CYCLES OF SALTMARSH EXTENSION AND CONTRACTION, CUMBERLAND BASIN, BAY OF FUNDY, CANADA

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Abstract
The purpose of this study was to document changes in the location of the seaward margin and tidal creek network for saltmarshes around the Cumberland Basin, Bay of Fundy, and to evaluate some geomorphic controls on the form and stability of these features at these marshes. Field measurements and observations, and measurements from historic aerial photographs were used to map changes in margin and creek positions over a 60-year period. To provide a framework for analysis, a conceptual model was created to describe observed patterns of cyclic saltmarsh development. The results suggest that there are important differences between the mechanisms by which Cumberland Basin marshes evolve and the mechanisms by which marshes in other locations evolve, and that understanding the cyclic nature of their evolution is key to understanding the marshes themselves and to predicting their futures.
Key words: *saltmarsh, evolution, model, Bay of Fundy.*

Resumen
El objetivo de este estudio ha sido documentar los cambios de localización del límite marino y de la red de canales de marea de las marismas alrededor de la Cuenca Cumberland, Bahía de Fundy, y evaluar algunos controles geomórficos en relación a la forma y estabilidad de estas formaciones. Trabajo de campo y mediciones a partir de fotos aéreas históricas se han utilizado para conocer los cambios que se han producido en estos ámbitos durante los últimos 60 años. Con el fin de proporcionar un marco para el análisis, se ha creado un modelo conceptual para describir los modelos de desarrollo cíclico observados en las marismas. Los resultados sugieren que hay diferencias importantes entre los mecanismos de evolución de las marismas de la Cuenca Cumberland y las de otras localidades, y que el conocimiento de la naturaleza cíclica de su evolución es clave para comprender las propias marismas y predecir su futuro.
Palabras clave: *marisma, evolución, modelo, Bahía de Fundy.*

Resum
L'objectiu d'aquest estudi ha estat la documentació dels canvis del límit marí i de la xarxa de canal de marea dels marenys de la Conca Cumberland, Badia de Fundy i l'avaluació d'alguns controls geomòrfics en relació a la forma i estabilitat d'aquestes formacions. Per tal de conèixer els canvis esdevinguts en els darrers 60 anys, s'ha fet treball de camp i s'han pres mesures a partir de fotografies aèries històriques. A més, amb la finalitat de proporcionar un marc per a l'anàlisi, s'ha creat un model conceptual per tal de descriure el desenvolupament cíclic observat als marenys. Els resultats suggereixen que hi ha diferències importants entre els mecanismes d'evolució dels marenys de la Conca Cumberland i de les altres localitats, i que el coneixement del caire cíclic de la seua evolució és clau per a comprendre els marenys i predir el seu futur.
Paraules clau: *maresme, evolució, model, Badia de Fundy.*

1. Introduction

SALTMARSHES form in the intertidal zone of protected areas along marine coasts and are colonised by a variety of vegetation, primarily grasses, that is tolerant to inundation by salt water. They are often thought of as zones of fine sediment accumulation because the vegetation acts to reduce flows and to promote deposition. Much attention has been focussed on the vertical growth of saltmarshes in response to organic matter accumulation as well as import of fine sediment. A generally accepted conceptual model for the evolution of saltmarshes with substantial mineral inputs is one of establishment of veg-

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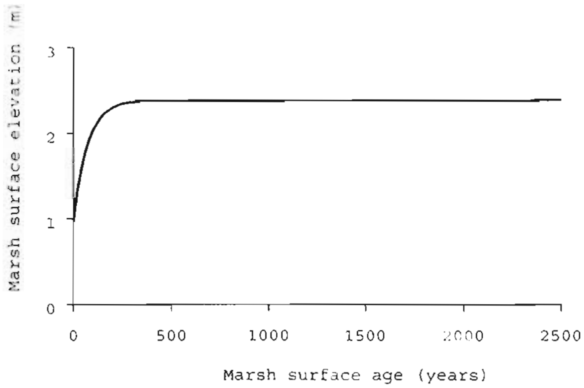

Fig. 1. Pethick's (1981) model of saltmarsh development: an initial period of rapid sedimentation is followed by an asymptotic increase in marsh elevation with time as the number of inundation cycles per year diminishes.

etation followed by accumulation of sediment. Sedimentation is rapid at first, but tapers off as saltmarsh elevation approaches the limit of tidal inundation as a result of the diminishing number of days annually when sediment can accumulate (e.g., Pethick, 1981; French, 1993; Fig. 1). The actual increase in saltmarsh elevation is complicated by factors such as below ground organic production and by decomposition and compaction, and it is also recognised that the shape of this curve (Fig. 1) will vary if there are changes in sediment input or sea level. These basic concepts have been used in a number of models of saltmarsh growth (e.g., Allen, 1990, 1997; Callaway *et al.*, 1996; Woolnough *et al.*, 1995).

This type of model applies initially to a point on a marsh but can be extrapolated to a marsh as a whole with the expectation that in the early stages of growth, the marsh platform is largely below the mean high tide and dominated by low marsh vegetation. As the marsh builds upward a much greater proportion of the surface approaches the upper limit of marsh development and consequently a mature marsh is dominated by high marsh vegetation. If the marsh is largely cut off from major disturbance, particularly wave action, it is possible to envision a gradual transition of large parts of the marsh to a terrestrial biome or to freshwater marsh.

Under this model, with stable sea level, the landward margin of a marsh is relatively stable in the initial stages and may gradually migrate seaward as the landward portions build above the limit of tidal influence. Where there is little disturbance by strong currents or wave action, the seaward margin of a marsh will migrate offshore as the vegetation spreads onto the mudflat, with growth ultimately occurring down to a point around the mid-tide line. Further seaward extension of the marsh is then limited by inundation time and thus in turn depends on the rate at which sediment accumulates on the lower intertidal flat, building it vertically to the point at which saltmarsh vegetation can establish.

Tidal creeks are an integral part of most marsh systems and can play a significant role in transfers of water and sediments to and from a marsh surface (Allen, 2000; French *et al.*, 1993). The type of creek network that develops depends on the tidal regime, topography, vegetation and sediment characteristics (Frey and Basan, 1978; Steel and Pye, 1997). Models of saltmarsh growth also envisage a pattern of tidal creek development in which the creek network initially expands and erodes headward and vertically during the early and middle phases of marsh development (e.g., Beeftink, 1966; French, 1993). Once creeks are established, Allen (2000, p. 1176) concludes that "...marsh creeks change in plan only very slowly, and perhaps as much as an order of magnitude more gradually than their fluvial and other intertidal counterparts".

In a number of areas, particularly where saltmarshes are exposed to some degree of wave action, saltmarsh development does not follow a simple pattern in which there is an asymptotic increase in saltmarsh elevation and seaward extension of the margin. Cyclic development of marshes has been recognised in a number of saltmarshes in Britain which are partially exposed to wave action (Gray, 1972; Allen, 1989; Pringle, 1995). In these marshes there are periodic episodes of erosion and recession of the marsh margin, often forming a marsh cliff followed by stabilisation and the development of new marsh in front of the old cliff. In these areas, therefore, cyclic marsh development may reflect a complex interaction between the trapping efficiency of saltmarsh vegetation and the effects of wave action. Another possibility, described in the model advanced by Schwimmer and Pizzuto (2000), is that cycles of marsh extension and contraction are controlled by changes in the relative rates of local relative sea level rise.

Observations and measurements at a number of marshes along the Cumberland Basin at the head of the Bay of Fundy point to the existence of some form

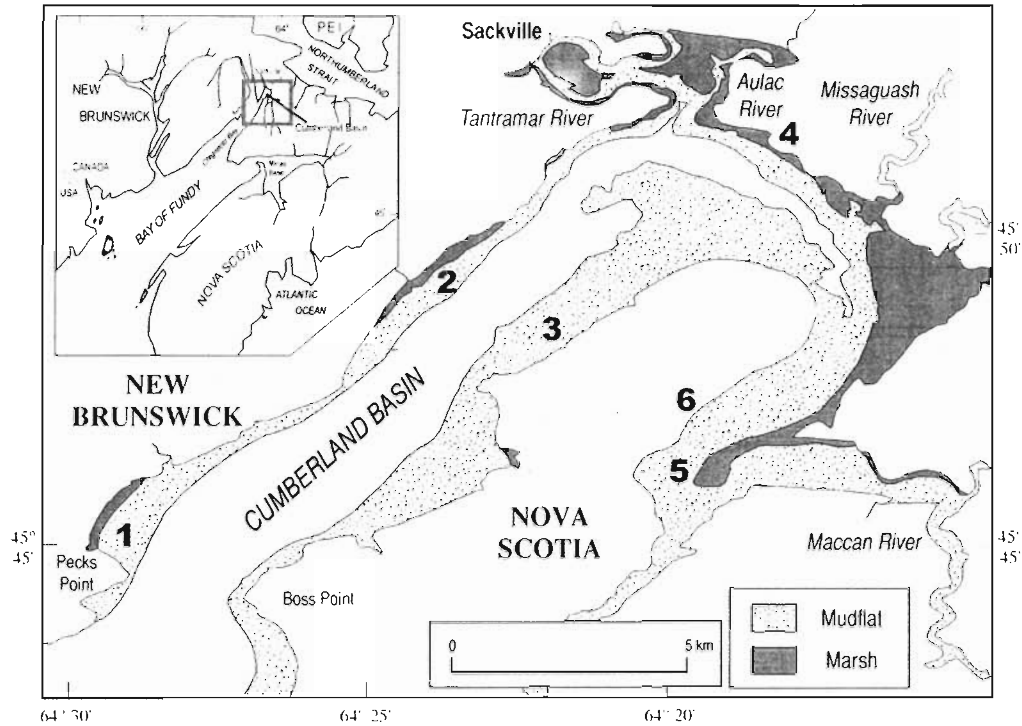

Fig. 2. Locations of marshes studied in the Cumberland Basin, Bay of Fundy. 1 = Peck's Cove, 2 = Allen Creek, 3 = Minudie West, 4 = Fort Beauséjour/Lusby West, 5 = Amherst Point, and 6 = Minudie East.

of cyclic development that resembles those reported for several sites in the UK and elsewhere. In some places the marsh margin is characterised by a distinct cliff ranging in height from a few cm to over 2 m. These cliffs often show evidence of rapid undercutting and measurements at selected locations show retreat in excess of 1 m/a in places. In other locations, cliffs exist but they appear to be stabilised and new vegetation is established in front of them. Finally, in some locations saltmarshes appear to be growing with vegetation becoming established further out onto the mudflats which lay seaward of the current margin. Measurements at one marsh suggest that much of the water flooding the marsh surface comes over the marsh margin and that the tidal creeks play a less significant role in the transfer of sediment than has been reported in other areas outside the Cumberland Basin (Schostak *et al.*, 2000).

The purpose of this paper is to document changes in the location of the seaward margin and tidal creeks at saltmarshes around the Cumberland Basin, to propose a model for cyclic saltmarsh development based on these measurements, and to evaluate geomorphic controls on the form and stability of the seaward margin and tidal creek networks at these marshes. Data on the dynamics of the marsh margins and the tidal creeks were derived from surveys at selected sites carried out on a seasonal or annual basis over several years as part of an ongoing study of saltmarsh sedimentation in the Cumberland Basin (e.g., Davidson-Arnott *et al.*, 2002) and from analysis of sequential aerial photographs at a decadal scale.

2. Study area

The Cumberland Basin is located at the upper end of the Bay of Fundy, between Nova Scotia and New Brunswick, and forms the north-east extension of Chignecto Bay (Fig. 2). The basin is a bedrock, dyke-bound estuary that is about 45 km long and 3 km wide at the entrance, with an area of about 118 km^2. The bedrock consists primarily of Carboniferous, Permian and Triassic sandstones and siltstones that are relatively weak (Amos *et al.*, 1991). Extensive deposits of fine sediment, derived largely from erosion of the bedrock and reworking of the seabed, have accumulated in the Basin and provide substrate for the development of extensive saltmarshes (Amos and Tee, 1989; Amos *et al.*, 1991; Gordon and Cranford, 1994). Total marsh area prior to European settlement has been estimated to be about 395 km^2. Over the past four centuries, much of this marsh was dyked and drained, leaving about 65 km^2 of natural saltmarsh today (Gordon and Cranford, 1994). Suspended sediment concentrations in the Basin are variable but generally high ranging from 150-200 mg/litre in the summer months to over 3000 mg/litre during fall storms (Amos and Tee, 1989; Parry *et al.*, 2001).

The Cumberland Basin is macrotidal with a normal spring tidal range of over 9 m at the entrance to the Basin, increasing to over 12 m at the head of the Basin. Sea level is rising at a rate of 0.3-0.4 m/century (Gordon *et al.*, 1985) and the tidal range is also increasing as the dimensions of the Bay of Fundy change. The tides are semi-diurnal and the difference between the height of successive spring tides can exceed 1 m. Strong tidal currents are generated in many parts of the Bay of Fundy, most notably in the Minas passage and the entrance to Chignecto Bay, as well as the Cumberland Basin and these are responsible in part for resuspension of muds and the high suspended sediment concentration in Bay waters. At neap high tides, water may flood only the tidal creek channels and the margins of the low marsh surface. At normal spring high tides, water depth over the marsh surface is 1-2 m. During storms, waves > 1 m high are generated by winds blowing over fetches exceeding 10 km and these waves can cause significant erosion of the exposed marsh margin along the sides of the Basin.

Saltmarshes in the Cumberland Basin increase their elevation primarily as a result of deposition of sediment, with only moderate contributions from below-ground organic production. Sediment accumulation is enhanced by the characteristically high suspended sediment concentration in Bay waters, consisting of 95% coarse silt with small amounts of clay (2.5%) and sand (1.5%) (van Proosdij *et al.*, 1999). For example, preliminary data suggest that the marsh surface around the mean high water line (MHWL) at Allen Creek marsh is accumulating sediment at an average rate of 2.2 cm/a (van Proosdij *et al.*, 1999). Marshes in the Basin vary considerably in width and exposure to waves and are bordered offshore by extensive mudflats that ultimately grade into sands and gravels near the low tide line (Gordon *et al.*, 1985; Dawson *et al.*, 1999).

The marshes can be divided into traditional low and high marsh zones on the basis of vegetation characteristics and contain a plant community referred to as a Bay of Fundy type marsh (Chapman, 1960). The low marsh zone is flooded frequently and is vegetated almost entirely by *Spartina alterniflora* with *Salicornia sp.* in the sub-canopy. The high marsh zone is flooded infrequently and is dominated by *Spartina patens* with many subordinate species including: *Pucinellia maritima, Plantago maritima, Triglochin maritima, Solidego sempervirens, Limonium nashii, Juncus gerardi, Hierochloe odorata, Glaux maritima, Sueda maritima, Elymus arenarius, Distichilis spicata* and *Atriplex sp.* (van Proosdij *et al.*, 1999). A sharp topographic division or terrace separating the two zones, which has been identified elsewhere in the Bay of Fundy and in New England (Redfield, 1972; Chmura *et al.*, 1997), does not occur at this location.

Vegetation begins to grow in late April or early May and dies off by the end of November. After this time, much of the vegetation is sheared off in the low marsh region and exported into the estuary (Gordon and Cranford, 1994). However, some standing dead vegetation will remain in the mid and high marsh regions, depending on the extent of snow and ice coverage. In northern marshes, thick, shorefast ice develops primarily over the low marsh region (Gordon and Desplanque, 1983; Dionne, 1989), and a ridge of ice blocks and slush may develop in the zone between neap and spring tides. Rafted ice floes can be stranded over the whole marsh surface and often remain there over much of the winter (Ollerhead *et al.*, 1999). During the spring, the stranded floes melt and deposit appreciable amounts of coarse and fine sediment, creating patches of bare sediment. This mechanism appears to be an important contributor of sediment to the marsh system, particularly in the high marsh (Gordon and Desplanque, 1983; Wood *et al.*, 1989; Ollerhead *et al.*, 1999). As well, vegetation clasts (composites of sediment, plant and root matter ripped up from the top of the margin cliff by wave and/or ice action) are frequently found scattered over both the low and high marsh in spring, particularly near the mean high tide line.

3. Methodology

Six study sites were chosen to represent the Cumberland Basin and to ensure contrast in wave exposure and tidal range (Fig. 2). The six marshes all had mini-

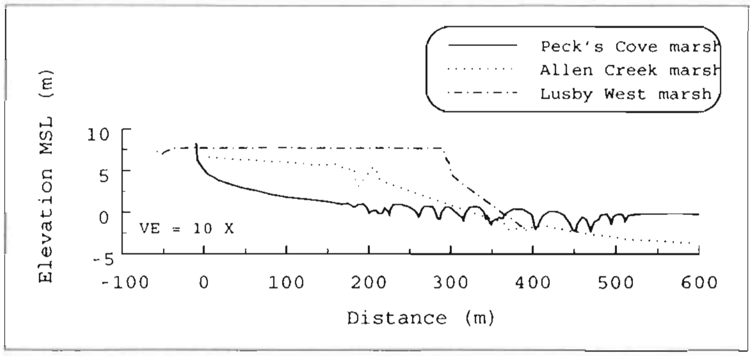

Fig. 3. Profiles for three of the marshes studied. Note the different shapes, slopes, and positions in the tidal frame. Elevations are relative to mean sea level (MSL) as defined by the EGM96 geoid model and the vertical exaggeration (VE) is 10 X.

mal anthropogenic impact and were easily accessible. At each site, two profiles were established 100 m apart perpendicular to the marsh margin, and extending from the landward edge of the marsh onto the mudflat (Scott, 2000). The lines were surveyed using a Leica TC600 total station and plant species were identified along the length of one of the lines. Five tidal creek cross-sections representative of the area from the low marsh to the high marsh were also surveyed (except at Amherst Point marsh where there were few tidal creeks and only two were measured).

Surface features on each marsh were mapped using a Trimble Pathfinder Pro XR global positioning system (GPS) receiver, which has sub-metre horizontal accuracy in differential mode. In addition to mapping the marsh margin and the thalwegs of major tidal creeks, the positions of a series of recognisable landmarks were also mapped for use as control points and for ground-truthing in the rectification of historic aerial photographs (Scott, 2000).

Vertical aerial photographs for the marshes for the period 1939-1985 were obtained from the Government of Canada and the provinces of New Brunswick and Nova Scotia. One photograph was chosen for each site for each year available and then each one was scanned at 600 dpi with 256 shades of grey or 256 colours using an HP Scanjet IIc with DeskScan software. Images were saved in TIFF format and then rectified using ESRI's ArcView 3.1 geographic information system (GIS) software with its Image Analysis 1.0 extension (an ERDAS product) and the control points mapped in the field. The RMS rectification error was calculated for each photograph and was found to be < 5 m for 90% of the photographs.

Digitizing of saltmarsh features, particularly the seaward marsh margin and the tidal creek network, was performed on-screen in ArcView 3.1. All interpretation was done at a nominal scale of 1:3000. Changes between each series of photographs were then determined in ArcView 3.1 using the measuring tool. Changes in the marsh margin were determined every 10 m along a 300 m margin-parallel transect and the positions of the tidal creeks were determined every 10 m along the channel. Average marsh width was also measured every 10 m along the 300 m margin-parallel transect. Expected positional error was

Marsh	*Distance from Entrance (km)*	*Orientation*	*Maximum Fetch (km)*	*Slope (°)*	*Present Trend at Margin*
Peck's Cove	7	S-N	14.4	3.05	Extending
Allen Creek	16	SW-NE	9.3	0.39	Contracting
Fort Beauséjour/Lusby West	24	NW-SE	19.9	0.44	Contracting
Amherst Point	31	SW-NE	5.7	0.03	Extending
Minudie East	31	SW-NE	4.5	0.42	Extending
Minudie West	16	SW-NE	8.1	0.23	Extending

Table 1. Environmental characteristics for the six marsh sites including: approximate distance from the entrance to the Cumberland Basin, approximate margin orientation, maximum fetch (marsh margin to marsh margin), marsh surface mean slope, and present trend at the margin.

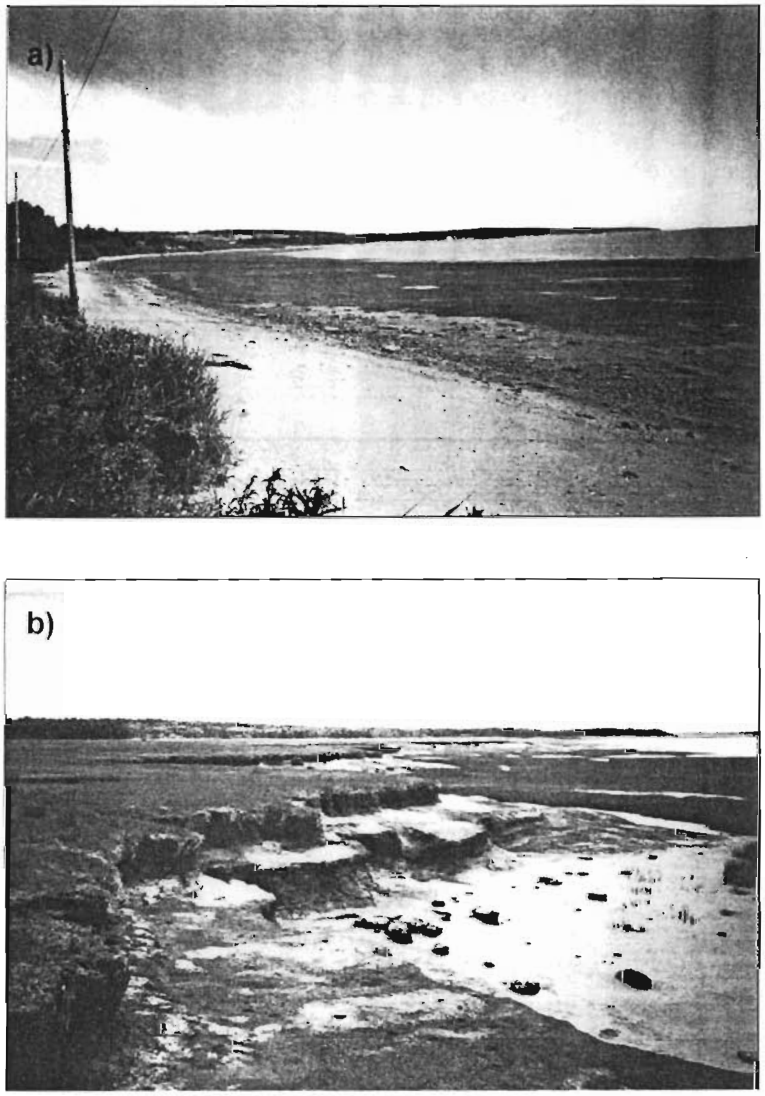

Fig. 4. Photographs of: a) Peck's Cove marsh showing the coarse sand and gravel beach face and *Spartina alterniflora* extending onto the mudflat, and b) Minudie West marsh showing the stable cliff and low marsh developed in front of it.

calculated to be 5.5 m, taking into account an RMS error of 5 m for the rectified photographs, a control point collection error of 1 m, and an error of 2 m in identifying features (e.g., marsh margin, creek edge) on the photographs.

4. Results

4.1. *Saltmarsh characteristics*

Some basic features of each marsh are summarized in Table 1 and representative profiles for 3 contrasting marshes are presented in Fig. 3. The following briefly describes the characteristics of each marsh:

1) Peck's Cove marsh is located on the northwest side of the Cumberland Basin closest to the entrance (Fig. 2). It is approximately 1 km long and was about 100 m wide in July, 2000. It is all low marsh and is vegetated entirely by *Spartina alterniflora* that is actively extending seaward onto the mudflats (Figs. 3, 4a). The boundary between the vegetation and the mudflats is irregular (Fig. 5). Observations at this site show that the vegetation line has advanced seaward across the mudflats by 10s of metres over the period 1999-2003. Tidal creeks are well developed on the mudflats and the network extends through the marsh nearly to the shoreline.

2) Allen Creek marsh stretches for about 4 km

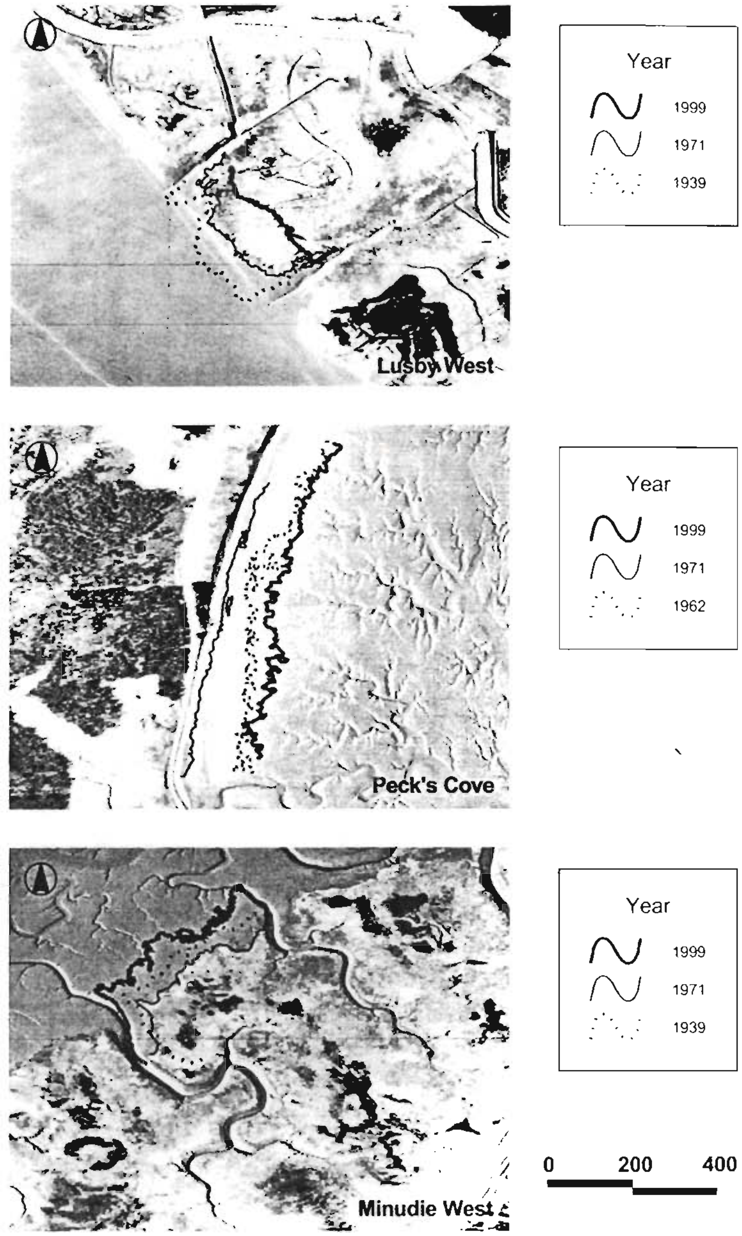

Fig. 5. Marsh margin change for selected years for the Lusby West, Peck's Cove, and Minudie West marshes. In all cases the underlying aerial photograph is from 1971.

alongshore on either side of Allen Creek (van Proosdij *et al.*, 2000; Schostak et al., 2000; Davidson-Arnott *et al.*, 2002). It varies from about 50 m wide at the southwestern end to about 200 m near the centre and there has been some dyking at the northeastern end. The central area is characterised by a marsh cliff 1-1.5 m high fronted by an erosional platform and mudflats (Fig. 3). The marsh cliffs are actively eroding at rates of 1-2 m/a (Davidson-Arnott *et al.*, 2002). A band of high marsh vegetation (dominantly *Spartina patens*) occupies the landward 15-30 m of the marsh and the remainder is dominated by low marsh vegetation (mainly *Spartina alterniflora*).

3) Fort Beauséjour/Lusby West marsh is located at the head of the main arm of the Cumberland Basin. The two sites studied are backed by an agricultural dyke and also separated by about 1 km of that dyke. The Fort Beauséjour marsh extends north from the site studied along the Tantramar River while the Lusby West marsh is part of the large John Lusby Marsh

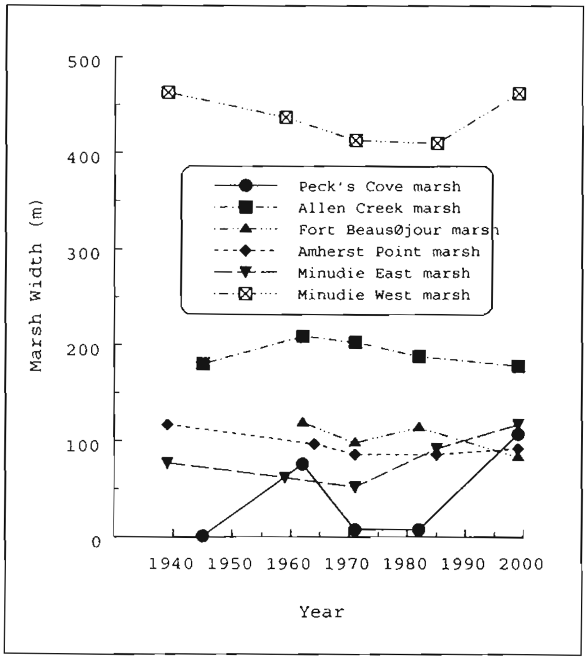

Fig. 6. Marsh width change for selected years for all six marshes.

located west of Amherst, NS (Fig. 2). The marsh ranges from 80-320 m wide, is flat and high in the tidal frame, and ends in a cliffed margin 1-4 m high that is being actively eroded (Figs. 3, 5). Most of the vegetation on the marsh surface consists of high marsh species (dominantly *Spartina patens*) with *Spartina alterniflora* present only near the margin and along some of the tidal creeks.

4) Amherst Point marsh is located at the upper end of the Cumberland Basin near the entrance of the Macaan River. The area was originally dyked but these were abandoned in the 1930s and most of the dykes have now disappeared. The marsh is about 2 km long and 700 m wide at its widest point. It is relatively flat, high in the tidal frame, and the dominant vegetation is the high marsh species *Spartina patens*. The margins are cliffed on both the east and west sides and are actively eroding in numerous locations. In a few locations on the west side, patches of *Spartina alterniflora* have established on the mudflats below the margin cliff.

5) Minudie East marsh is located across from Amherst Point at the head of the Basin (Fig. 2). The marsh is about 2 km long and 150-200 m wide. It consists mainly of high marsh vegetation (mostly *Spartina patens*) with patches of *Spartina alterniflora* growing along the tidal creeks that drain into the Macaan River. A low scarp about 0.2 m high marks the boundary between the high and low marsh adjacent to the largest tidal creek, and the outer marsh margin is the relatively steep bank of the Macaan River.

6) Minudie West marsh is located on the southeast side of the Cumberland Basin opposite Allen Creek. The marsh is about 2 km long and extends seaward about 800 m from the base of a dyke. Much of the marsh consists of high marsh vegetation (mostly *Spartina patens*) on a gently sloping platform, which terminates abruptly in a cliff about 2 m high that is stepped or terraced (Fig. 4b). The cliff appears to be stable and is fronted by a zone about 80 m wide of low marsh *Spartina alterniflora* that is extending onto the mudflats. There are few tidal creeks on the main marsh surface and salt pans (ponding) are present.

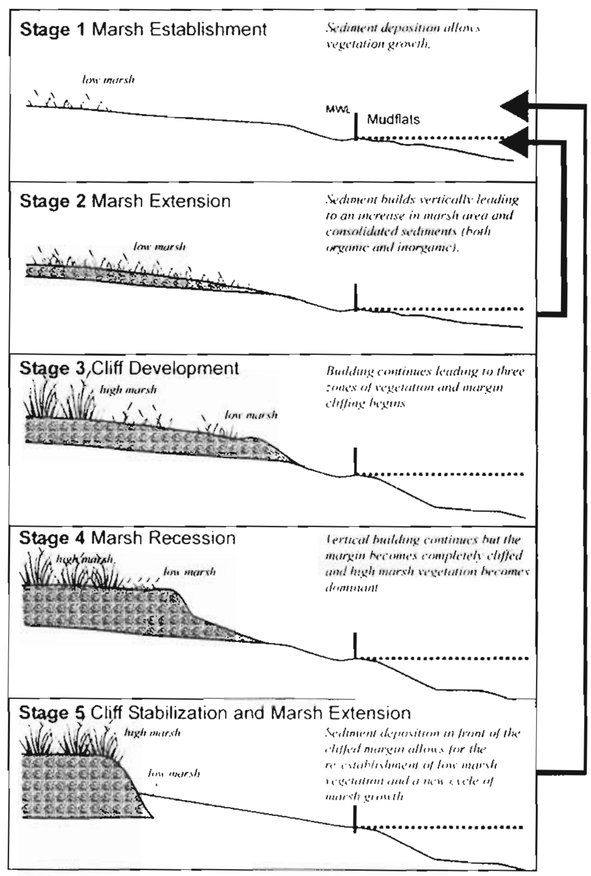

Fig. 7. Conceptual model of Cumberland Basin saltmarsh development. MWL = mean water level.

4.2. *Saltmarsh dynamics*

Examples of the mapped position of the marsh margin for different years at the Lusby West, Peck's Cove, and Minudie West marshes are provided in Fig. 5 and changes in marsh width over the study period are illustrated for all six marshes in Fig. 6. The following briefly describes the recent evolution of each marsh margin:

1) Peck's Cove marsh was very dynamic over the period 1945-1999. There has been no high marsh development here over the six decades covered by this study. In 1945 the marsh was only a few metres wide; it was essentially a thin, irregular fringe of vegetation on the mudflat just seaward of the beach face. Marsh vegetation spread seaward onto the mudflats reaching a width of about 80 m in 1962 (Figs. 5, 6). The marsh was then eroded right back; by 1971, it was less than 10 m wide in most locations and this persisted until at least 1982. Between 1982 and 1999, marsh vegetation once again spread across the mudflats reaching a width of just over 100 m by 1999. This extension of vegetation seaward continues to this day.

2) At Allen Creek marsh there was an initial seaward growth of the low marsh in the period 1945-1962, but since then the marsh margin has receded at a rate of 1-2 m/a leading to the formation of a marsh cliff 1-1.5 m high. Sedimentation on the marsh surface has continued with the result that cliff height has increased through time and a high marsh zone 15-30 m wide has developed (Davidson-Arnott *et al.*, 2002).

3) The Fort Beauséjour/Lusby West marsh has been steadily eroding over the study period (Figs. 5, 6). At Fort Beauséjour, there has been steady erosion of the marsh margin at a rate of approximately 1 m/a since at least 1962 (the earliest photograph obtained). At Lusby West, the margin retreated about 200 m over 60 years, a rate of > 3 m/a (Fig. 5).

4) Amherst Point marsh has also been eroding steadily over the past 60 years at a mean rate of about 0.4 m/a. However, the rate appears to have slowed in recent years (1964-1985). Since 1985 the marsh cliffs appear to have become more stable and areas of low marsh vegetation are spreading onto the mudflats in front of the cliff on the NW side.

5) Minudie East marsh exhibits some interesting trends. Margin erosion is dominant from 1939-1971 at a mean rate of about 0.8 m/a. This period is followed by a period of rapid margin extension at a mean rate of 2.3 m/a (1971-1999). Note that expansion of the low marsh during this period was not linear; it was more rapid during the period 1971-1985 than during the period 1985-1999. Note also that the low scarp referred to in the previous section (that marks the boundary between the high and low marsh) likely also represents the landward limit of margin contraction (~ 1971) prior to new margin extension.

6) Minudie West marsh experienced a period of margin contraction between 1939 and 1971 at a mean rate of 1.6 m/a followed by a period of rapid extension between 1985 and 1999 at a mean rate of 3.7 m/a (Figs. 5, 6). The erosion between 1939 and 1971 produced a terraced cliff about 2 m high and the new low marsh has developed on the mudflat in front of the cliff.

Changes in the position of tidal creeks at each marsh were measured at 10 m intervals. Overall, the creeks appear to be very stable with any change in position taking place relatively slowly; the mean rate of change for all marshes was < 1 m/a over the study period and in most cases the rate of change was much less than 1 m/a. For example, at Allen Creek marsh total tidal creek migration was less than 8 m over the study period (1945-1999). Except where cliff recession leads to the removal of a creek channel oriented roughly parallel to the cliff itself, the creek systems only show small changes around the meander bends. Where marsh extension occurred, it was observed that the creek network present on the mudflats was inherited by the marsh, as marsh vegetation spread onto the mudflat surface.

4.3. *Conceptual model of saltmarsh cycles*

Based on the measured changes in the seaward margins of the six marshes described, on field observations of these and other marshes along the shoreline of the Cumberland Basin, and on several assumptions about the processes controlling vegetation establishment and profile development, a conceptual model of saltmarsh cycles was developed (Fig. 7):

Stage 1: The cycle is envisaged to begin with a gently sloping profile backed by a small beach and uplands along the side of the Basin and fronted by mudflats. Low marsh vegetation becomes established just seaward of the beach and extends seaward. As the vegetation zone becomes wider and vegetation density increases, wave action is reduced at the landward edge of the marsh, promoting sediment deposition and vertical growth.

Stage 2: Vegetation continues to extend seaward – as the marsh grows vertically the thickness of the root zone increases and a resistant layer develops, capable of maintaining a vertical face. Depending on exposure, storm occurrence, or heavy ice in the winter months, the developing marsh may be eroded. If the thickness of the root zone is small the whole layer may be sheared away without a significant scarp or cliff developing. This has been observed at the edge of a marsh on the west side of Allen Creek. If this happens, erosion can return the marsh to stage 1 and a new cycle is initiated.

Stage 3: Vegetation continues to expand seaward and vertical growth occurs over the surface. A thick layer of consolidated marsh sediment is now developed which is capable of maintaining a cliff face and resisting wave erosion. Seaward extension of the vegetation is limited by increasing exposure to waves and vegetation becomes more vulnerable to wave and ice erosion. Vegetation extension is also slowed by increased duration of flooding. When erosion of the outer margin occurs because of ice or a major storm, a scarp is created leading to wave reflection during periods when the water level is at the scarp; this promotes block failure and re-entrant development. Wave reflection prevents mud from accumulating in front of the scarp and vegetation cannot establish on the hard, eroded surface in front of the scarp.

Stage 4: Recession of the marsh cliff continues while at the same time sedimentation on the marsh results in an increase in elevation. The remaining marsh thus becomes dominated by high marsh species. Because of the continuing upward growth of the marsh, cliff height tends to increase. Continued recession of the marsh cliff leads to the development of a gently sloping platform. In very exposed areas, it is possible that the whole marsh is eroded back to the side of the Basin leaving a wide platform on which vegetation can become established and start the cycle again.

Stage 5: As the margin retreats it tends to become more sheltered from direct wave action from the largest waves propagating along the length of the Basin while at the same time the increasing platform width dissipates more wave energy. This increases the potential for sediment deposition and the successful establishment of low marsh vegetation (e.g., patches of *Spartina alterniflora*) in the mud seaward of the marsh cliff base. If low marsh vegetation becomes well established, it in turn protects the cliff from wave action and further erosion. The old marsh cliff thus becomes preserved as a new marsh cycle is initiated in front of it, as appears to have happened at Minudie East.

5. Discussion

The cycle of saltmarsh extension and contraction proposed here for the Cumberland Basin assumes that there is sufficient wave action to erode established vegetation and to initiate the development of a scarp or marsh cliff. Because of the elongate nature of the Basin, most of the marshes have open water fetches >10 km and are subject to waves with significant wave height > 0.5 m. Similar fetches are common for many marshes in semi-exposed bays and estuary mouths and it is notable that marshes where similar erosional cycles have been reported are also exposed to significant wave action (Allen, 1992; Pringle, 1995). In the Cumberland Basin, the effects of ice may aid wave erosion during the winter (Ollerhead *et al.*, 2003). Erosion occurs primarily as a result of ice freezing to the marsh surface and subsequent removal of a layer of vegetation and substrate as ice blocks are floated away by wave action on spring high tides. Erosion can also occur as a result of the dragging and scraping action of large ice floes. A second factor that is an important control on the nature of the marsh cycle is the high rates of sedimentation on the marsh surface promoted by high suspended sediment concentrations in the water (van Proosdij *et al.*, 2000; Parry *et al.*, 2001). The development of substantial marsh cliffs over relatively short time spans reflects the high rate of sedimentation on the marsh surface.

The behaviour of the marsh margin, and in particular the transitions from extension to contraction and vice versa, are clearly key controls on the development of cyclicity. Our observations suggest that once the front edge of a marsh becomes disturbed or scarped, wave action on this incipient cliff face on the rising and falling tides tends to scour the area in front of it, leading to the development of an erosional surface in the consolidated sediments of the root zone. In turn, this hard surface together with the scouring effect of waves tends to prevent deposition of mud and thus it inhibits re-establishment of vegetation. A positive feedback cycle is therefore initiated with the amount of scouring and reflection increasing as the scarp is eroded and the cliff face becomes higher.

Once *Spartina alterniflora* is established on the shore of the Basin it can readily propagate seaward across the mudflats as is evident from the recent rapid extension of the marsh at Peck's Cove and in front of the marsh cliff at Minudie West. Assuming that net accretion is promoted by the presence of vegetation and increases with increasing height and density of vegetation, a steepening of the profile is expected as there is greater accretion on the landward portions of the vegetated surface. Ultimately, on a sloping surface, the rate of seaward propagation is limited by decreasing light exposure and thus time available for photosynthesis. Growth is also limited by lack of oxygen and cold temperatures, both of which increase with increasing time submerged. However, the data presented here suggest that the contraction portion of the cycle is usually triggered before this ultimate limit is reached, by some combination of storm wave action and/or ice action during a severe winter. Indeed, the potential for this occurring increases as the marsh extends seaward and as the rate of vegetation growth is slowed; thus, extension of a mash to the mid-tide level is likely to occur rarely.

Transition from a contraction phase to a new extension phase depends on the establishment of *Spartina alterniflora* in areas protected from major wave scour. In some cases, for example at Peck's Cove, this may not occur until the contraction cycle is complete and the former marsh has been largely destroyed. In other cases, wave energy at the cliff face may be reduced sufficiently as a result of dissipation over the gentle platform slope and protection from wave action by shoals and headlands on either side. Vegetation propagation onto the platform may begin by plants spreading outward from sheltered areas around the mouths of tidal creeks. This has been observed over the past 3-4 years at Allen Creek marsh. Once established on the platform in front of the cliff, the vegetation acts to further dampen wave energy, trap sediment, and a new cycle of extension is initiated.

The pattern of cyclic marsh development documented here is similar to cycles reported from several areas of Britain (Gray, 1972; Allen, 1989, 1992; Pringle, 1995) and parts of western Europe (reviewed by Allen, 2000). The dominant controls on cyclicity in the Cumberland Basin appear to be exposure to wave action, particularly that generated by winds blowing along the length of the Basin, the effects of ice in many winters, and the high rates of vertical marsh accretion due to the high suspended sediment load in the Bay of Fundy. The duration of marsh cycles may be as little as one or two decades to more than five decades and may be controlled in part by local shoreline geometry and wave exposure. Stages of cycles within the Basin do not appear to be synchronous and this suggests that local influences outweigh the effects of temporal variations in winter ice and/or wind climate and that changes in the relative rates of local relative sea level rise cannot be, as suggested by Schwimmer and Pizzuto (2000), the primary control on observed marsh cycles.

Unlike many British and western European marshes (Steel and Pye, 1997; Allen, 2000), the tidal creek network at Cumberland Basin marshes is quite stable and shows little evidence of an evolutionary cycle as the saltmarshes grow vertically and horizontally. The creek network appears to be established in the mudflats of the intertidal zone prior to marsh development and the pattern becomes fixed as the marsh accretes. Thus, there appear to be many important differences between the mechanisms by which Cumberland Basin marshes evolve and the mechanisms by which marshes in other locations evolve.

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