Lessons Learned from Recovering Marshes:
the Hydrological Network in Abandoned Dykelands

Final Report

by

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Executive Summary
In this study we characterized the channel network in a pair of salt marshes on the lower Bay of Fundy and on the Cumberland Basin in the uppermost reaches of the Bay. This represents a dramatic gradient in tidal amplitude and suspended sediment supply. Each pair was comprised of a marsh recovering from agricultural reclamation for ~50 years and a reference marsh, never drained for agriculture. Our field-mapping covered >20 km of channels and over 776,000 m^2 of three marshes. We used data collected in a previous field campaign for the fourth. This data was incorporated into a GIS to calculate channel length, density and maximum distance of marsh areas to any channel. The latter indicates the potential for drainage, and access of nekton during flooding, as well as transfer of detritus and dissolved organic carbon and nutrients.

On the recovering marshes we verified the existence of a hybrid channel network, comprised of original creeks and agricultural ditches. By overlying our field data on recent aerial photos we determined that field mapping is essential as aerial photos do not reveal which channels are functioning parts of the marsh network. Both original creeks and parts of the extensive agricultural grids of ditches have been abandoned, but are visible on photos taken within the last decade. Abandonment of these channels may result in greater pond area in recovering marshes – a characteristic we are now studying.

Comparison of recovering and references marshes suggests that recovering marshes have a higher channel density, but this difference could be due to the larger size of agricultural marshes and a disequilibrium with present tidal conditions. In the lower Bay marsh we were able to use aerial photos to make a historical comparison which indicated that the recovering marsh has a channel density comparable to its original conditions, but a reduction in sinuosity, a characteristic that contributes to the value of channels as habitat for nekton.

Our calculation of channel density ignored the clustering of channels around major channels which is revealed by a marsh-channel proximity analysis. Proximity of any marsh areas to a channel enhances soil drainage, exchanges of organic carbon and nutrients, as well as access by nekton during marsh flooding. An assessment of the area of marsh within 3 m of any channel does not distinguish recovering from reference marshes, but does indicate that our lower Bay recovering marsh has enhanced ecological function in this regard. When larger distances are considered, recovering marshes are distinguished by greater proportions of marsh area far from effects of channels. This could be an artifact of the larger size of the recovering marshes.

Channels in the hybrid networks of recovering marshes have developed a variety of morphologies and may not have retained equilibrium with respect to the present tidal amplitude and relative sea level, as both have increased since marshes were reclaimed. Because value of channels as habitat for nekton and benthic fauna depends, in part, on channel morphology, further research on channel morphology is merited.

Introduction

If we return flooding to Fundy dykelands can we restore the original ecosystem? If not, what differences would we expect? This research project has begun to address these questions by comparing "recovering" marshes, where dykes have been abandoned, to "reference" marshes, where dykes and drainage systems were not installed.

Drainage of Fundy dykelands was accomplished by preventing tidal flooding and construction of an intensive network of ditches to facilitate soil drainage into the aboiteaux system. Thus, as dykes are abandoned tidal flooding is restored to a marsh with a greatly altered and presumably expanded hydrological network. Observations of recent aerial photographs of abandoned dykelands indicated that parts of the anthropogenic system are incorporated into the tidal network, suggesting an increased drainage density – but no empirical studies had been performed.

These constructed channels may play a role in salt-marsh function similar to that of natural creeks: providing habitat for nekton and benthic fauna, conduits for sediment transport and soil drainage, and therefore affecting plant production and species distribution. Alternatively, clogged ditches could disrupt flows, isolate organisms transported by high tides, and impede drainage – also affecting vegetation.

The physical, or geomorphologic characteristics of channels affect their role in habitat provision. In a study of nekton distribution at an intertidal marsh in Georgia, Kneib (1994) found that fish were more abundant in high intertidal habitats of a high drainage density in comparison to a low density site, suggesting that the spatial arrangement of creeks may control the degree to which fish use available habitat for foraging.

On the Bay of Fundy addition of the anthropogenic network might increase channel density and marsh drainage. Lathrop et al. (2000) examined a New England marsh grid-ditched for mosquito control, and found channel density was more than twice that of a nearby reference site. Our cursory observations of recovering agricultural marshes on the coast of Fundy led us to assume that incorporation of ditches from the anthropogenic drainage grid also would cause these marshes to have a denser channel network. Additionally, in their consideration of historic dyke-breached sites in Britain, Crooks et al. (2002) had suggested that recovering marshes possessed higher channel densities than unmodified marshes. However, neither assumption had been supported by empirical data from British or Fundy marshes.

In this study we examined the nature of the channel networks at recovering Fundy marsh which underwent both dyking and ditching. A combination of aerial photograph interpretation and field surveying was used to compare channel networks at two recovering marshes with nearby reference sites. We used a geographical information system (GIS) to determine length, density and sinuosity of channel networks at two recovering marshes with nearby reference sites.

Study Area

Tidal range and suspended sediment supply vary greatly from the head to the mouth of the Bay so our study examined response of marshes in these two locations. We targeted two recovering dykelands: John Lusby Wildlife Sanctuary on the Cumberland Basin and Saints Rest Marsh near Saint John on the lower Bay. Each marsh was compared to a reference, or control marsh, never isolated from tidal flooding: Allen Creek/Wood Point on the upper Bay and Dipper Harbour on the lower Bay (Figure 1).

Our recovering marsh in the lower Bay is Saints Rest marsh in Saint John, New Brunswick with a tidal amplitude of 6.7 m (Canadian Hydrographic Service, 1995). The marsh was dyked and ditched for agriculture beginning in the mid-19th century. Other disturbances at the site have included construction of barns and roads, and use as a military training site prior to WWII, as well as adjacent gravel and forestry extraction (Noel et al., 2005). Historical photos and local accounts indicate that the dykes at this site failed due to lack of upkeep and breaching by storm waters starting in the mid-1950s, allowing for the return of tidal flow. Today, the marsh is characterized by low-marsh vegetation, predominantly *Spartina alterniflora* (Noel, 2006). The lower Bay reference site is Dipper Harbour (tidal amplitude 6 m), located 28 km southwest of Saint John. Dipper Harbour marsh is characterized by a low marsh of *Spartina alterniflora* and a high marsh dominated by *Spartina patens* (Chmura et al., 1997).

John Lusby Marsh, on the Nova Scotia coast of the upper Bay, has been recovering since dykes breached sometime between 1931 and 1945. Originally, it was part of Beaubassin, settled by Acadians in 1671 (Clark, 1968) and likely dyked by 1698 – thus under agricultural management for 100 years longer than Saints Rest. Historical photos show that Lusby Marsh supported many barns, roads, and even a government wharf. Today much of the marsh surface is vegetated by *Spartina patens* with *Puccinellia maritima*, while *Spartina alterniflora* dominates the vegetation of creek banks and low areas. Across the Cumberland Basin, on the New Brunswick shore, is Allen Creek (also referred to as Wood Point) Marsh, our reference site that has never been dyked or ditched. Vegetation at Allen Creek is similar to that of Lusby and the tidal range in this part of Cumberland Basin is as great as 12 m on spring tides.

Methods

We walked and field mapped a total of over 20 km of channels at Saints Rest, Dipper Harbour, and John Lusby during May 2005 when channels were most visible. The channel network at Wood Point was derived from a digital elevation model provided by Dr. D. van Proosdij (in press) at St. Mary's University. In the lower Bay our survey followed a roughly similar distance along the primary creek and we also made efforts to locate our target areas at approximately equivalent distances from the mouth of the primary creek. In the upper Bay target areas were bordered by approximately equal distances along the Cumberland Basin and equal distances back from the Bay. To maintain comparable sizes of study areas we mapped only two portions of John Lusby Marsh (the largest salt marsh on the Bay of Fundy today).

Functioning tidal channels were identified as any marsh hydrological feature with potential to carry both flood and ebb waters. The criteria used to identify these channels included depth and observed connections to other channels. Small rivulets in the marsh surface <1 m apart were excluded from the channel measurement. Rivulets which did not extend laterally away from the banks of larger channels were also excluded.

A Carrier Phase Trimble 4700 Differential Global Positioning System (DGPS; horizontal and vertical precision of ±3-5 cm) was used with a post-processing kinematic survey method to collect data points along all channels identified within the study area. This data was tied into the New Brunswick and Nova Scotia survey control network via local survey benchmarks (monuments NB #20091, 20704, and 20379, as well as NS#215056). Where possible, the channel thalweg was measured. Points were collected at regular intervals along linear segments, curves and meanders, as well as at junctions in order to capture sinuosity and channel bifurcation. Where channels were too large to reach the thalweg (deep mud presents hazards in creek channels), the channel edge was measured at the approximate transition between vegetation and mud flat.

Survey points were post-processed using Trimble GP Survey and Trimble Survey Office v. 1.52 (Trimble Corp., Sunnyvale, California). Survey benchmark coordinates were transformed to the International Terrestrial Reference Frame (ITRF 2000) to facilitate post-processing. Corrected survey points were then imported into a geographic information system (GIS), for further data processing. All geographic data was transformed to the Canadian Spatial Reference System, NAD 83 (CSRS98), and projected as UTM zone 19N in the lower Bay and UTM zone 20N in the upper Bay. Data points were connected manually as digitized polyline layers using ArcGIS v. 9.1 (ESRI, Redlands, California). Where feasible, an automated program in ArcView GIS v.3.3 (ESRI, Redlands, California) was used to form polylines from sequentially collected points which were then manually error-checked. For each of the polyline layer a database was developed with information from the survey points (e.g., elevation above MSL, channel drainage characteristics and thalweg connections) as well as measurement location. Where the channel thalweg was measured, polyline layers were directly constructed from survey points. georeferenced aerial photographs as guides to extrapolate the thalweg and represent channels as simplified, single polylines. Functionality and digitized connections of channels were checked through field reconnaissance of 30 randomly selected locations in each marsh to error-check network maps.

The cumulative length of the original channel network at Saints Rest was identified by interpretation of vertical aerial photographs taken in 1950 and 1958 (1:20,000; Department of Energy Mines & Minerals) before tidal flooding was returned to the channel network. Channels were identified based upon detectable differences in texture and shading, as well as connectivity with upland drainages or with other creeks in the tidal network. Ditches were distinguished from natural channels based upon their lack of sinuosity and connection to other ditches. Poor resolution of older aerial photographs available for Dipper Harbour prevented documentation of the historical channel network was not measured, but qualitative interpretation of historical photos suggest that little change has taken place in the network (1:20,000; Department of Energy, Mines &

Minerals, 1945). We suspect that, at John Lusby, the quality of the early aerial photography and, probably the more extensive agricultural history obscured the traces of the original creek system. For example, the 1945 (1:20,000, Department of Energy Mines & Minerals) shows long, straight channels which drain directly through the dyke system. As drainage networks were designed to take advantage of existing, natural channels by construction of aboiteaux, we presume these linear features are canalized creeks – thus it was impossible to accurately determine the extent of the original creek network.

We also interpreted present-day networks using aerial photographs from 1994 at Saints Rest (1:12,500; Natural Resources Canada), 1995 at John Lusby (1:10,000), 1994 photography at Dipper Harbour (1:12,500), and 2001 at Wood Point (1:12,500). The network identified from the georeferenced photos was then corrected to exclude channels identified as non-functioning during field surveys.

The length of channel networks and sinuosity were measured using ArcView GIS v. 3.3 (ESRI, Redlands, California). Channel density was calculated as cumulative length of all channels divided by the approximate marsh area mapped (Pestrong, 1965). Sinuosity was calculated for individual channel segments for the historical and contemporary periods. The sinuosity ratio is calculated as total sinuous length of a channel segment divided by total straight length (Pestrong, 1965). Channel sinuosity is shown at various levels using a classification scheme that reflects channel order with respect to source of tidal flooding. Sinuosity ratios were aggregated for channel segments branching off the primary creek at each higher level where a junction between two channels occurred.

All functioning channels were considered equivalent in the channel density measurement except for primary creeks. At Dipper Harbour, some channels were present which showed bank slumping and partial infilling (Figure 2). These partially filled channels are typical of a more mature marsh (Davis, 1978), and showed subterranean water-flow carrying surface drainage, but no connectivity with the channel network at the surface. Each of these was measured separately. The historical-contemporary comparison was restricted to channel lengths detectable in the aerial photographs, using field survey data to verify channel functionality.

We used buffer analysis to quantify the proximity of 3-m increments of marsh areas to channels. Polygons were constructed using survey points and aerial photographs for marsh surface area and area of large channels at both the recovering and reference sites. This necessitated a simplification of channel widths for buffering. All channels >2 m in width (based upon survey data) were given their actual width; channels <2 m in width, or where only channel thalweg was measured, were simplified to 0.5 m wide polygons to account for the wide range of channel widths in the network. Buffers were drawn from the two polygon layers representing all channels at 3 m intervals to a maximum of 45 m, ensuring comparability between the sites.

Results

There are distinct differences in the channel networks at the recovering and reference marshes, particularly in terms of channel density (Table 1, Figures 3 - 6). Based upon field mapping, channel density in the lower Bay marshes is comparable when the length and area of the primary creeks are included. However, when the length and area of the primary creeks are excluded, channel density at recovering Saints Rest is roughly twice that at the Dipper Harbour reference marsh. Inclusion of filled-in channels at Dipper Harbour increases channel density by 3%. However, ditches are also part of the contemporary channel network at Saints Rest and represent 13-14% of the channel network. Exclusion of ditches reduces the density of natural channels in the contemporary network at Saints Rest by 4%, a value likely within the error of the network derivation from aerial photographs. Regardless of whether ditches are included or excluded, channel density at Saints Rest is still much higher than at Dipper Harbour.

Channel density at the upper Bay reference site, Allen Creek, is comparable to Saints Rest and area 2 of the upper Bay recovering site, John Lusby, with or excluding primary creeks. Area 1 of John Lusby has the highest drainage density of all sites.

Comparison of the original and hybrid networks at Saints Rest was based upon aerial photo interpretation with field verification. There is <1% difference in the total length of the original network compared to the contemporary network (Table 1). The contemporary network visible in aerial photographs is ~4450 m shorter than that derived with field surveying, as only longer channels were visible. Abandoned portions of the original network are visible in the contemporary aerial photograph and field observations confirm that they only hold standing water (Figure 7). With the exclusion of smaller channels visible only through field survey, 20-26% of the total channel length (identified in the contemporary aerial photograph) is comprised of reactivated ditches (Figure 8).

Sinuosity of the contemporary channel network is slightly lower than the original network (Table 2). The sinuosity of the primary creek has increased by 5%, whereas the channel segments at 1st and 2nd level junctions from the primary creek have decreased by 12% and 9%, respectively. Although the loss of sinuosity from the original network is in large part due to the incorporation of reactivated ditches in the contemporary network we observed sinuous and dendritic side-channels developed along the banks of ditches incorporated in the modern network.

The recovering and reference marshes differ with respect to proximity of marsh areas to channels (Figure 9). Buffer analysis reveals that 37% of marsh surface area at Saints Rest is located within 3 m of a channel, while nearly 12% of the marsh surface is located at distances >45 m from a channel. At Dipper Harbour 15% of the marsh area is within 3 m of a channel, while only 4% of the marsh area is located at distances >45 m. Similar, to Dipper Harbour, both upper Bay marshes have 15% of the marsh area within 3 m of a channel, but ≥30% of the marsh area surveyed is located >45 m from the edge of the Bay or a channel.

Discussion

Channel Density

The contemporary channel network at the recovering marshes is a hybrid of the original creek network and the drainage ditch system. The contemporary network is morphologically consistent with the 'super-imposed' network type described by Allen (2000) wherein reticulate channels are inherited from previous agricultural drainage features into the modern regenerated channel network.

Observation of a higher channel density at the recovering marshes supports our original assumptions – in line with those of Crooks et al. (2002) about unintentionally restored marshes with agricultural ditches in Britain and observations by Lathrop et al. (2000) at a New England marsh grid-ditched for mosquito control. The geomorphology of the reference marshes has likely influenced the proximity analysis and channel density results. Dipper Harbour is geomorphologically distinct from Saints Rest as the marsh surface is relatively constricted by the steep slope of the adjacent upland. The shallow depth of Allen Creek Marsh means that upland drainages also influence the hydrology of the study area, while the areas of John Lusby likely affected by upland drainage were excluded from our survey.

Despite having a higher channel density than the reference site the channel density at Saints Rest is the same as, or has been only slightly reduced from the original network. Only a small portion of the previous ditch system identifiable in Figure 8 has been incorporated into the contemporary network as functioning channel, suggesting that the higher channel density at Saints Rest versus the reference site is not entirely attributable to ditching. Although not quantified in this study, field investigation indicated that a number of ditches and portions of natural channels have lost connection with the channel network and now hold standing water (Figure 7).

Our simple assessment of channel density, total channel length divided by marsh area surveyed, does not reveal the distribution of channels on the marsh surface, a characteristic that drives ecological functions of the marsh. Ecological function of the entire network is better assessed by our channel-proximity analysis. This analysis shows that a higher proportion of the marsh surface at Saints Rest is within 3 m of a channel than at any of the three other marshes (Figure 9). Marsh function may be enhanced at Saints Rest due to an increased concentration of ecological edge and greater access to the marsh surface for fauna and transfer of sediment carried with tidal waters.

Proximity to channel also affects the water table of the adjacent marsh. In a study of a New England salt marsh, Nuttle (1988) found that within 2.5 m of a creek bank, tidal flooding in creeks drove an oscillatory horizontal water flux between the creek and marsh sediment. At distances >15 m, no horizontal water movement to the creek was observed, meaning that there was little impact of creeks on sediment drainage at these greater distances. The channel-proximity results suggest an enhanced potential for exchange of water between the marsh sediment and tidal channels at the recovering Saints Rest marsh with respect to its reference site Dipper Harbour. Our calculation of higher channel densities masks the actual channel distribution at both upper Bay marshes where channel systems are highly clustered around a few major drainages so that >50% of marsh area is beyond the distance identified by Nuttle for effective gravity drainage of marsh soils. A parallel study in these same marshes indicates that macrotidal marshes are less sensitive to tidal flooding, so differences in channel proximity may not be as significant to marsh soil drainage in Fundy systems.

The results of buffer analysis in the lower Bay are comparable to those reported by Lathrop et al. (2000), for their analysis of a mosquito-ditched and reference site. Their study also indicated that ditching resulted in an enhanced proximity of marsh surface to channel. However, at both recovering sites there is a larger percentage of marsh surface located at distances >45m, as compared to the reference sites. Conversely, Lathrop et al. (2000) found a larger difference for marsh-channel proximity for their mosquito-ditched and reference marshes. For the mosquito-ditched site, 90% of the cumulative marsh surface was within 25 m of a tidal channel, whereas at the reference site, only ~55% of the cumulative marsh surface was accounted for at 25 m. The differences between the findings of this study and Lathrop et al. (2000) can likely be explained by the changes that have occurred to the hybrid channel network at Saints Rest over time with marsh recovery, as this has resulted in loss of considerable portions of the grid-ditch network.

Current techniques and technologies in the field of remote sensing offer many rapid and efficient methods of extracting tidal network characteristics using remotely-sensed imagery (e.g., Fagherazzi et al., 1999). However, many of these techniques involve expensive acquisition of remotely sensed imagery, such as laser altimetry (LiDAR) and problems of spatial resolution in this imagery may affect the level to which the entire channel networks at a site are extracted, particularly the smallest channels. Rinaldo et al., (1999) and Lawrence et al. (2004) suggested that the smallest channels extracted by advanced remote sensing methods must have cross-sectional areas ≥ 1 m^2. Lawrence et al. (2004) indicate that for full description of the channel networks in most marsh systems, at least some detailed field surveying used in conjunction with remote imagery is necessary.

Results from our study confirm the limitations of using only remote sensing techniques to derive channel networks. The channel network detected by field surveying at Saints Rest was approximately 4450 m longer than that derived solely from interpretation of aerial photographs. Thus, for adequate comparison of sites in Fundy, field surveying is important for capturing all of the channels within a network.

Channel Form and Sinuosity

If ditches incorporated into the hybrid channel network retain their steep banks and straight flow paths, then a hybrid channel network would be expected to have reduced ecological value as compared to its original network or its reference site. We also expected a loss of sinuosity in the hybrid channel networks compared to the original networks. Loss of channel sinuosity may reduce channel habitat diversity due to reduced occurrence of deep pools and areas of relatively low velocity flow (Hood, 2004). McIvor & Odum (1988) suggested that sinuosity impacts the relative risk of predation for fish in a tidal channel, and that meanders function to provide optimal subtidal habitat, as meander deposition bars are areas where small fish are able to forage on benthic organisms. Sanderson et al. (2000) also showed that plant species richness along sample transects in a California salt marsh was significantly greater for natural channels than constructed channels of the same order, which were identified by their less sinuous nature than natural channels. The sinuosity ratios computed for ditches in the contemporary network at Saints Rest show that they are much less sinuous than natural channels of the same order.

The geomorphologic profile of a channel is in part a function of its sinuosity and the, which in turn may affect habitat value (McIvor & Odum, 1988). McIvor and Odum (1988) found that channel-bank characteristics could be used to differentiate patterns of marsh surface use by fish, implying a predictable habitat value for constructed and natural channels. They found that densely vegetated marsh surfaces adjacent to gradually sloping, depositional creek banks had higher fish densities than those adjacent to steep, erosional banks with limited vegetative cover, possibly as a result of predator encounter rates and food availability being mediated by the bank characteristics. Similarly, multivariate analyses by Williams & Zedler (1999) showed that fish assemblages in a California marsh were associated with habitat characteristics that may differ between natural and constructed channels, such as ratio of width to depth, bank slope, temperature and salinity.

Although originally constructed with vertical banks along straight paths, we observed variable geomorphic profiles in the ditches now functioning in the hybrid networks. Some ditches have retained their original linear nature and vertical banks, as seen in figure 11, but others have developed curvilinear paths (Figure 12). Banks of some ditches have developed significant slopes and some display considerable heterogeneity due to collapse of anthropogenic features (rocks, timbers) along the channel. Interestingly, some original channels have highly incised vertical banks. It is likely that channels of the two recovering systems are still not in equilibrium with tidal currents and volumes. Future research aimed at modelling flow regimes and channel form would improve our understanding of these conditions.

Conclusions

After a 50 year recovery period, Saints Rest and portions of John Lusby have extensive hybrid tidal channel networks comprised of original creeks and ditches. These larger marshes may always have had channel networks more extensive than the reference sites to which they were compared. Saints Rest, where a historical analysis was possible, had greater extent of natural channels than the reference site. Analysis of the pre-breaching and contemporary network at Saints Rest suggests that only negligible changes in length and channel density have occurred, attributable to the balance of natural channel losses from the original network by incorporation of reactivated ditches. Comparison of John Lusby to its reference site indicates that its channel network is equivalent or more extensive and we assume that little channel length has been lost from this system.

The hybrid channel networks at the recovering marshes may have a reduced ecological value in terms of the extent of natural channels, but investigation of channel morphology and its equilibrium with flow regime is required. We have not mapped distribution of marsh pools, which seem to be more prevalent at the recovering marshes (and which M.Sc. student P. Noel began to study in the lower Bay). This may be a result of the larger size of recovering marshes, particularly the greater distance between primary creeks and the upland drainage. We hope to examine pond distribution in the upper Bay sites during the 2006 field season.

Through this study we have identified critical challenges the Bay of Fundy presents in finding appropriate reference sites. First, agricultural marshes are more extensive than any that were not targeted for reclamation – and distance is a critical feature in marsh drainage. Second, tidal range increases exponentially up the Bay, which means tidal prisms experienced by channels varies, reducing the value of the reference site approach.

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Table 1. Characteristics of channel networks in reference and recovering salt marshes on the New Brunswick coast of the Bay of Fundy. Field indicates that function of channel was confirmed by field observation.

	Saints Rest			Dipper Harbour	John Lusby		Allen Creek
	field	photo derived		field	field derived		field
	derived	1994	original	derived	area 2	area 1	derived
marsh area mapped (m^2)	318,161			70,745	259,700	127,539	169,549
length (m)							
network	9,312	4,915	4,866	1,992	4,829	4,423	3,803
primary creek	1,146	1,146	1,154	1,299			
ditches	1,176	979					
filled-in channel				184			
channel density ($m\ m^{-2}$)							
overall	0.029	0.015	0.015	0.028	0.024	0.053	0.022
excluding primary creek	0.030	0.012	0.012	0.014	0.023	0.056	0.022
excluding ditches	0.022	0.009					
excluding filled-in channel				0.013			

Table 2. Descriptive statistics for sinuosity ratios (m m^{-1}) for channel segments by level of junction from primary creek in the original and hybrid networks at Saints Rest marsh, New Brunswick.

	# junctions	n	mean	min	max	st. dev.
Historical network	0 (primary creek)	1	1.6			
	1	15	1.3	1.0	2.7	0.5
	2	22	1.2	1.0	1.9	0.2
Contemporary network	0 (primary creek)	1	1.7			
	1	26	1.2	1.0	1.7	0.2
	2	32	1.1	1.0	2.1	0.2

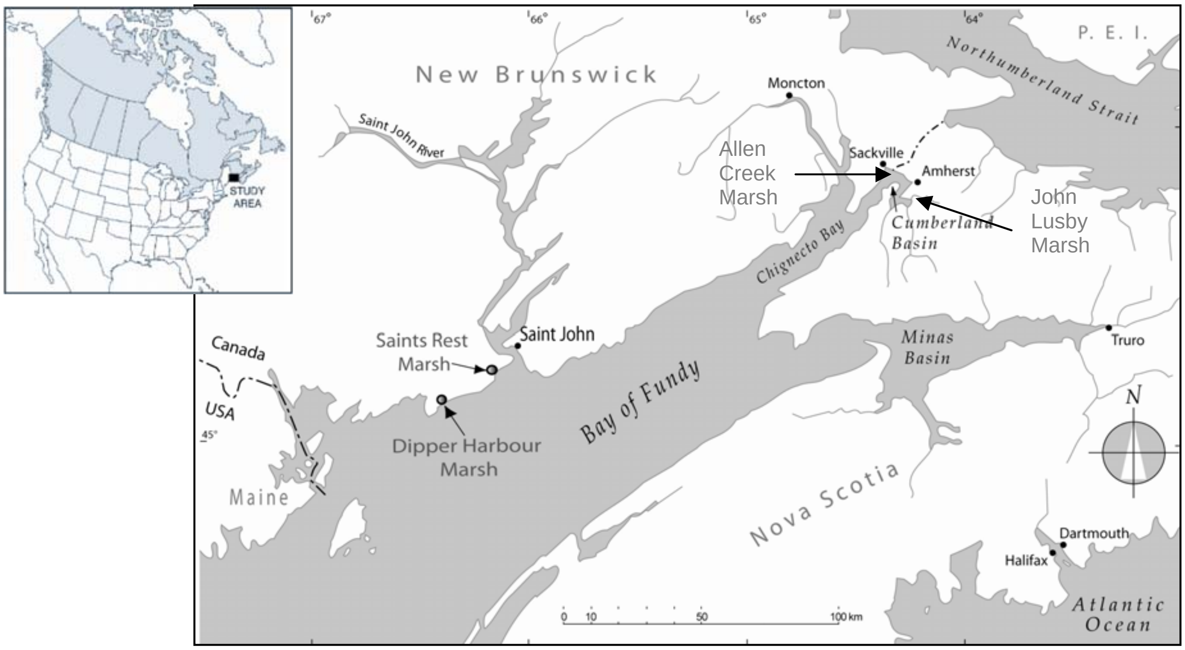

Figure 1: Map of Bay of Fundy region, showing study sites at Saints Rest and Dipper Harbour, Allen Creek, and John Lusby Marsh (Modified from Connor et al. (2001)).

Figure 2: Example of a filled-in channel at Dipper Harbour marsh, New Brunswick, showing subsurface water flow. Photo G. MacDonald.

Figure 3: Aerial photographs (1:5000) taken in 1994 showing tidal channel networks (blue) and boundaries of study sites (orange) at Dipper Harbour marsh (A) and Saints Rest marsh (B). Dark blue lines were derived from field surveying alone. Light blue lines were derived from aerial photographs and confirmed by field survey. Dashed orange lines overlaid on channels at Saints Rest demarcate reactivated ditches. (Photo sources: Dept. of Natural Resources, 1994)

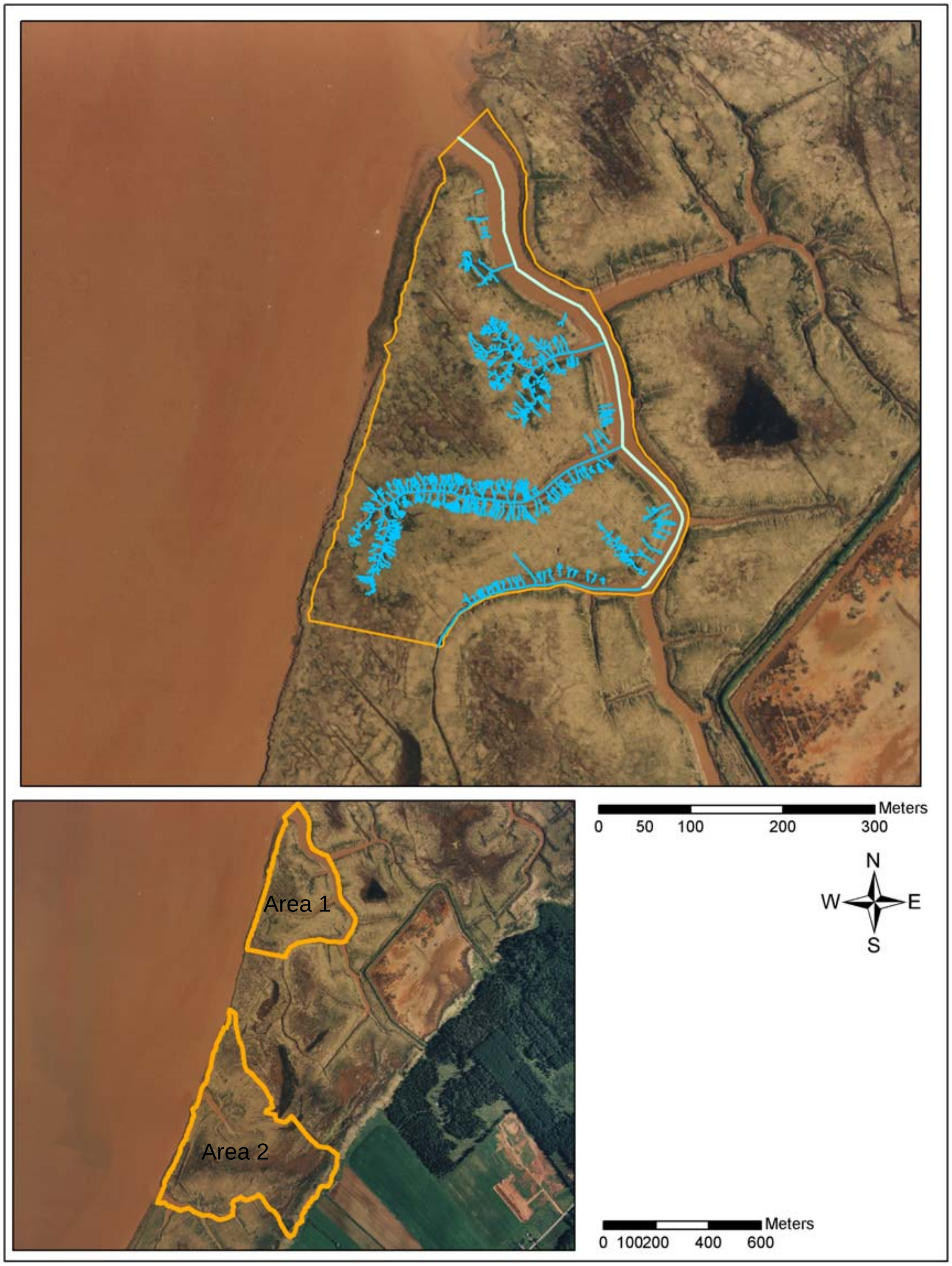

Figure 4: Aerial photograph (1:10,000) taken in 1995 showing field surveyed tidal channel network in blue and boundaries of study sites (orange) at study area 1 of John Lusby marsh. (Photo source: Dept. of Natural Resources, 1995)

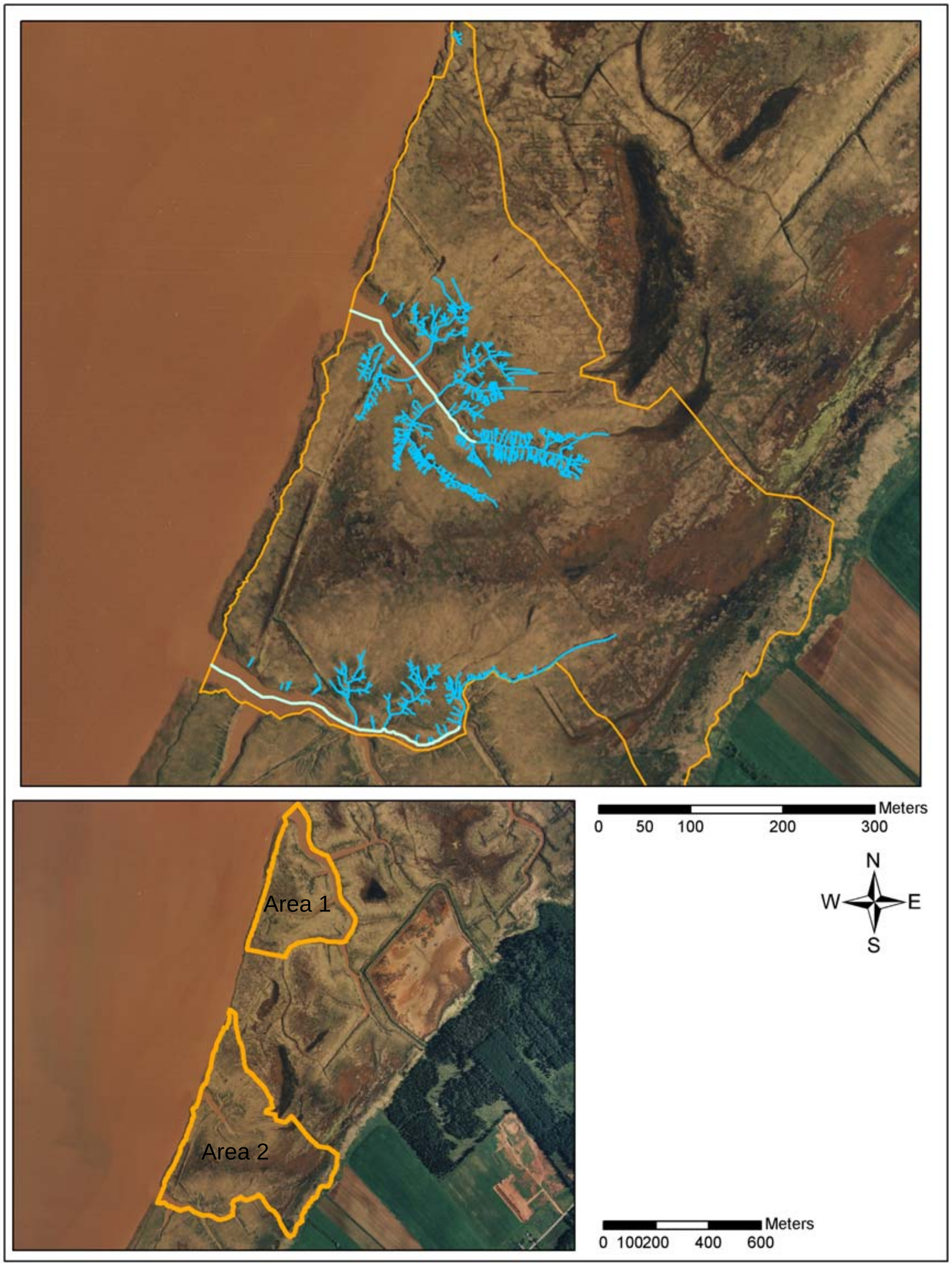

Figure 5: Aerial photograph (1:10,000) taken in 1995 showing field surveyed tidal channel network in blue and boundaries of study sites (orange) at study area 2 of John Lusby marsh. (Photo source: Dept. of Natural Resources, 1995)

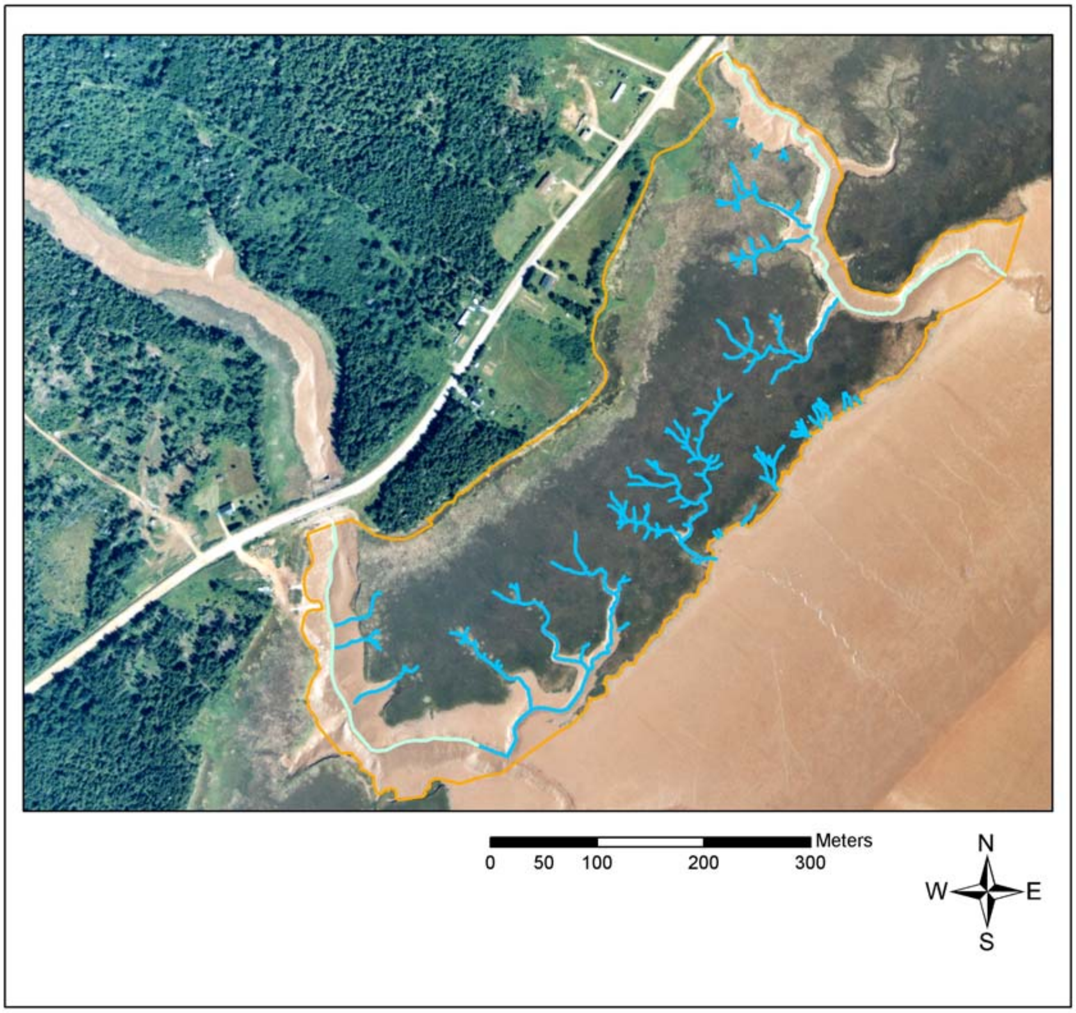

Figure 6: Aerial photograph (1:10,000) taken in 2001 showing field surveyed tidal channel network in blue and boundaries of study site (orange) at Allen Creek marsh. (Photo source: Dept. of Natural Resources, 2001)

Figure 7. Photo from Saints Rest marsh showing former agricultural ditch filled with standing water. (Source: C. Boylen, 2005).

Figure 8: Aerial photographs of Saints Rest marsh (1:5000), showing original pre-breaching tidal channel network interpreted from 1950 photos (A) and the hybrid network interpreted from 1994 photos. The primary creek is indicated by a light blue line and all other channels by dark blue lines. A dashed orange line is overlaid on channels identified as ditches in the contemporary network. (Photo sources: above Dept. of Energy, Mines and Resources; below Dept. of Natural Resources)

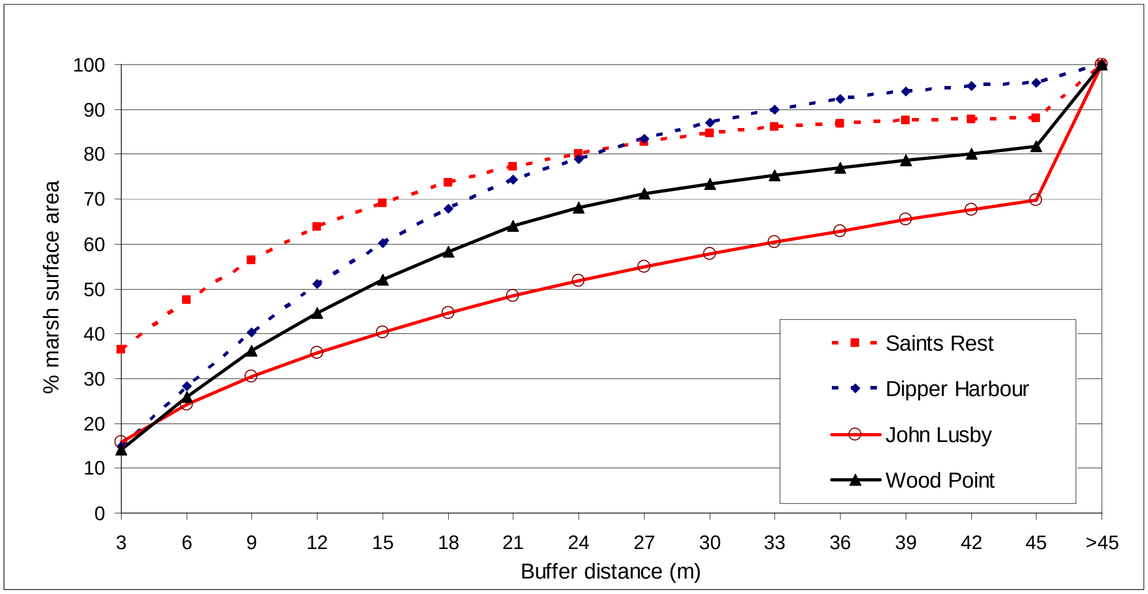

Figure 9: Results of proximity analysis, minimum distance of marsh area from channels, for reference (black) and recovering (red) marshes in the lower (dashed) and upper (solid) Bay of Fundy.

Figure 11: Photos from Saints Rest marsh showing channel characteristics of a reactivated ditch (left) and a natural channel (right) of the same order. (Source: P. Noel, 2005; C. Boylen, 2005).

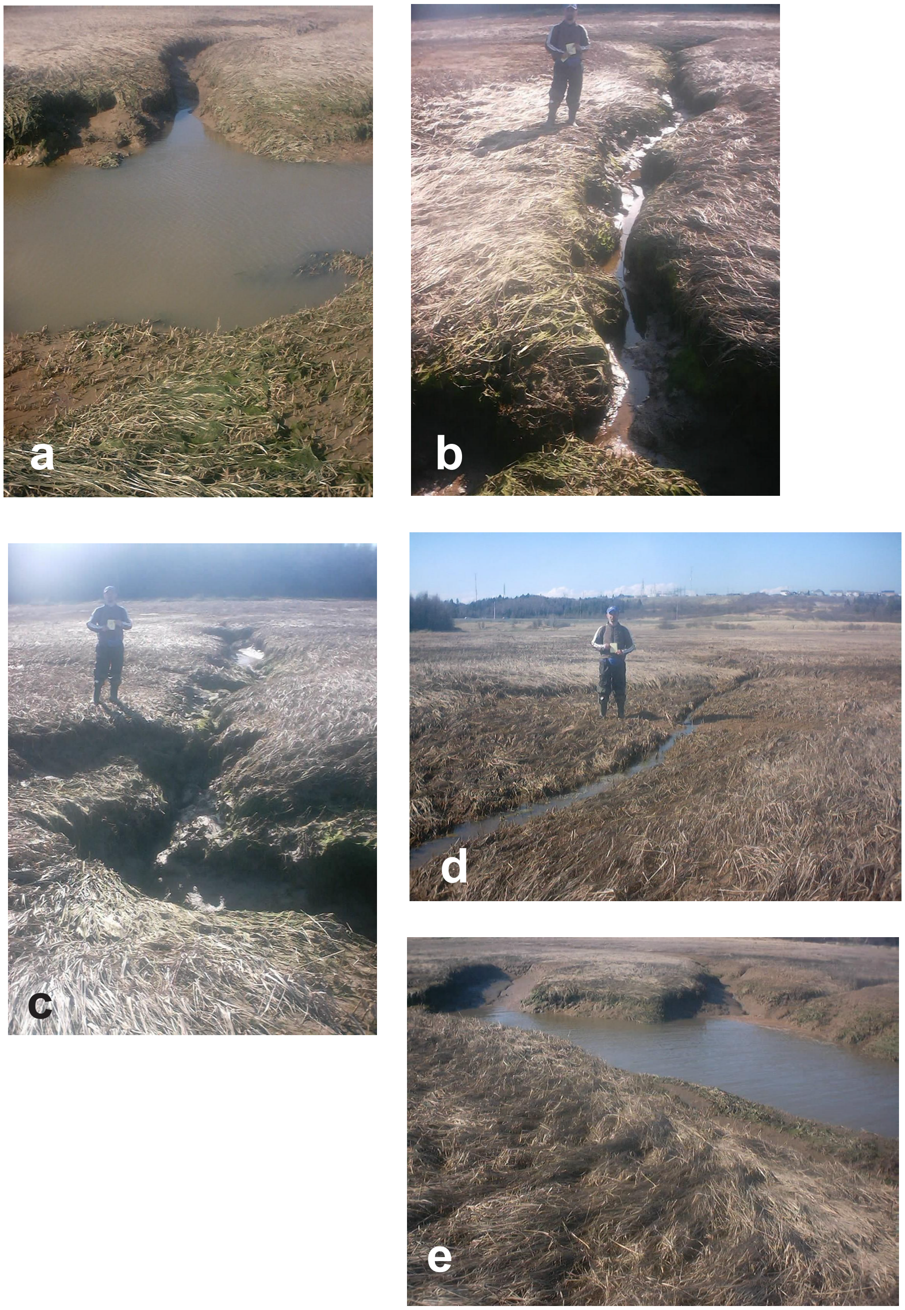

Figure 12. Photos of Saints Rest marsh showing variable channel morphologies: a. facing the mouth of an original creek with nearly vertical banks; b. a ditch developing a curvilinear path; c. a ditch with highly heterogeneous bottom due to collapse of anthropogenic artifacts (extending towards the background of photo); d. a ditch with vertical banks; and e. looking onto the mouth of two parallel ditches developing sloping banks.