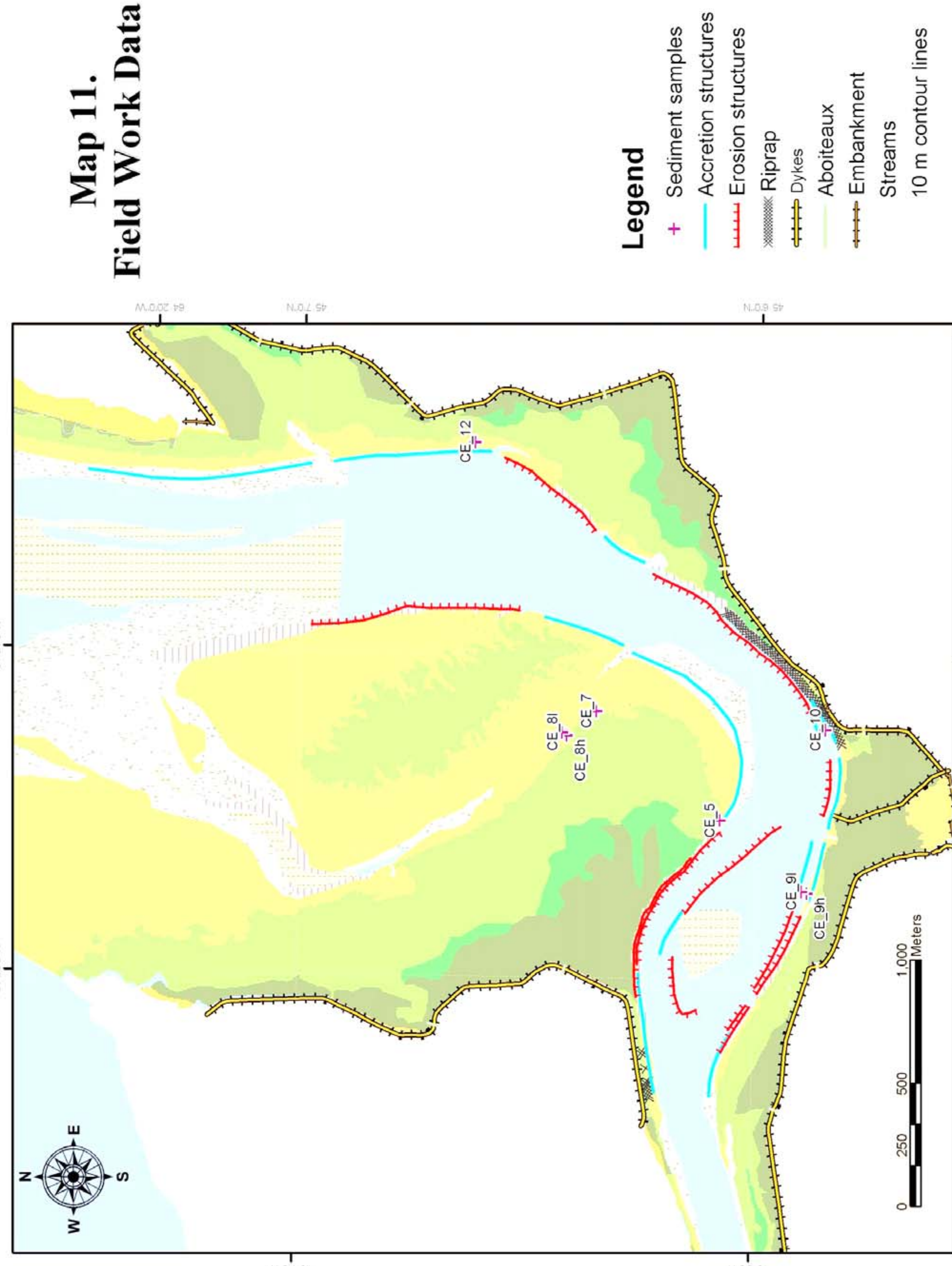
Map 8. Aerial photograph Mosaic set of September 1992



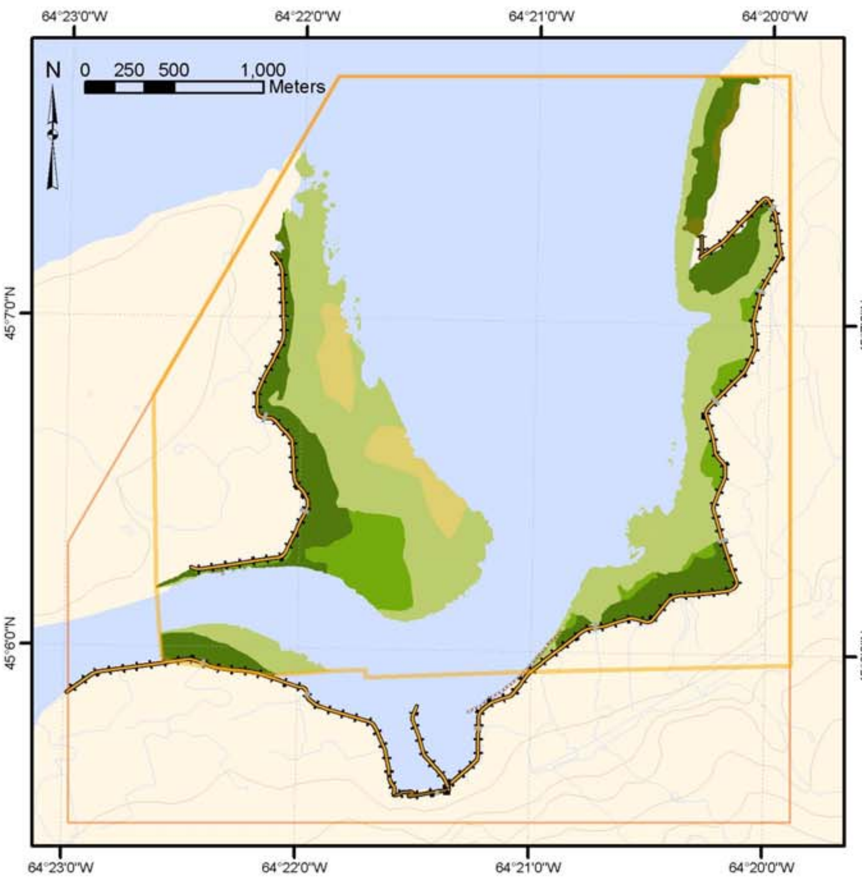

Map 9.
Aerial photograph
Set and Mosaic of
July and Sept. 2002
Legend
1977 Study area
General study area
Meters
0 250 500 1,000 1,500
45°8'0"N
45°7'0"N
45°6'0"N
64°20'0"W
64°21'0"W
64°22'0"W
64°23'0"W
N
S
E
W


Map 10.
National Topographic System (NTS) Map Sheet (21H01)
Legend
Roads
Highway
Dyke/levee
Railway
Water streams
Wetland
Waterbody
Built-up area
Vegetation - Orchard
Vegetation - Wooded area
10 m isohypses
0 0.5 1 2 3 Kilometers
N
E
S
W
Kingsport
Oak Point
Vaughn Brook
Porter Point
Lower Canard
Habitant
Habitant River
Annapolis Valley
Canning
Canard River
Starrs Point
Church Street
Cornwallis River
Terrys Creek
Port Williams
Evangeline Beach
North Grand Pre
Long Island Head
Long Island
Ransom Creek
Grand Pre National Historic Park
Parc Historique National Grand-Pre
Hortonville
Grand Pre
Evangeline Trail
Glooscap Trail
Lower Wolfville
Wolfville
Acadia University
Ridge Brook
Greenwich
Nearys Brook
Hancock Brook
Wolfville Ridge
Gaspereau River
Melanson
Wallbrook
Wall Brook
45°10'0"N
45°9'0"N
45°8'0"N
45°7'0"N
45°6'0"N
45°5'0"N
64°18'0"W
64°19'0"W
64°20'0"W
64°21'0"W
64°22'0"W
64°23'0"W
64°24'0"W
64°25'0"W
64°26'0"W

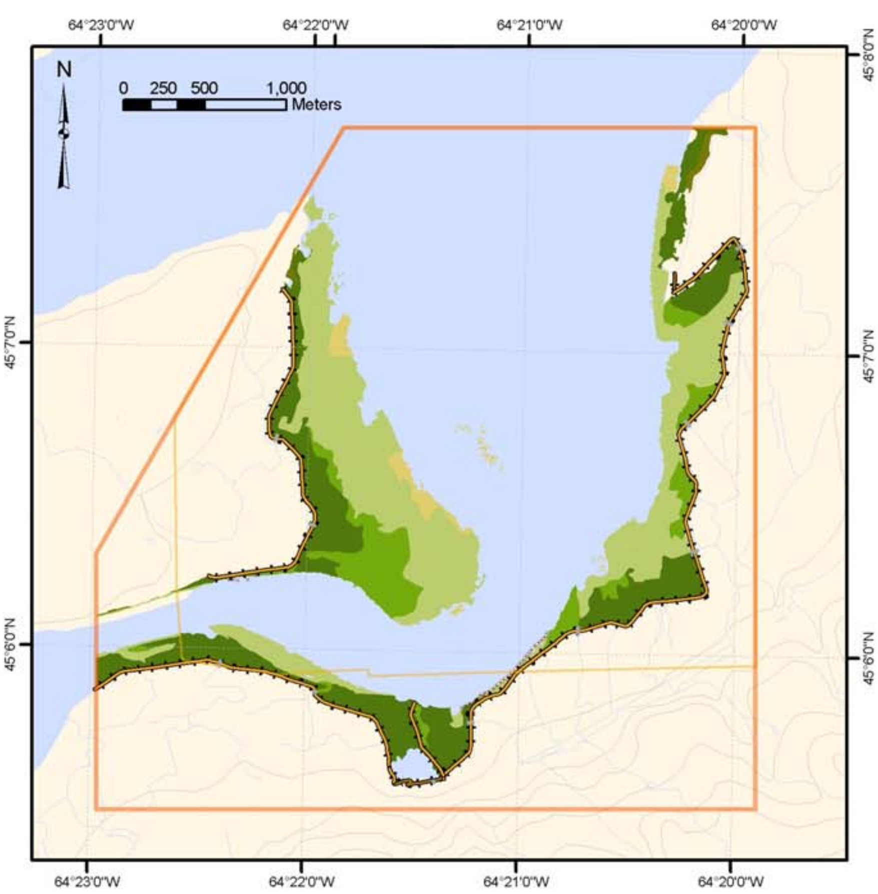
Map 11. Field Work Data



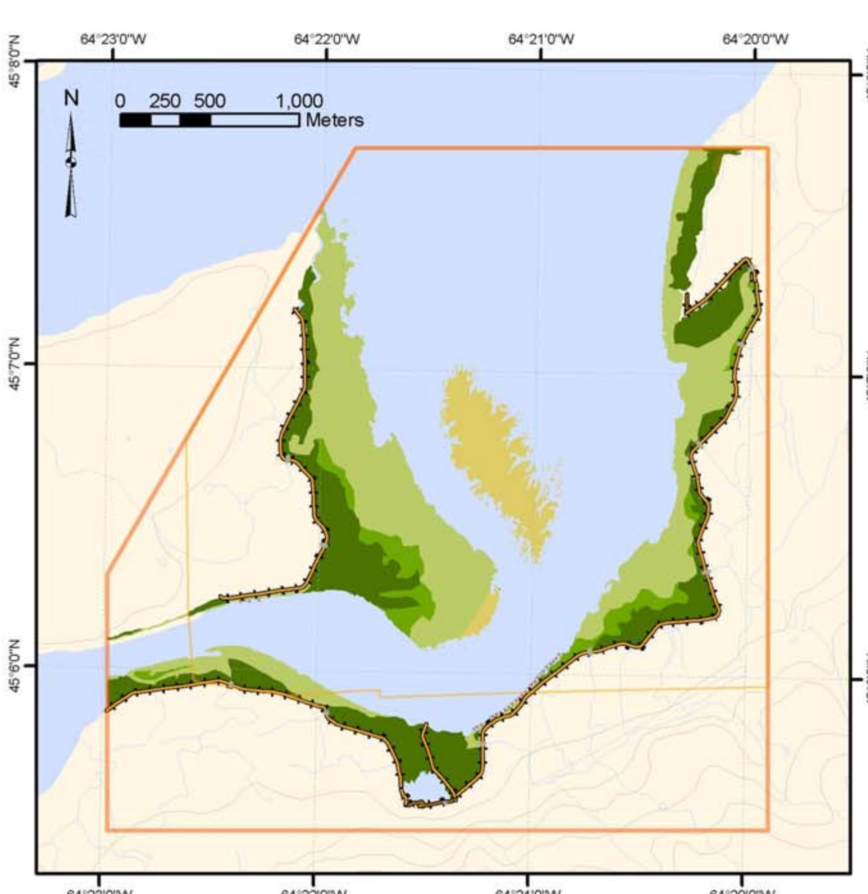
Map 12. Salt Marsh Vegetation Evolution



Salt Marsh in 1977

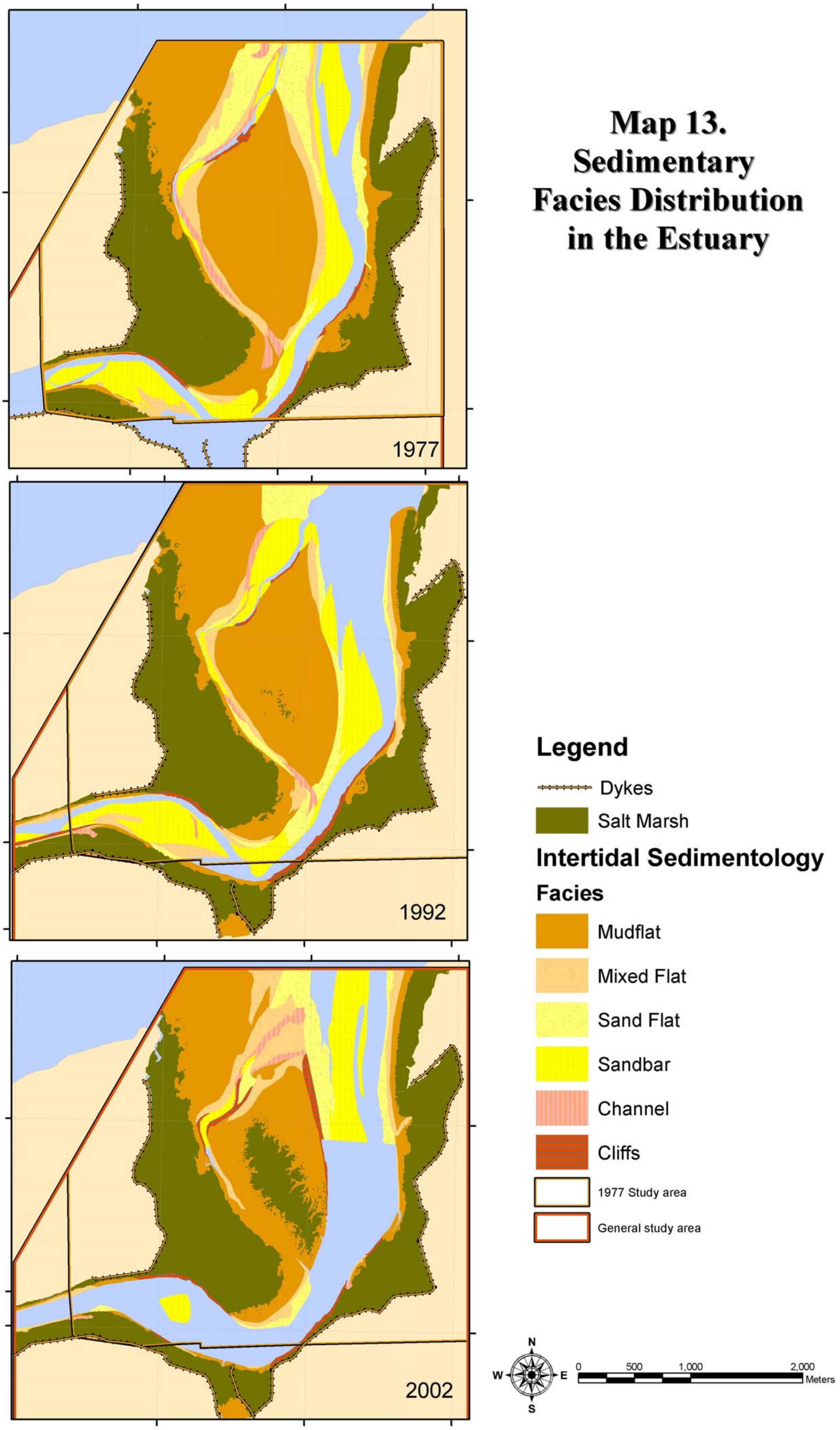


Salt Marsh in 1992

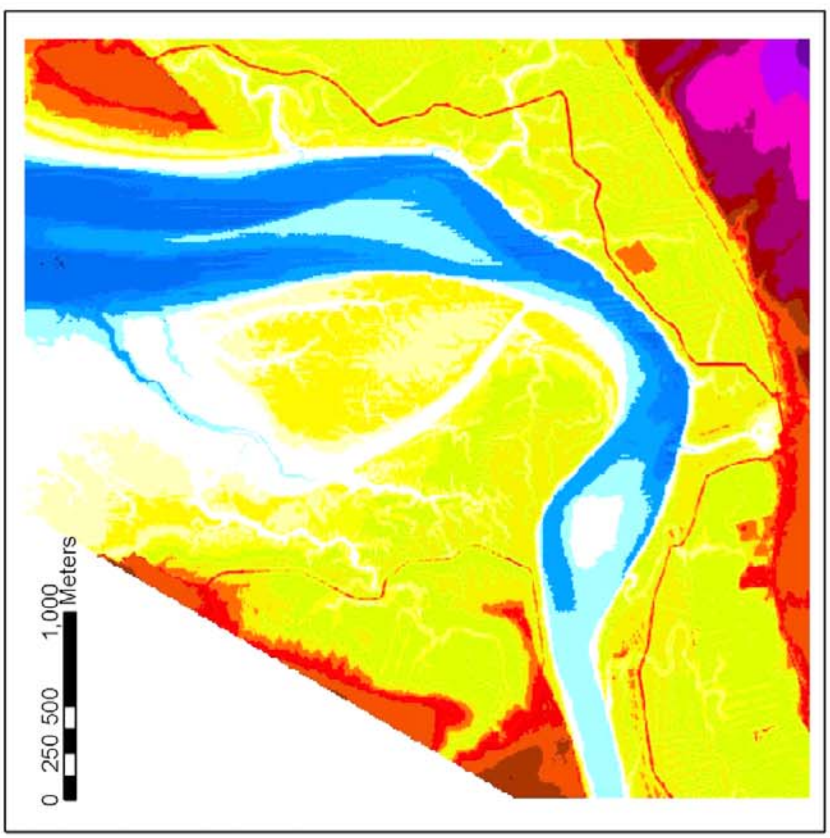


Salt Marsh in 2002

Map 13. Sedimentary Facies Distribution in the Estuary



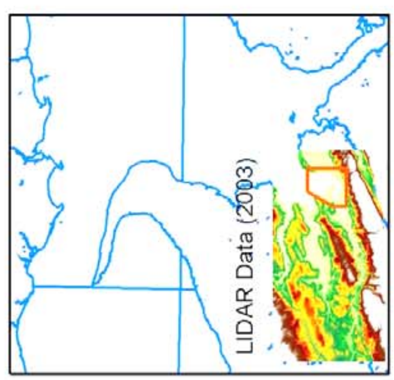
Map 14 LIDAR DEM Analysis

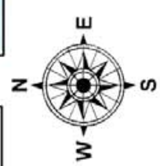


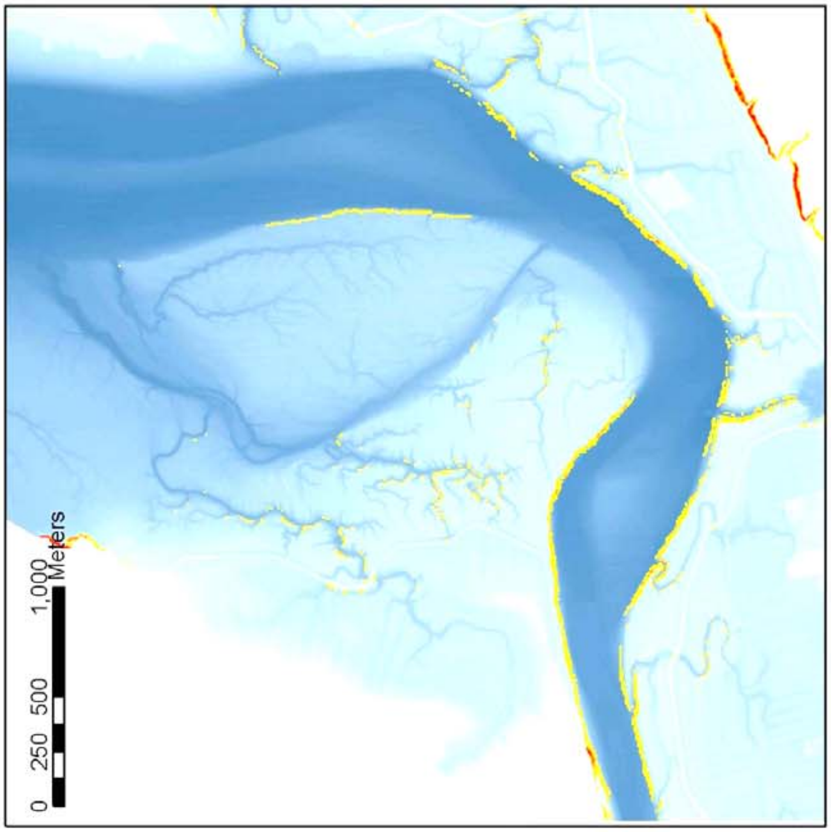
LIDAR DEM 2003

Legend

Altitude (m)
- < -7
- -7 - -6
- -6 - -5.5
- -5.5 - -4.5
- -4.5 - -3
- -3 - -2
- -2 - -1
- -1 - 0
- 0 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8 - 9
- 9 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- 30 - 40
- 40 - 50
- > 50



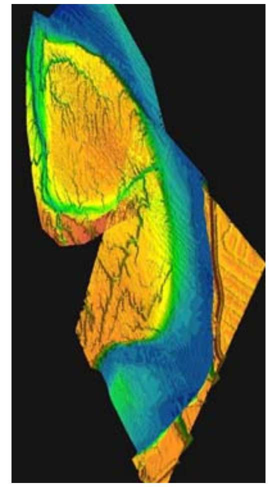




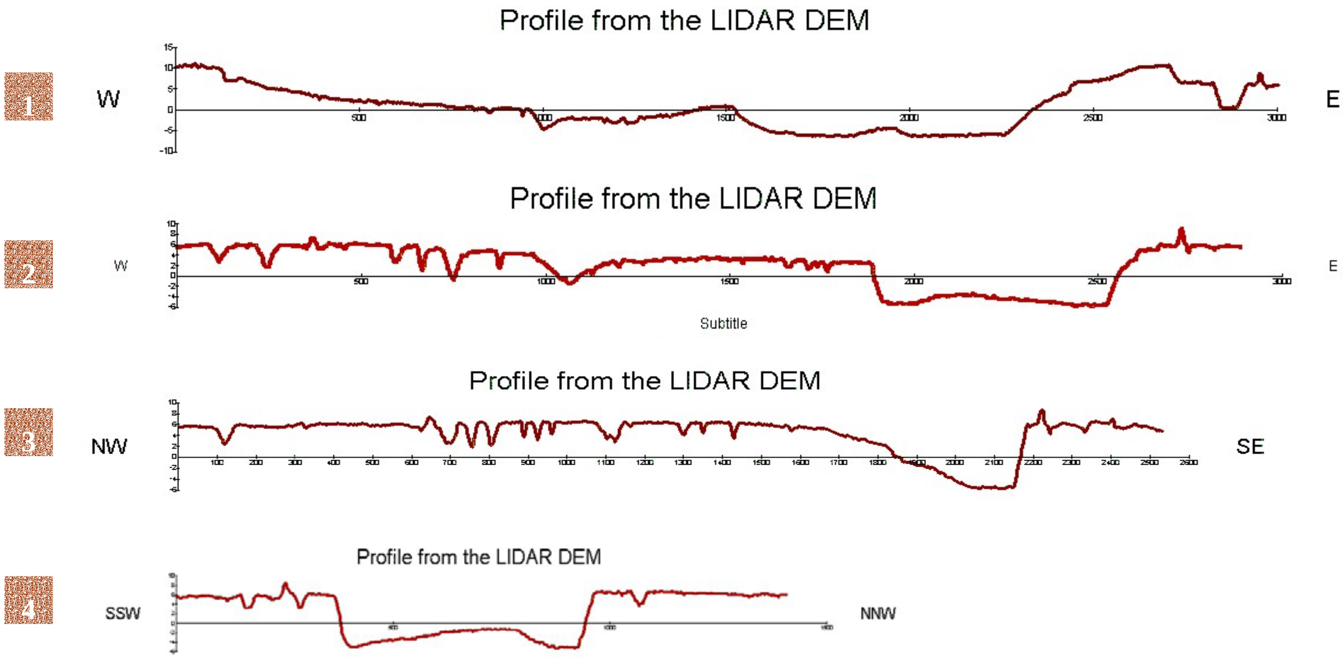
Slope from LIDAR data 2003

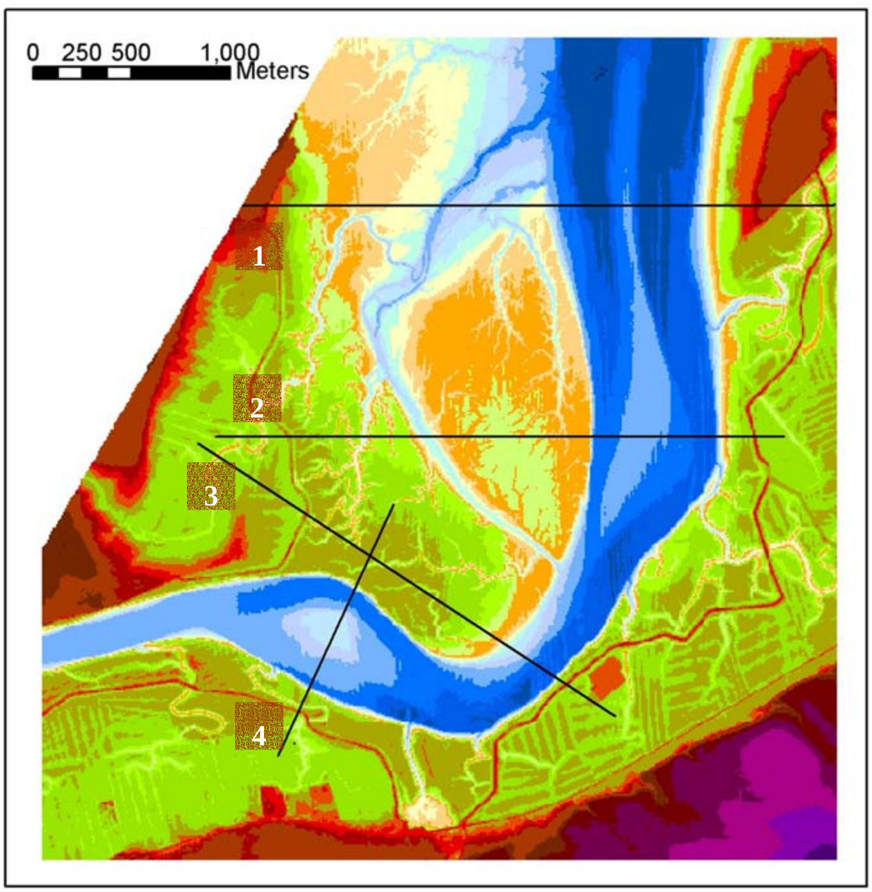
Legend

Slope (degree)
- 15 - 20
- 20 - 25
- 25 - 30
- > 30



3D view from ArcScene

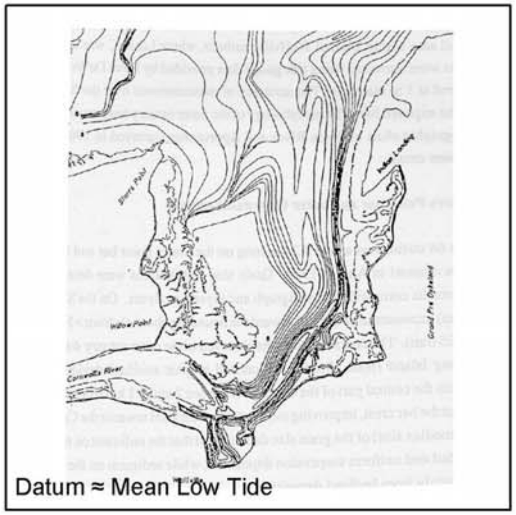




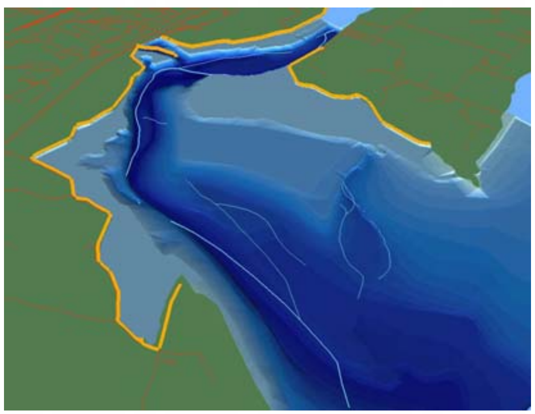
LIDAR DEM 2003

Map 15.

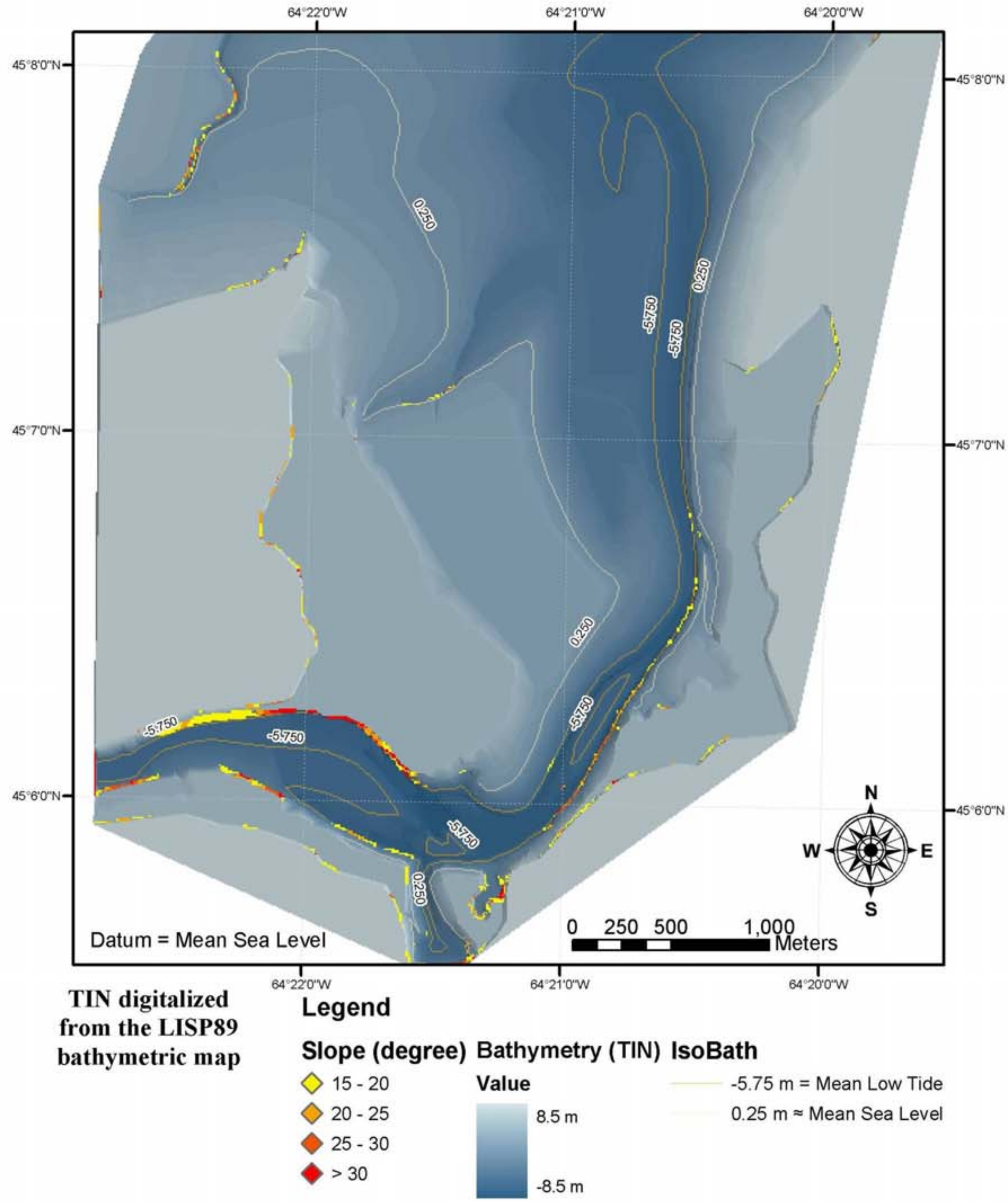
Profiles from the



Bathymetric Map from LISP 89 (1989)

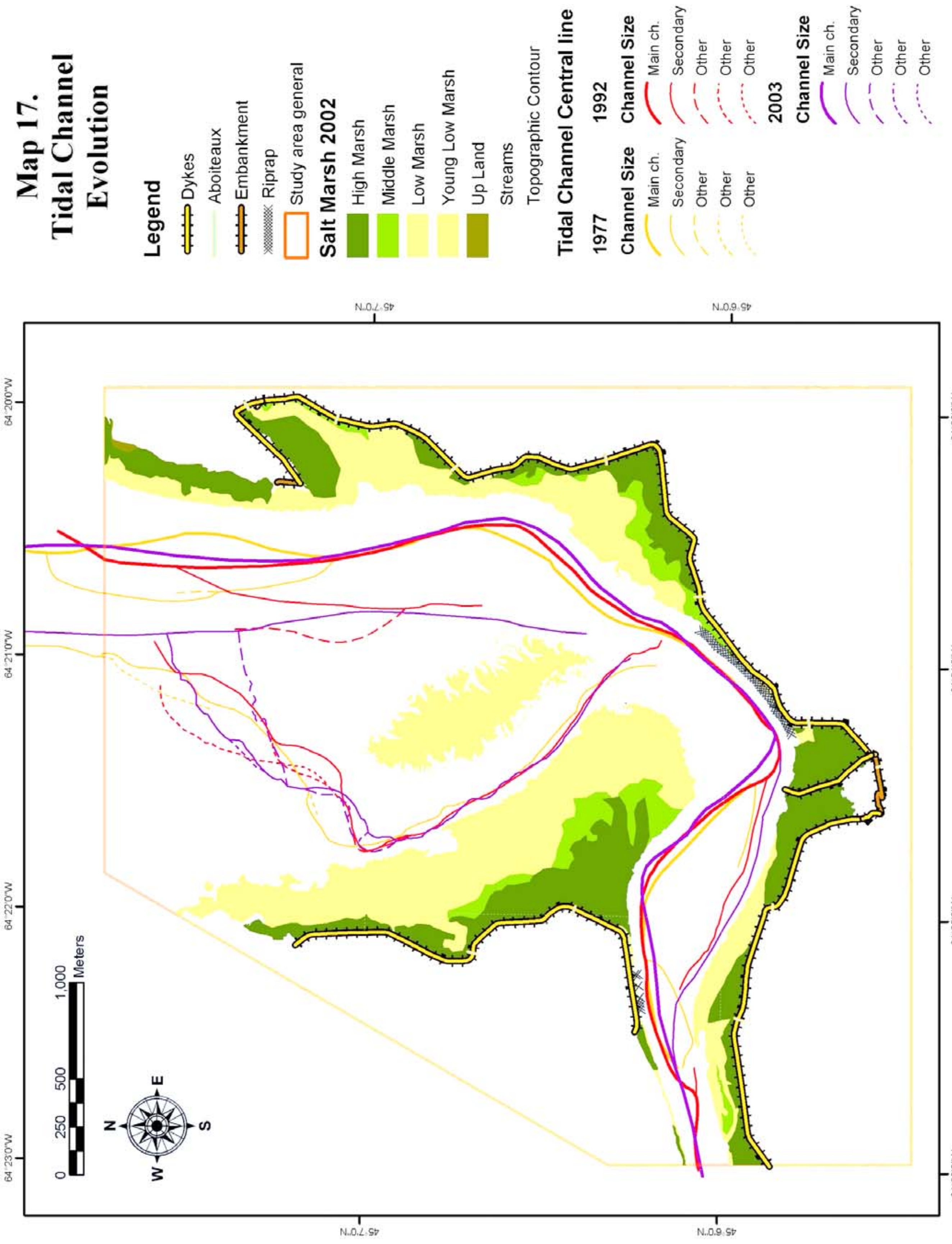


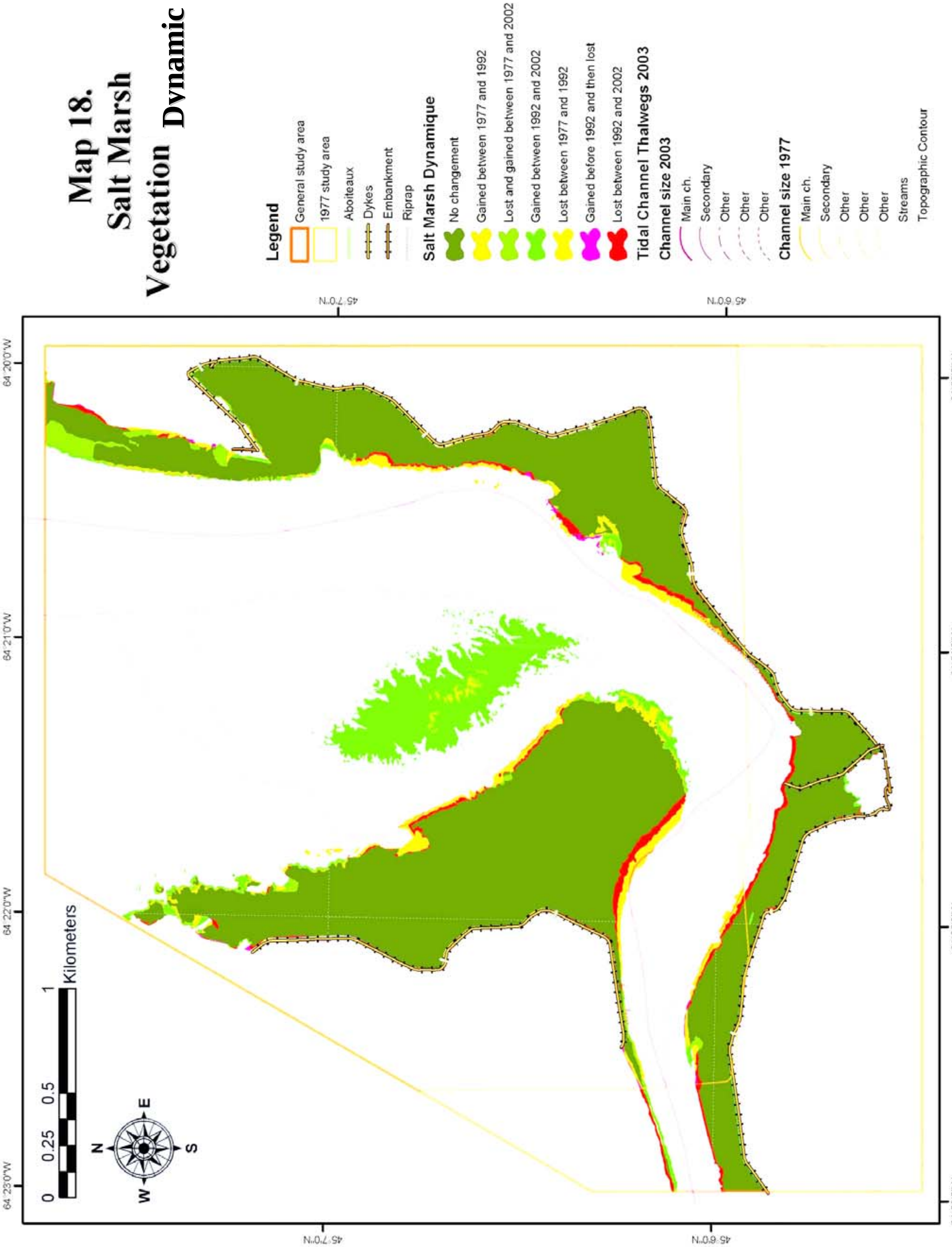
3D view from ArcScene

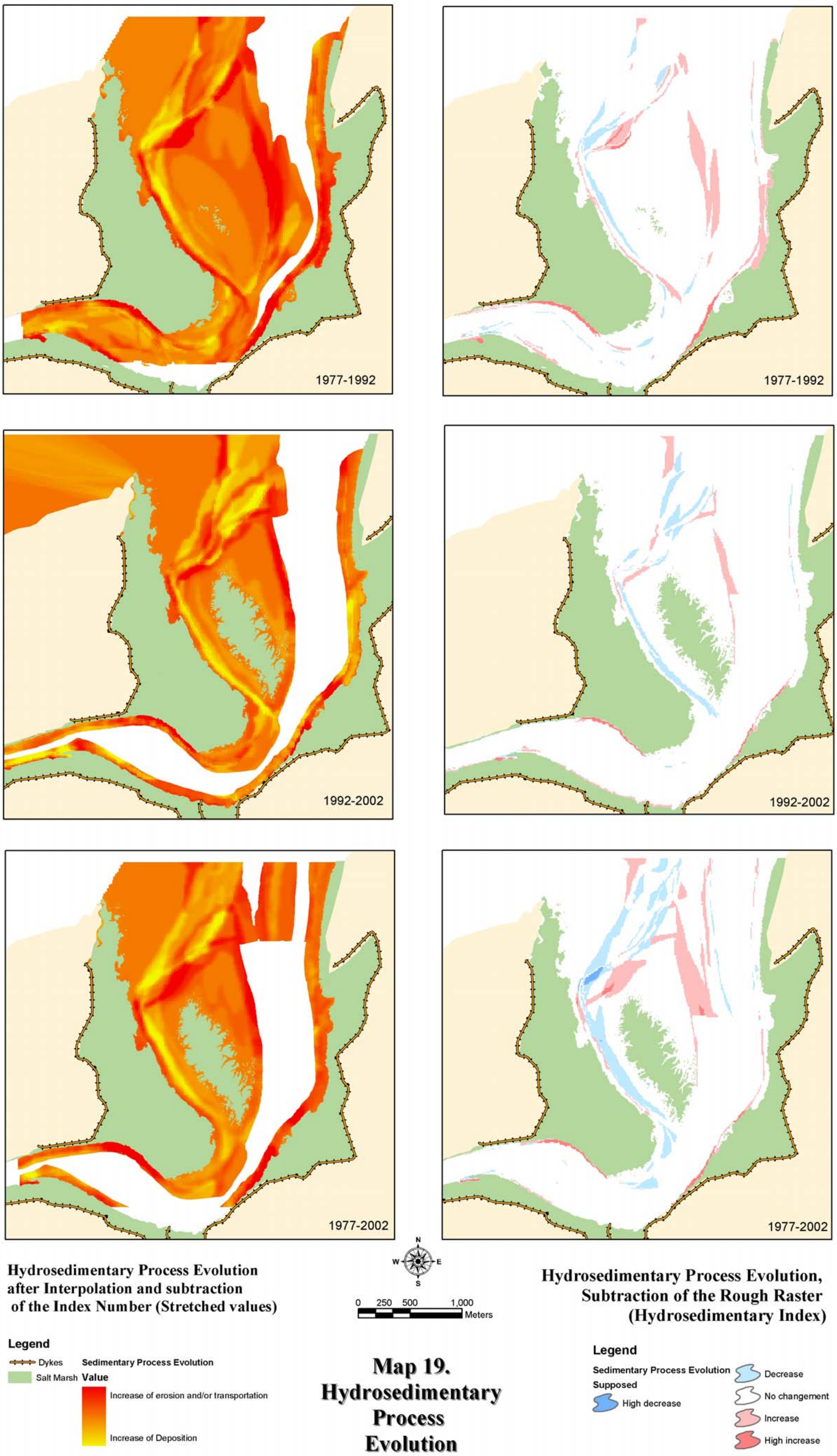


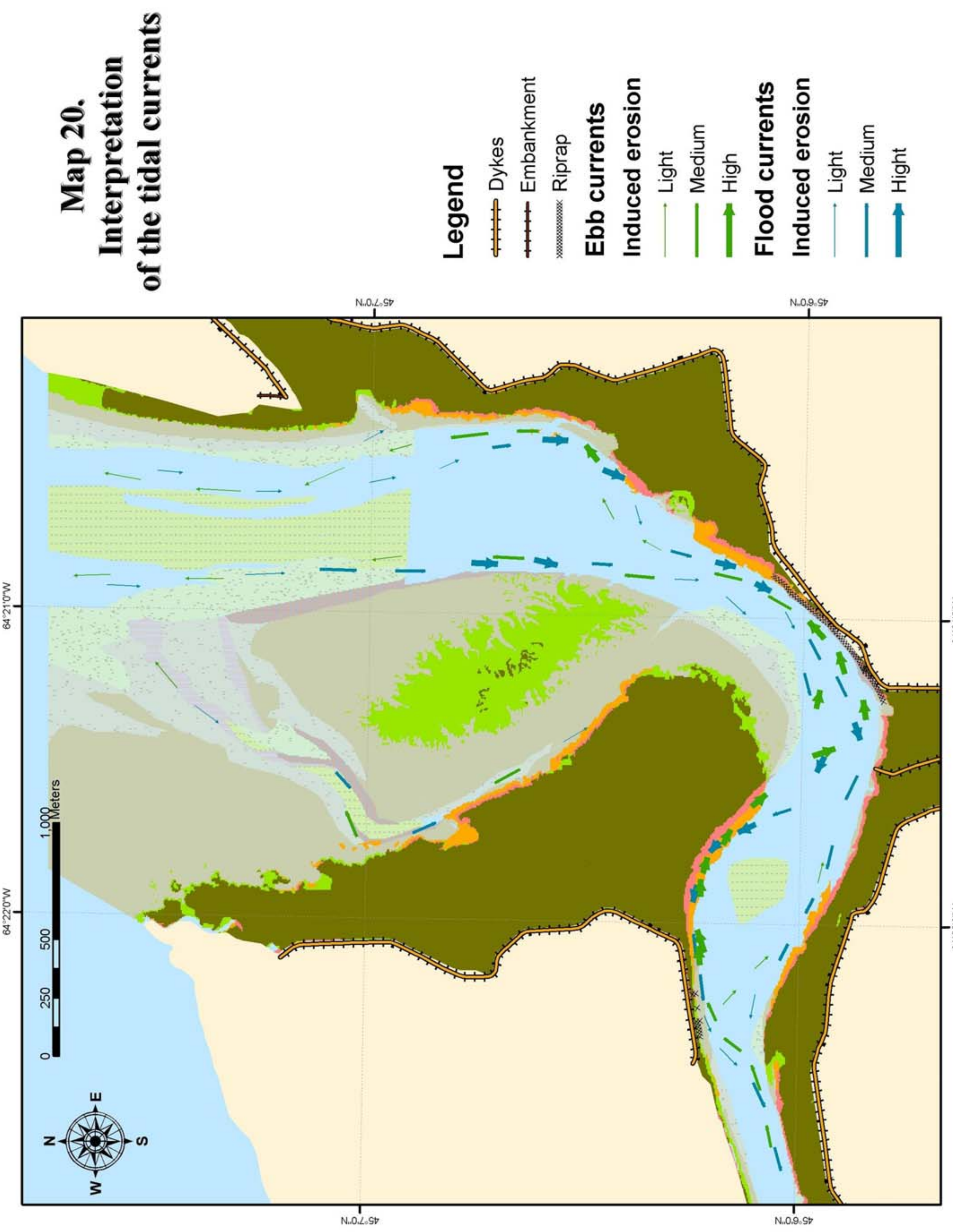
TIN digitalized from the LISP89 bathymetric map

Map 16. Bathymetric Map from LISP 89 (1989)

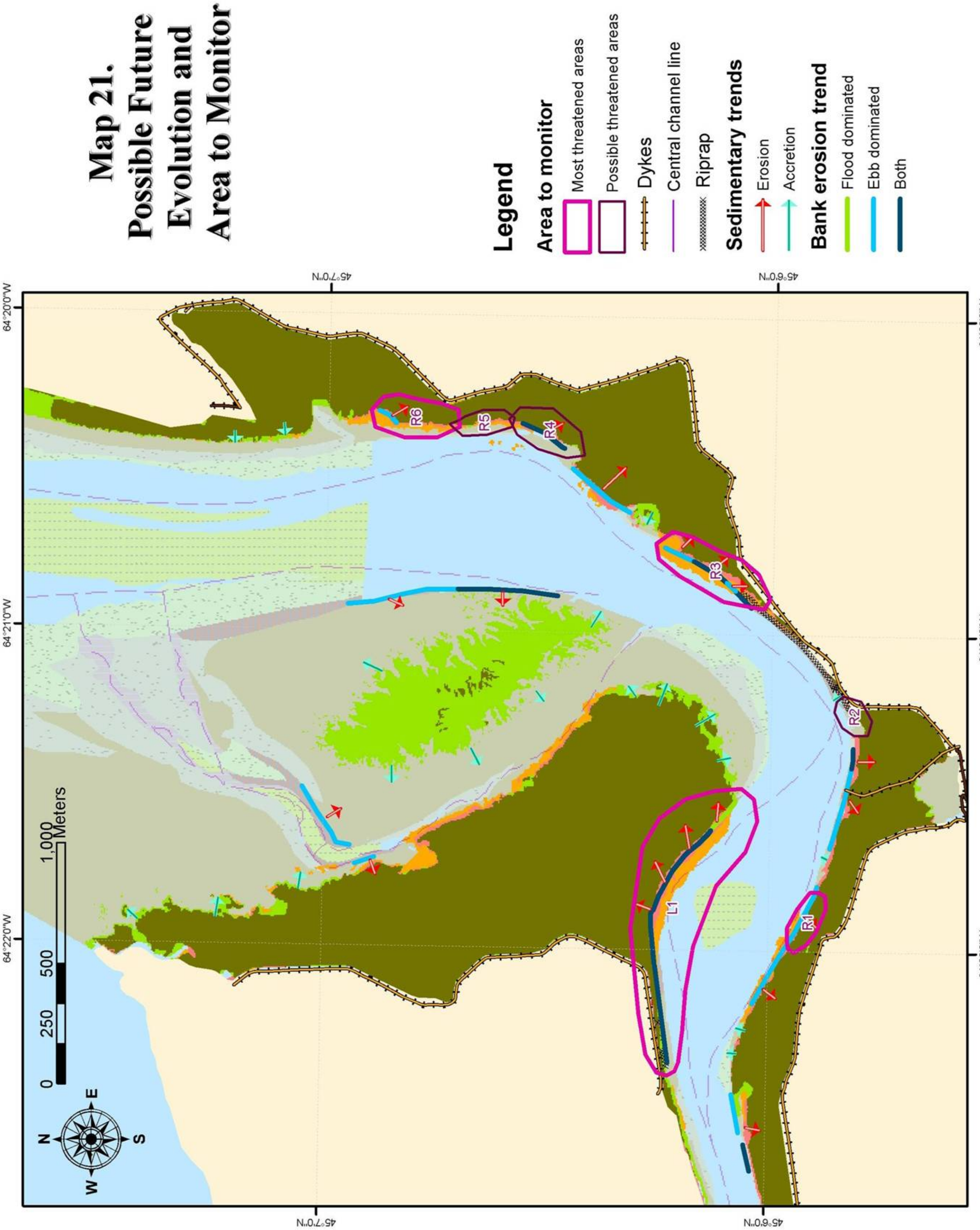

Map 17.
Tidal Channel Evolution
Legend
Dykes
Aboiteaux
Embankment
Riprap
Study area general
Salt Marsh 2002
High Marsh
Middle Marsh
Low Marsh
Young Low Marsh
Up Land
Streams
Topographic Contour
Tidal Channel Central line
1977
Channel Size
Main ch.
Secondary
Other
Other
Other
1992
Channel Size
Main ch.
Secondary
Other
Other
Other
2003
Channel Size
Main ch.
Secondary
Other
Other
Other
0 250 500 1,000 Meters
N E S W
64°20'0"W
64°21'0"W
64°22'0"W
64°23'0"W
45°7'0"N
45°6'0"N


Map 18.
Salt Marsh
Vegetation Dynamic
Legend
General study area
1977 study area
Aboiteaux
Dykes
Embankment
Riprap
Salt Marsh Dynamique
No changement
Gained between 1977 and 1992
Lost and gained between 1977 and 2002
Gained between 1992 and 2002
Lost between 1977 and 1992
Gained before 1992 and then lost
Lost between 1992 and 2002
Tidal Channel Thalwegs 2003
Channel size 2003
Main ch.
Secondary
Other
Other
Other
Channel size 1977
Main ch.
Secondary
Other
Other
Other
Streams
Topographic Contour
0 0.25 0.5 1 Kilometers
N E S W
64°20'0"W
64°21'0"W
64°22'0"W
64°23'0"W
45°7'0"N
45°6'0"N


1977-1992
1977-1992
1992-2002
1992-2002
1977-2002
1977-2002
Hydrosedimentary Process Evolution after Interpolation and subtraction of the Index Number (Stretched values)
N
W
E
S
0 250 500 1,000
Meters
Hydrosedimentary Process Evolution, Subtraction of the Rough Raster (Hydrosedimentary Index)
Legend
Dykes
Salt Marsh
Sedimentary Process Evolution
Value
Increase of erosion and/or transportation
Increase of Deposition
Map 19. Hydrosedimentary Process Evolution
Legend
Sedimentary Process Evolution Supposed
High decrease
Decrease
No changement
Increase
High increase



Map 20. Interpretation of the tidal currents


Map 21.
Possible Future
Evolution and
Area to Monitor
Legend
Area to monitor
Most threatened areas
Possible threatened areas
Dykes
Central channel line
Riprap
Sedimentary trends
Erosion
Accretion
Bank erosion trend
Flood dominated
Ebb dominated
Both
R1
R2
R3
R4
R5
R6
L1
0 250 500 1,000 Meters
N
E
S
W
64°20'0"W
64°21'0"W
64°22'0"W
45°7'0"N
45°6'0"N

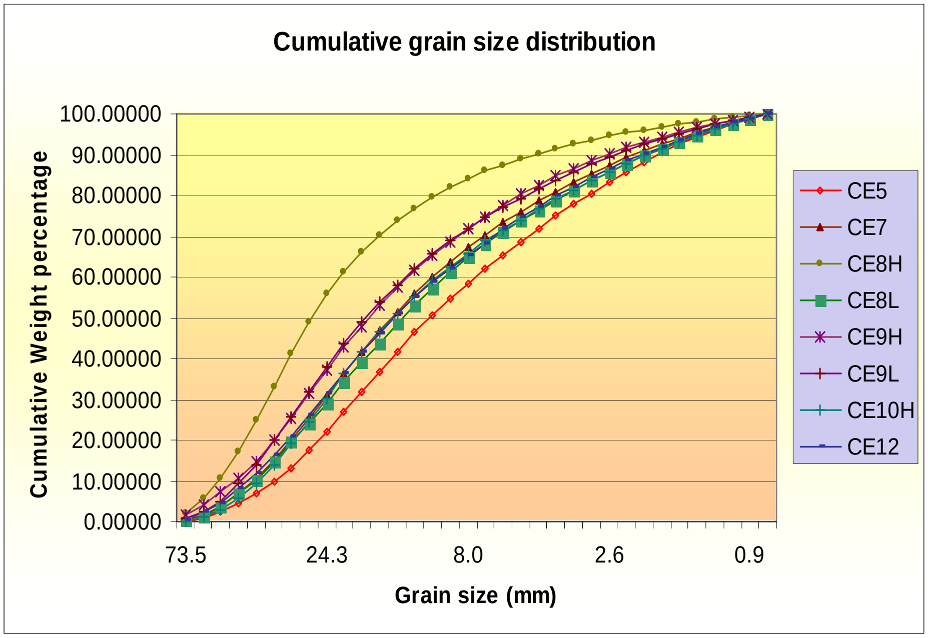
PHOTOGRAPHS

Photo 1. Boulders on the left bank that protect against erosion, near the old dyke. Looking eastward.

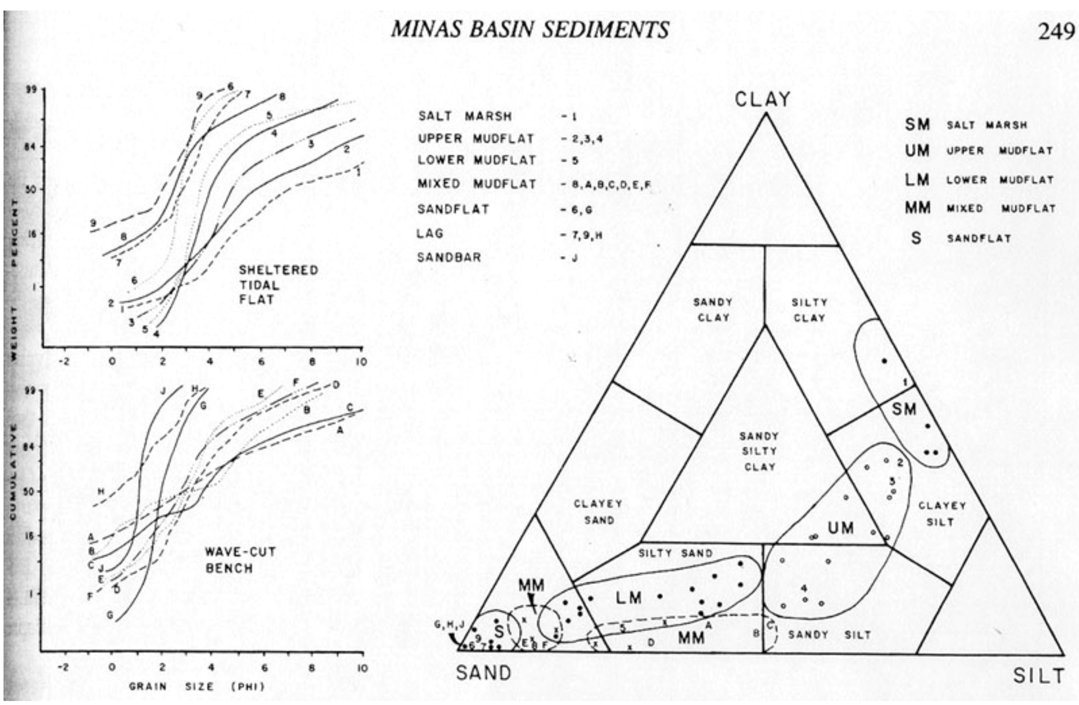
Photo 2. Cliff erosion on the southern edge of the left bank salt marsh (landslips).

Photo 3. Mud deposition at the left bank point bar, downstream from the photo 2. Colonization by *Spartina alterniflora*.

APPENDIXES



Appendix 1. Cumulative grain size distribution curve of the sediment samples.



Appendix 2. Grain size of intertidal zone sedimentary facies in the Minas Basin (Yeo and Risk, 1981).