Collection and Analysis of Information Required for Design of Remediation Measures for Shoreline Erosion Control at Fort Anne National Historic Park

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1. EXECUTIVE SUMMARY

This study, a cooperative effort between members of the Acadia Centre for Estuarine Research and the Atlantic Geoscience Centre of the Geological Survey of Canada, was carried out to better refine the prospects for appropriate design of remedial works to protect the currently eroding Fort Anne shoreline. Field studies were carried out to obtain additional information required for calibration and validation of a hydrodynamic-sedimentological simulation model previously developed by the Institute of Marine Dynamics of the National Research Council of Canada (NRCC). The field studies included deployments of Excalibur to determine the significance of intertidal sediment pore pressures in the erosion process, subtidal and intertidal current meters to better characterize the current and wave climate within the area surrounding Fort Anne, and Cyclops, a continuously recording turbidity sensor, to obtain information on the times and magnitudes of sediment erosion and deposition. In addition, a biological survey of the Fort Anne intertidal zone was conducted in order to better characterize its biological community.

Measurements of sediment pore pressures over a nine day period indicated that the intertidal sediments are sensitive to tidal loading effects and are in a state of continuous destabilization, particularly at the moment of exposure during each falling tide which makes them susceptible to wave induced erosion. It therefore appears that any long-term remedial action will require that an overburden sufficient to counteract the positive pore pressures be reinstated, together with measures to reduce wave action.

Current meter data obtained from the field studies indicated that, although the NRCC model underpredicts subtidal current velocities in an offshore area near Fort Anne, it gives reasonable predictions of current velocities within the area of the Fort Anne intertidal. The hydrodynamic output of the NRCC model was therefore used as input to SEDTRANS92, a sedimentological model that incorporates the erosional affect of wave action, to determine if the remediation scenarios previously examined with the NRCC model would be effective in reducing erosion within the Fort Anne intertidal zone. The results of model simulations of existing conditions indicated that current velocities within the Fort Anne intertidal are not of sufficient magnitude to cause the level of erosion currently existing, and that the primary cause of erosion is wave activity. Model simulations of a re-constructed Queen’s Wharf, a constructed Allain Creek jetty and an increased flow cross-section at the Allain Creek bridge indicate that these potential remediation options would have little effect on wave action and would therefore not result in a significant decrease in erosion of the intertidal zone.

Additional model simulations, carried out using TIDAL1, a simple one dimensional model that computes the balance of sedimentation for a time-series input derived from SEDTRANS92, were carried out to determine the time course of sediment deposition/erosion under various levels of ambient suspended sediment concentration. The model was driven with current velocity data obtained from deployments made within the Fort Anne intertidal zone. These simulations also indicated that erosion of the Fort Anne shoreline is due largely to waves as opposed to currents. Simulations of erosion/deposition indicated that, under conditions of no wave activity and an ambient suspended sediment concentration of 30 mg/L, an annual rate of deposition of 5 and 30 cm/yr would occur on the upper and lower tidal flat respectively.

A biological survey of the Fort Anne intertidal revealed a relatively sparse biological community with little evidence of any unique characteristics. It is therefore unlikely that remediation activities impacting the intertidal zone would have serious consequences for the existing biological community.

A literature survey relevant to re-establishment of a *Spartina alternaflora* marsh within the Fort Anne intertidal zone suggests that this would be possible, but only if the intertidal zone were protected from severe wave action and a neutral or depositional environment was established.

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2. Introduction

During the period 1992-95 the Acadia Centre for Estuarine Research (ACER), in conjunction with the Atlantic Geoscience Centre (AGC) of the Geological Survey of Canada (Atlantic), the Institute of Marine Dynamics of the National Research Council of Canada (NRCC) and the Nova Scotia College of Geographical Sciences (COGS), carried out studies to assess the prospects for and appropriate design of remedial works to protect the embankments at Fort Anne National Historic Site from continuing erosion. The results of these studies (summarized by Daborn et al. 1995) were used to design a temporary stabilization structure and to initiate discussions of more long-term engineering solutions to the erosion problem.

The measures already taken to stabilize the ground beneath the southwest ravelin are of a temporary nature and cannot be relied upon as a long term solution to the problem of slope instability. At best, the improvement in static factor of safety against sliding is marginally sufficient to prevent further movements. The major improvement is of an indirect nature through the protection provided against wave undercutting of the slope.

As a result of discussions between Parks Canada, Public Works Canada and others, a number of potential long-term solutions have been identified. There was, however, a need identified for additional information and analyses prior to implementation of any of these proposed solutions. In particular, the evaluation of the effectiveness of a number of proposed remediation measures required refinement of the hydrological-sedimentological model previously developed by the NRCC. The model needed to be better validated against existing and new hydrodynamic and sedimentological data sets, and upgraded to incorporate the effect of wave activity on erosion rates.

There was also a need to more thoroughly evaluate the potential for remediation by natural processes such as restoration of the original salt marsh, to obtain information necessary for maintenance and augmentation of the temporary remedial works already carried out, and to better characterize the intertidal biological community in terms of its composition and contribution to sediment stabilization/destabilization processes.

2.1 Acknowledgments

Angus Robertson of AGC and Jamie Gibson of ACER assisted in the collection and analysis of suspended sediment and biological data. Dr. Terry Sutherland of AGC and Shelly Patterson of ACER assisted in various aspects of the field program. Assistance in recording water levels in the monitoring wells was provided by Sidney Burrell of the Fort Anne staff. We also acknowledge the support of Lillian Stewart, Park Superintendent, and the Project Manager, Warren Peck of Public Works Canada.

3. Objectives

The general objectives of this study were to provide information necessary for:

(1) reassessment of potential engineered remediation structures for stabilization of the upper and lower shoreline immediately below Fort Anne National Historic Site,

(2) determination, if possible, of the long-term impact of potentially suitable engineered stabilizing structures on areas upstream and downstream to the Fort Anne shoreline, and

(3) evaluation of the potential for natural protection of the shoreline through re-establishment of salt marsh vegetation.

Specific objectives of the proposed project were to:

(1) determine the extent of, and evaluate the impact of, any excess pore pressures on slope stability through monitoring of in situ groundwater levels in the previously established groundwater wells, particularly during the spring when groundwater levels tend to be highest,

(2) establish a monitoring program to evaluate the success of 1994 emergency stabilization measures along the southwest ravelin,

(3) obtain additional data on the extent of excess pore pressures within the sediments of the intertidal zone to determine the degree to which this may influence the erodibility of the sediments

(4) provide baseline data on sediment erosion and supply within the intertidal and subtidal area in the immediate vicinity of Fort Anne,

(5) further develop the hydrological-sedimentation model previously developed by the National Research Council in order to refine predictions of the effectiveness and impact of remedial actions,

(6) carry out a literature review of procedures for stabilization of shorelines based on the re-establishment of salt marsh vegetation, and

(7) continue monitoring of the biological characteristics of the intertidal zone in order to further determine the presence or absence of biological stabilization processes and the nature of the biological community present on the Fort Anne intertidal shoreline.

4. Geothechnical Monitoring and Analyses

4.1 Slope Stability

4.1.1 Monitoring of Water Levels in Monitoring Wells

In order to determine the extent of excess pore pressures on slope stability resulting from elevated groundwater levels during the spring, when groundwater levels tend to be highest, water level data from monitoring wells previously installed on the southwest ravelin were collected by Fort Anne staff and provided for analysis. The results indicated that there did not appear to be any increase in the height of the groundwater table, compared to when the wells were installed. Therefore the original assumption made in the slope stability analyses appear to be valid. Based on this finding, additional stability computations were not required and effort instead was placed on field monitoring of tidal variations and pore pressures within the intertidal zone.

4.1.2 Installation of Survey Pins

To provide a reference for monitoring slope stability, three survey pins have been set in concrete embedded within the rockfill placed along the upper shoreline of the southwest ravelin during 1994. The location of these pins was surveyed in by Baird & Associates Ltd. during February 1997. Future surveys to determine the extent of movement of the pins should be carried out on a routine basis at least once per year.

4.2 Field Monitoring of Intertidal Pore Pressures

4.2.1 Introduction

The impact of wave and tidal loading on bed stability is partly time-dependent and partly material-dependent. While estimates of pore pressure response can be made based on existing knowledge of geotechnical behavior, it is advantageous to make physical measurements under actual loading conditions, which may be of a transient nature. For example, the influence of confined groundwater seepage depends on the existence of permeable layers, as well as on the amount of pressure head existing in the backslope, which in turn depends on factors such as frequency, duration and amount of precipitation over time. Also, unusual conditions, such as the presence of gas in the sediment, can lead to erroneous assumptions about pore pressure response. It is therefore important to determine, through field studies, the degree to which cyclic loading by tides and waves contributes to a softening of the upper levels of the exposed red clay deposit.

In order to obtain this information, Excalibur, a specialized pore pressure monitoring instrument was deployed above the low water line on the intertidal mudflat to record both the tidal amplitude and the internal pore pressure response, as a function of time. As memory capacity was limited at the time of deployment, Excalibur was configured for slow data acquisition over an extended time period in order to monitor tidal effects rather than waves. The probability of having significant wave events was considered too low to justify individual deployments to cover single tidal inundations.

4.2.2 Methodology

Excalibur has been described by Christian (1993) and Amos et al. (1994). It consists of an electronics and sensor package, connected to a push-in pore pressure (piezometer) probe. The system has the capability of storing data for a period of 10 days, at a data sampling rate of 1 reading on all channels, every 2 minutes. Faster data rates are possible, although memory life is correspondingly shortened. To extend the duration of the experiment, an external battery pack was connected to the electronics package to drive the onboard Tattletale 8 computer and to power onboard pressure transducers.

A Data Instruments HP100 psig (range of 100 lbs./in^2 relative to atmospheric) was fixed at the elevation of the mudflat (External sensor) and a Data Instruments AB100 psi gauge was mounted at an elevation 0.2 m above the mudflat (Case sensor), as shown in Figure 4.1. These sensors were referenced to atmospheric pressure, which varied throughout the study period by as much as 0.5 m. A third pressure measurement was made, at a depth of 0.4 m below the surface of the mudflat, using another AB100 psig transducer, also referenced to the atmospheric datum (Subseabed sensor). This sensor was located inside the electronics housing of Excalibur, and was hydraulically-connected to a water-filled 16 mm diameter probe, pushed into the clay substrate by hand. A filter stone located 10 diameters behind the probe tip provided an inlet for fluid pressure. All hydraulic lines were filled with distilled water prior to instrument deployment. The Data Instruments pressure transducers were capable of resolving pressure variations of +/- 1.7 cm (AB Model) and +/- 0.9 cm (HP Models).

A high-resolution differential pressure (Validyne P300D) transducer was mounted inside the electronics housing, to monitor pressure differences between the probe tip and the water column (atmospheric datum). This sensor was capable of resolving changes in pressure of +/- 1.2 cm.

Data were downloaded to a portable computer immediately following recovery of the instrument, was processed and displayed in ScanVu software. Digital data were decimated by a factor of 10 and output as ascii files for preparation of graphs and to streamline interpretation of results.

4.2.3 Results

A complete record of tidal elevation above the mudflat, for the period 19 October 1996 (Julian Day 294) to 27 October 1996 (Day 302), based on output from the two water column pressure transducers, is shown in Figure 4.2. Pressure datum shifts are evident as baseline variations during each low tide period, when the instrument was fully exposed on the mudflat. These low-end daily variations correlate to changes in barometric pressure.

Fig. 4.1

Fig 4.2

The data indicated a consistent time delay in subsurface pore pressure response of about 1 hr, compared to the tidal curve. The amplitude of the subsurface pressure response was equivalent to the tidal amplitude throughout the measurement period. At low tide, water column transducer ports were exposed to atmospheric pressure and so did not continue to track tidal variation. Comparison of Excalibur tide data to nearby subtidal S4 current meter data showed that the pressure inlet on the S4 was 1 m lower in elevation on day 295 at 1100 hrs. This reference point provided a useful means of fine-tuning Excalibur transducer pressure calibrations, to remove uncompensated temperature bias.

The subsurface data also indicate a small residual pore pressure during each low tide period, of about 0.6 m in head. Since the probe tip allowed pressure entry at a depth of 0.4 m below the bed, the unbalanced pore pressure at the surface of the mudflat was therefore 0.2 m. Prior to instrument deployment, groundwater was observed to be seeping from the entire intertidal zone in this area, as well as on the grassy slope just below the Fort Anne office. Some possible effects of confined artesian flow are discussed below. Figures 4.3 through 4.10 show Excalibur pressure data, for each day during the study period.

Differential pressures are also shown in Figure 4.2. Measured differential pore pressures are shown in comparison to values obtained by subtracting the water column (External sensor) readings from the internal (Subsurface sensor) readings. The data indicate that the maximum residual pore pressure approached 2 m, coincident with the moment of exposure of the mudflat during a falling tide. This is due to the 1 hr time delay in pore pressure response and explainable as a time-dependent drainage effect, in response to rapid tidal drawdown.

4.2.4 Conclusions

There appear to be two major effects evident in Excalibur data from the lower intertidal deployment at Fort Anne. A 1 hr time lag existed at all stages of the tide, attributed to impeded dissipation of pore pressures set up during high tide within the subsurface fine-grained sediments, which can be characterized as being of low permeability, based on previous studies of engineering properties (Daborn et al., 1993; Daborn et al., 1995). A secondary effect was manifested as a small residual or unbalanced pore pressure after each exposure of the mudflat, equivalent to 0.2 m in head. This is attributed to the development of onshore - offshore groundwater flux on the falling tide, through subsurface drainage of perched waters held within the Fort embankments.

It is concluded that the sediments comprising the intertidal mudflat are sensitive to tidal effects and are in a state of continuous destabilization, maximizing at the moment of exposure during each falling tide. Falling tides are known to present a particular hazard for steep shorelines cut in fine-grained deposits, through retarded drainage of high pore pressures set up during each high tide. This is most readily visible as excessive cliffline erosion, where repeated wetting during high water is allowed to occur. The process continues on flat slopes across the intertidal zone, as the instability stems from a reduction in cohesive forces (softening) between sediment particles, through absorption of water.

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The intertidal zone at Fort Anne is susceptible to erosion since there appears to be a thick sequence of firm, consolidated clay exposed to wave and tidal action, which readily absorbs seawater and softens. The primary resistance to erosion is the sediment cohesion, developed through a previous history of burial loading and consolidation. Erosion reverses the consolidation process and the sediment deposit swells a small amount, as water is reabsorbed. Also, replacement of fresh pore water held within these clays with saline estuary water would lead to particle flocculation and hindered settling, once resuspended in the water column.

At a time when the salt marsh capped the intertidal zone, pore pressure effects would have had a negligible effect on stability, as internal residual pressure variations would have been dissipated within the overlying organic mat, which had a high intrinsic strength as a result of its interwoven nature. Therefore, it is recommended that any long term increase in lower intertidal mudflat stability will only arise if some thickness of eroded overburden material can be reinstated, in combination with measures to reduce wave action. Preventing wetting of fresh, intact consolidated sediment is the key to mitigating the erosion of this susceptible clay deposit.

5. SEDTRANS92 Modeling Study

5.1 Introduction

The NRCC numerical simulation of sedimentation off Fort Anne (Willis et al. 1995) appeared to be questionable due to two major uncertainties: (1) the discrepancy between the observed and predicted current velocities off Fort Anne (the model underpredicts by 50%); and (2) the lack of a rigorous representation of the effect of wave action on erosion, which was believed to be at least partly responsible for erosion of the foreshore. These uncertainties were addressed by collection of additional current and suspended sediment concentration (SSC) data and refinement of the NRCC model to incorporate the effect of wave/current interactions within the benthic boundary layer on sediment transport. The latter was accomplished by using the hydrodynamic output from the NRCC model as input to SEDTRANS92 to predict bed shear stresses and subsequent erosion/deposition.

5.2 Field Measurements for Model Calibration

5.2.1 Subtidal Current Velocities

Subtidal current velocities were measured continuously for a 31 day period between 16 May - 12 June 1996 at a subtidal station located just north of the Fort Anne foreshore (the same location as used for meter 8207 of the 1994 study) to see if the cause of the underprediction in the NRCC model was due to the model itself or due to the current meter (perhaps through inaccurate calibration).

The results indicated that the peak currents recorded by meter 8207 and collected during June, 1994 were correct. We found that these currents peaked between 40 and 50 cm/s and the mean currents were between 20 and 25 cm/s (Figure 5.1). We conclude from this time-series that the discrepancy between the observed currents and those predicted by the NRCC model is not due to errors in the original current meter measurements, but should be attributed to the numerical model. Conditions during the period of the deployment were relatively calm, so the effect of wind forcing on the peak currents cannot be considered as a reasonable explanation for the differences between the model output and our observations.

5.2.2 Intertidal Current Velocities

Four deployments of an S4 current meter were carried out at an intertidal site located approximately 1 m above lowest low water (in a region of deposition of brown mud) and about 50 m downstream of the tip of Queen’s Wharf. The meter was set at a height of 0.30 m above the bed and programmed to burst sample X and Y components of flow and water depth at 2 Hz for 60 seconds each 90 minutes.

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The four deployments covered the periods May, May - June, June and October - November, 1996. The duration of the four deployments were: May (90 hours); May - June (322 hours); June (213 hours); and October - November (544 hours). Peak tidal currents were about 20 cm/s but averaged only about 5 cm/s. Time-series of all data collected are shown in Figures 5.2 to 5.5.

5.2.3 Intertidal Suspended Sediment Concentrations

Ambient SSC measurements were carried out within the intertidal zone at the same location and during the same time periods as the S4 current measurements. Measurements were made using Cyclops, a specially constructed instrument consisting of an Optical Backscatter Sensor (OBS) and data logger fitted to a tripod. Cyclops was programmed to log data continuously at 20 second intervals. A sediment trap was attached to the frame to collect sediment with which to calibrate the OBS. In general, the response of the sensor was linear and a good calibration of SSC to OBS voltage was obtained (Figure 5.6).

The time-series plots of turbidity show that the spring/summer resuspension differs greatly from the fall conditions. In the spring, the wave energy is low and the resuspension is limited to brief times around the tidal exposure. Background concentrations of suspended sediment are below 10 mg/L. During the fall, background concentrations modulate with the spring/neap cycle from 10 to 30 mg/l. Wave resuspension is more common but is still restricted to the period about tidal exposure. During these periods, SSC concentrations are in excess of 400 mg/L.

5.2.4 Intertidal Profile off Fort Anne

A profile across the intertidal mudflats off Fort Anne was surveyed on 21 January, 1997. The profile was not surveyed into geodetic datum so the exact position of the profile relative to chart datum is unknown. However, several levels are defined: the level of the S4/Cyclops instruments; and the transition from net erosion to deposition (Figure 5.7). The lowermost part of the profile is dominated by soft gray clay that has been recently deposited. (We know this because footprints left during instrument deployment were systematically infilled with time.) The remainder of the profile (approximately 2 m above the level of the S4) is erosional and composed of compacted red clay overlain by a thin veneer of shelly gravel. The region between erosion and deposition is separated by a rocky zone inhabited by abundant molluscs (mainly *Littorina* sp.).

The mudflat is separated from the salt marsh by a 0.5 m high scarp. Above the scarp, marsh plants dominate and the profile is flat; below this scarp the profile is steep, planar and heterolithic.

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5.3 Prediction of Sedimentation/Erosion Using SEDTRANS92

5.3.1 Introduction

5.3.2 Overview of SEDTRANS92

SEDTRANS92 (Li and Amos 1993) is a one-dimensional model that estimates sediment transport rates for a given set of oceanographic conditions and sediment characteristics. The model evaluates the combined seabed shear stress due to the ambient current and surface waves, and then predicts the magnitude and direction of the sediment transport by integrating the effect of the seabed stress over time. SEDTRANS92 requires specification of the following inputs: water depth, ambient current speed and direction, surface wave height, wave period, wave direction and bed roughness sediment characteristics. For the prediction of the transport of cohesive sediments, the critical shear stresses for erosion and deposition, the settling velocity, and the initial erosion rate must also be known.

5.3.3 Application of SEDTRANS92 to Fort Anne

SEDTRANS92 has been previously applied in a 2-dimensional, finite difference, time-dependent model of sand transport on Sable Island Bank (Anderson, 1995). In that model, the net sand deposition or erosion at each model grid point was estimated by computing the horizontal divergence of the sediment transport throughout the model domain. This required that the spatial variation of the time-independent parameters (bathymetry, sediment grain size), and the time-dependent fields (tidal currents, surface waves) be known at every point in the model domain at each time step. On Sable Island Bank, high-resolution bathymetric surveys and sediment sampling (Amos and Nadeau, 1988) provided the time-independent fields. A previous numerical modelling program had mapped the variation of the tidal currents over the bank (deMargerie and Lank, 1986), and a fine-mesh wave model (Gunther, 1992) was used to hindcast the surface wave field over the bank for a well-documented severe winter storm (Cardone, *et al*, 1994).

At Fort Anne, the magnitudes and spatial variation of these parameters are far less well-known. It is known that the sediment properties (critical shear stresses, settling velocities, initial erosion rates) vary over the area of interest, but the spatial distribution of sediment parameters has not been mapped. Very little is known about the wave field in the vicinity of Fort Anne, particularly its time dependence during storms, when the most severe erosion would occur. Sources and sinks of sediment material have not been quantified. Finally, the available NRCC hydrodynamic input made available to us was limited to one tidal cycle (12.4 hrs) for each of four scenarios examined by NRCC. As a result, although the Fort Anne SEDTRANS92 model could perform two-dimensional sediment transport simulations given the required input fields, a somewhat different approach had to be taken at Fort Anne than on Sable Island Bank.

The limited spatial information on the sediment character and the wave field at Fort Anne precluded any attempt to forecast the sediment transport and its divergence. Instead, the objective was to map the areas of erosion and deposition over a tidal cycle, using the NRCC current and water level predictions, and various uniform imposed wave fields approaching the Fort Anne shoreline from the most likely direction. The effects on the erosion/deposition patterns caused by several modifications to shoreline configuration and bottom topography were also examined.

5.3.1.1 Model Domain

The Fort Anne SEDTRANS92 model domain is an 800 m × 1000 m rectangle shown in the location map in Figure 5.8. The model covers 950 m of shoreline of the Annapolis River extending from a point 250 m north of Queen's Wharf southward past the Fort Anne embankments, then 350 m into the mouth of Allain Creek. On the offshore side, the model includes the channel of the Annapolis River. The salt marshes extend from Queen's Wharf to the road bridge crossing Allain Creek.

5.3.3.2 Model Co-ordinate System

The Fort Anne SEDTRANS92 model uses the NRCC co-ordinate system, a right-handed Cartesian system, dimensioned in meters, x increasing to the east, and y, to the north. The origin ($x = 0$, $y = 0$) is at longitude $65^{o}46'00''$W, and latitude $44^{o}38'00''$N. All Fort Anne SEDTRANS92 model outputs are mapped in this co-ordinate system. Co-ordinates in the model domain are in the ranges 19,000 m $\leq x \leq$ 19,800 m, and 11,400 m $\leq y \leq$ 12,400 m (Figure 5.8).

5.3.3.3 Model Grid

The NRCC finite element mesh was adopted in this study to avoid re-gridding the NRCC bathymetry, currents, and water level data. The full NRCC mesh consists of 2567 nodes, the node spacing generally decreasing from a maximum of approximately 600 m in the Annapolis Basin just inside Digby Gut, to 25 m in the Annapolis River adjacent to Fort Anne, and less than 10 m in the confines of Allain Creek. The Fort Anne SEDTRANS92 domain includes 524 of the NRCC nodes.

5.3.3.4 Wave Calculations

SEDTRANS92 first uses linear wave theory to calculate (1) the wavelength, and (2) the amplitudes of the oscillatory bottom current and bottom particle displacement of the applied surface wave. The specified wave height is then compared to the breaking height for the calculated wavelength and given depth. If the height exceeds the breaking height, the bottom stress and sediment transport cannot be calculated accurately by any known method. Consequently, SEDTRANS92 normally provides no output under breaking wave conditions. In Fort Anne SEDTRANS92, however, in order to obtain as much information as possible about the erosion/deposition environment, the wave height is automatically limited to the breaking height at all nodes where the linear theory predicts breaking to occur. This procedure is reasonable, since in reality, breaking continually reduces the wave height as wave energy is converted into turbulence.

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5.3.3.5 Bed Shear Stress

SEDTRANS92 uses the most recent theory of Grant and Masden (1979, 1982, 1986) to estimate the bed shear stress in the combined wave-current bottom boundary layer. This calculation uses the wave-induced bottom velocity and particle displacement estimated from linear wave theory, as described above.

5.3.3.6 Prediction of Sediment Erosion and Deposition

When dealing with cohesive sediments, as in the case of Fort Anne, SEDTRANS92 uses the method of Amos and Greenberg (1980, 1992) to predict the rate of sediment erosion or deposition, and the change in suspended sediment concentration over a specified time interval. Recent improvements enable SEDTRANS92 to account for the variation in the erosion rate for cohesive sediments due to the variation in erosion critical shear stress with depth below the top of the sediment bed. To fully utilize the Amos and Greenberg method, appropriate field measurements must be made at the site in question. Measurements must include the critical shear stresses for sediment deposition and erosion, the particle settling velocity, sediment density, initial erosion rate, and the variation in critical shear stress with depth in the sediment bed. These parameters have been estimated for the Fort Anne site, for the gray clay at the intertidal S4 current meter site (Daborn, et al. 1995). At each time step, SEDTRANS92 compares the calculated combined wave-current bed shear stress t_{csw} for that time step to the critical shear stresses for deposition, t_{cd}, and erosion, t_{ce}. Three cases are possible:

> (1) Deposition ($t_{csw} \leq t_{cd}$): The estimated bed shear stress is less than the critical stress for deposition, and suspended material is deposited at a rate determined by the bed shear stress and the settling velocity. Suspended sediment concentration decreases during the time step, and may fall to zero if all the suspended material in the water column has time to settle to the bottom,
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> (2) Steady state ($t_{cd} < t_{csw} < t_{ce}$): The bed shear stress is sufficient to prevent deposition, but not sufficient to cause erosion. SSC remains constant during the time step,
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> (3) Erosion ($t_{ce} \leq t_{csw}$): Bed shear stress exceeds that required for erosion. Bottom sediment is eroded and goes into suspension, increasing SSC. The erosion rate for a given bed shear stress varies with erosion depth.

The change in SSC over one model time step (30 minutes) is estimated by numerically integrating the magnitude of either the deposition or erosion occurring during that time step. The change is added to the initial SSC to obtain the SSC at the end of the time step. The rate at which sediment is transported by the ambient current is computed as the product of the current magnitude, water depth, and SSC. The direction of transport is the direction of the current.

5.4 Model Inputs

NRCC used TELEMAC-2D, a two-dimensional hydrodynamic model, in their study of erosion at Fort Anne. The bathymetry and hydrodynamic outputs for portions of several runs of the NRCC Annapolis Basin model were made available to us for use with Fort Anne SEDTRANS and are described in this section.

5.4.1 NRCC Model Output

The NRCC hydrodynamic model predicted the depth-averaged current and water surface elevation as functions of time, in the Annapolis Basin from the Bay of Fundy to the causeway in the Annapolis River at Annapolis Royal. The model divided the Basin and River into triangular finite elements extending from the water surface to the bottom, and was forced by the tidal fluctuation in sea level in the Bay of Fundy outside Digby Gut. Every half hour, the surface elevation and current was calculated at 2567 nodes located at the corners of the finite elements.

5.4.2 Bathymetry

The NRCC bathymetric data were digitized by NRCC from Canadian Hydrographic Service (CHS) Chart 4396, Annapolis Basin (July 1993 ed.), aerial photographs, and site surveys. The datum (zero elevation) is chart datum, or lowest normal tide. The NRCC bathymetric data consisted of the x- and y coordinates and bottom elevation for each model node. Figure 5.9 is a contour plot of the NRCC bathymetry for the June 1994 existing conditions, with bottom contours drawn every two meters. The locations of all nodes within the model domain are shown as unlabelled dots, and the locations of three nodes (2565, 1429, and 416), for which time series will be presented, are labeled. The 1996 intertidal S4/Cyclops site is also indicated. The symbol indicating the location of Queen's Wharf extends approximately to the offshore end of the ruined portion of the wharf. The bottom contours around Fort Anne are generally aligned parallel to the shoreline, with the exception of the prominent knoll (elev. 2 m above datum) separating the channels of Allain Creek and the Annapolis River.

5.4.3 Shoreline Modifications

To investigate the effects of shoreline alteration, NRCC used the model to examine several different cases of bottom topography. Each of these cases is described in the following section.

5.4.3.1 Queen's Wharf (case 'queent')

This case involves raising the elevation of the existing ruined western end of Queen's Wharf. Beginning at 60 m (200 ft) from the shore, where the top of the ruined wharf is 2 m (6.5 ft) below the elevation at the shore, the top of the wharf is raised by up to 1.5 m (5 ft) for the next 70 m (230 ft), to a point 130 m (430 ft) from shore. Figure 5.10 is a general bathymetric chart for the

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‘queent’ case. Figures 5.11 and 5.12 compare the bottom contours around Queen’s Wharf as they exist at present (Fig. 5.11) and as they would appear if Queen’s Wharf were reconstructed (Fig. 5.12). The reconstructed Queen’s Wharf would extend above the water surface, and therefore form a solid barrier to longshore flow, over its full length of 130 m (430 ft), for approximately 5 hours over the low-water half of the 12.4-hour tidal cycle.

5.4.4.2 Allain Creek Jetty (case ‘jetty’)

A jetty with a constant top elevation of approximately 9 m above datum was assumed to extend from the shore approximately 190 m (625 ft) along a bearing of 245^o T (Fig. 5.13). The top of the jetty would be above water over its entire length at all times.

5.4.4.3 Allain Creek Bridge (case ‘bridge’)

Relic bridge abutments at the site of the modern bridges over Allain Creek reduce the flow cross-section of Allain Creek. The NRCC model examined the effects of reducing the flow constriction by removing the old bridge abutments. The modified bottom topography would effectively increase the flow area from approximately 310 m^2 to 455 m^2 below elevation 6.0 m, an increase of nearly 50%.

5.4.4 Water Levels and Currents

The NRCC hydrodynamic data consisted of the depth-averaged currents (u,v) and water levels at 30 minute intervals over a complete tidal cycle (12.4 hours) at 1234 model nodes east of Goat Island in the mouth of the Annapolis River. Of those nodes, 524 fell in the Fort Anne SEDTRANS92 model domain. The water depth at any node and time is equal to the difference between the NRCC water level and the NRCC bottom elevation for that node.

5.4.4.1 Existing conditions

The June 1994 NRCC run used the bottom topography and shoreline as they existed. 24 June 1994 was a spring tide, and is used in this report to represent the existing situation at Fort Anne. Case ‘june24’ represents this NRCC run.

NRCC model current vectors for the ‘june24’ case are plotted on hourly maps of the Fort Anne SEDTRANS92 domain in Figures 5.14-5.26. Model nodes which are dry at a given hour are shown as small dots. Currents at the remaining nodes (larger dots) are indicated by line segments proportional to the current magnitude and pointing in the direction of current. In the figures, the line segments are the distance the water would travel in 100 s (1.67 minutes).

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At low water (2 hrs, Figure 5.16), the intertidal flat around Fort Anne, and the knoll are dry. Currents of up to 1.25 m/s flow out of Allain Creek, while currents in the Annapolis River are generally less than 0.10 m/s. One hour later (3 hrs, Figure 5.17), flow is into Allain Creek, while a weak outward flow (0.1 m/s) remains in the Annapolis River. Maximum flood tide is at 5 hrs (Figure 5.19), with currents of up to 0.30 m/s in the Annapolis River, and 0.6 m/s entering Allain Creek. During flood tide, the maximum currents around Fort Anne are about 0.18 m/s on the tidal flat west of Fort Anne, and about 0.40 m/s on the flat along Allain Creek (Figure 5.19).

At high water (7 hrs, Figure 5.21), currents are nearly zero in both the Annapolis River and Allain Creek. Maximum ebb flow occurs at 12 hrs (Figure 5.26), with outward currents of up to 1.2 m/s in Allain Creek, and up to 0.30 m/s in the Annapolis River. Table 5.1 summarizes the tidal cycle around Fort Anne.

	Time
Low water	2 hrs
Maximum flood tide	5 hrs
High water	7 hrs
Maximum ebb tide	12 hrs

Table 5.1 Tidal Stages at Queen's Wharf

5.4.4.2 Modified Shoreline

The current patterns over a tidal cycle are the same for all NRCC cases, except for local effects due to the shoreline modifications of each case. Currents for the 'queent' and 'jetty' cases are shown in Figures 5.27-5.30, and Figures 5.31-5.34, respectively, for the tidal stages listed in Table 5.1.

A comparison between Figures 5.12 and 5.28 shows that raising the top elevation of Queen's Wharf would shift the flood tide currents offshore, resulting in a general reduction of the current magnitude over the mudflat south of Queen's Wharf, particularly within 100 m of the wharf.

Figures 5.19 and 5.32 show that the Allain Creek jetty, if constructed, would reduce the flood current magnitude over the tidal flat, primarily within 100 m north of the jetty. Along the south side of the jetty, current strengths would be reduced somewhat, but there seems to be little effect on the current in the mouth of Allain Creek itself. At ebb tide (Figures 5.26 and 5.34), the tip of the jetty would greatly reduce the current flowing from Allain Creek north around the inshore side of the knoll, but the effect of the jetty on the flow velocity in the Allain Creek channel is minimal due to the low water level at ebb tide.

Current maps are not shown for the 'bridge' case because the channel widening considered by NRCC had no effect on the general current pattern. The effects of the channel modifications, which are limited to areas around the bridges spanning Allain Creek, are discussed below.

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5.4.4.3 NRCC Model versus S4 Intertidal Current Velocity Measurements

A comparison was made between the NRCC model currents and water level at node 2565 and the currents and depth measured by the S4 current meter 50 m from node 2565 along the 0 m depth contour. Figure 5.35 shows the observed depth and current at the intertidal S4/OBS site for the tidal cycle beginning at 1800 hrs on 21 October 1996. Plotted on the same axes are the NRCC model depth and current magnitude at node 2565 over one tidal cycle for the 'june21' case. Figures 5.36-5.39 are similar comparisons for other tidal cycles in October 1996. (The NRCC curves are the same in each figure.) The comparisons prove to be very good if allowance is made for (1) the slight phase misalignment is taken into account and (2) the fact that the S4 current meter often records erroneously high currents when the sensor is right at the water surface, as it is near low water.

Some tidal cycles can be found where the comparison between modeled and measured currents is not favorable (e.g., Figures 5.40-5.42), but even in these, the model and measured water level variations are in agreement.

These comparisons indicate that, in the area of interest around Fort Anne, the NRCC modeled currents and water levels agree with observations. Therefore, the NRCC hydrodynamic data appear to be a valid basis for studies of sediment dynamics in the immediate foreshore around Fort Anne and it was unnecessary to scale the NRCC model output to conform with measured current velocities.

5.4.5 Surface Wave Climate

A surface wave climatology for the Annapolis Basin and River does not exist. Therefore, model runs of Fort Anne SEDTRANS92 were made with several assumed surface wave fields. Examination of the S4 current meter data indicated a typical surface wave period of around 2-3 seconds, a range which was consistent with short-term visual observations.

The wave direction was assumed to be 270^{o}T for all model runs. This corresponds to waves propagating from the west along the axis of the Annapolis Basin, and approaching the shoreline at Fort Anne perpendicular to the shore and the general direction of the bottom contours.

As the waves move into shallow water, the imposed height will, at some point, reach the breaking height for the specified wave period. As described previously, the model automatically reduces the wave height to the breaking height in shallow water.

5.4.6 Sediment Characteristics

The model sediment parameters were taken to be those of the gray clay which was found at the S4 current meter site and which were determined in previous studies (Daborn, et al. 1995). These are summarized in Table 5.2.

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Critical shear stress for deposition (t_{cd})	0.134 Pa
" " " for erosion (t_{ce})	0.300 Pa
Settling velocity (w_s)	0.0004 m/s
Mean grain size (D)	0.00001 m
Wet bulk density (r_s)	1850 kg/m^3

Table 5.2 Sediment parameters used in SEDTRANS92.

5.5 Model Runs

The model runs presented here include three runs in each of the NRCC cases listed in Table 5.3, each with 3 s-period waves of 0.0, 0.2, and 0.5 m height. Predictions of the deposition/erosion environment are presented by plotting a numerical code at the position of each model node, as follows: 0 = dry node; 1 = deposition; 2 = steady state; 3 = erosion.

Run	Case	Wave period (s)	Wave height (m)
da	june24	3	0
db	"	"	0.2
dc	"	"	0.5
ca	queent	"	0
cb	"	"	0.2
cc	"	"	0.5
ba	jetty	"	0
bb	"	"	0.2
bc	"	"	0.5
ea	bridge	"	0
eb	"	"	0.2
ec	"	"	0.5

Table 5.3 Fort Anne SEDTRANS92 model runs.

5.5.1 Existing Conditions

Time series of water depth, bed stress, and current magnitude are plotted for node 2565 in Figures 5.43-5.45 for the existing conditions (‘june24’ case). The water level variation for the entire tidal cycle is evident, since node 2656 is inundated at all times. The mean current is generally less than 0.05 m/s for 9 hours of the tidal cycle, with an abrupt increase to a maximum of 0.18 m/s during the flood tide. With no surface waves (Figure 5.43), the bed shear stress is negligible over most of the tidal cycle, and remains well below the depositional critical stress even during flood tide.

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When a 0.2 m, 3 s period wave field is imposed, (Figure 5.44), a sharp increase in bed shear stress (up to 0.5 Pa) occurs at low tide (hrs 1-2), when the effect of the wave is strongest due to the small water depth. The bed stress due to the combined current and wave during flood tide (hrs 4-7) is no higher than the stress due to the current alone because the increased depth decreases the effect of the surface waves. If a 0.5 m, 3 s period wave is applied (Figure 5.45), the bed stress peak at low tide is increased so that erosion would occur over hours 12-3 of the tidal cycle, but the stress during flood tide (hrs 4-7) due to the current and waves remains unchanged and well below the depositional limit.

Similar time series plots for existing conditions (‘june24’ case), and a wave height of 0.2 m, appear in Figures 5.46 and 5.47 for nodes 1429 and 416. As at node 2565, increased bed shear stress occurs near low water when the decreased depth increases the surface wave effects on the bed.

To asses the effects of the shoreline modifications examined by NRCC, comparisons can be made between the time series for (1) the ‘june24’ and ‘queent’ cases at NRCC node 2565 (Figures 5.44 and 5.48), (2) the ‘june24’ and ‘jetty’ cases at node 1429, 75 m away from the jetty (Figures 5.39 and 5.49), and (3) the ‘june24’ and ‘bridge’ cases at node 416, on the mudflat 125 m from the bridges (Figures 5.47 and 5.50). At the nodes considered, these comparisons show that the shoreline modifications do not cause any perceptible differences in the water levels, currents, or bed stress.

Figures 5.51-5.63 are hourly plots of deposition/erosion for the ‘june24’ case (existing conditions) with no surface waves. At low tide (2 hrs, Figure 5.53), the mudflats around Fort Anne are dry, and the only erosion indicated is in the channel of Allain Creek. At flood tide (5 hrs, Figure 5.56), the salt marshes are inundated, but the currents are weak, and a depositional environment is indicated. The flow is now into Allain Creek, but current velocities are sufficiently low that sediment remains in suspension or is deposited in the creek channel except under the bridges, where erosion is indicated. At high tide (7 hrs, Figure 5.58), currents are weak everywhere around Fort Anne and in Allain Creek, and deposition is expected everywhere.

If a uniform surface wave field is imposed on the model, the increased bed shear stress due to the presence of waves changes the deposition/erosion environment as shown in Figures 5.64-5.71 for the ‘june24’ case. As expected, higher waves produce larger bed shear stresses, and a larger area of erosion.

Figures 5.64-5.67 are for 0.2 m high waves with a 3 s period, propagating from the west. Erosion now appears along the waterline where the water is shallowest, and the effect of the waves on the bottom is therefore the greatest. At low tide (2 hrs, Figure 5.64), erosion would tend to occur along the outer fringe of the salt marsh. At flood tide (5 hrs, Figure 5.65), neutral conditions appear at the high water line where deposition was indicated in the zero wave case (Figure 5.56). Deposition is indicated everywhere at high tide (7 hrs, Figure 5.66) due to the low currents and increased depth at the water line. On the falling tide (12 hrs, Figure 5.67), large areas of erosion appear over the outer tidal flat, over the knoll, and in Allain Creek. In the intermediate stages of the tide (not shown), the erosion zone moves with the waterline up and back across the mudflat.

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If the wave field is increased to 0.5 m (3 s period, propagating from the west, Figures 5.68-5.71), conditions are similar, but the erosion zones are widened as the general bed stress levels are increased by the higher waves.

5.5.2 Queen's Wharf

Figures 5.72-5.75 show the erosion/deposition maps for a 0.5 m 3 s period wave field for comparison with the existing conditions (Figures 5.64-5.67). The effects of the Queen's Wharf reconstruction are limited to within about 100 m of the wharf. At low tide (2 hrs, Figure 5.72) deposition is indicated adjacent to the wharf, but the erosion zone just to the south (y = 12,100 m) extends to one additional node when compared to existing conditions for the same tidal stage (Figure 5.64). The effects of the wharf reconstruction are barely evident during flood tide (5 hrs, Figure 5.73 compared to Figure 5.65). During ebb tide (12 hrs), the bed stress level appears to be slightly reduced adjacent to the wharf when compared to existing conditions (Figure 5.75 compared to Figure 5.67).

5.5.3 Allain Creek Jetty

The constructed Allain Creek jetty, Figures 5.76-5.79, does not affect conditions at low water (2 hrs, Figure 5.76) because the mudflat around the jetty is dry at that stage of the tide. With a 0.2 m, 3 s period wave field during flood tide (5 hrs, Figure 5.77 compared to Figure 5.65), the jetty would change the existing erosional environment (Figure 5.65) to a steady state or depositional environment within about 100 m north of the jetty. The jetty has little effect at high water (7 hrs, Figure 5.79 compared to Fig. 5.66), but during ebb tide (12 hrs), the jetty protects a portion of the mudflat from the discharge from Allain Creek, and therefore slightly reduces the tendency for erosion close to the jetty (Figure 5.79 compared to Figure 5.67).

5.5.4 Allain Creek Bridge

The increased flow cross section has no effect on the tendency for erosion or deposition on the mudflats along Allain Creek (Figures 5.80-5.83), primarily because the flats are dry at the stages of the tide when the increased channel area is effective in reducing the discharge velocity in the creek.

5.6 Discussion

The Fort Anne SEDTRANS92 model was used to evaluate the combined wave-current bed shear stress due to specified waves, and currents and water levels provided by the NRCC. The stress distribution over a spring tidal cycle under existing conditions was examined, and the stress distributions due to three separate shoreline modifications were compared to the distribution due to existing conditions. Model runs were made with currents but no waves, and with currents plus

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waves of 0.2 m and 0.5 m height propagating from the west. Sediment characteristics were uniform over the model domain.

The model provides additional insight as to the causes of erosion at Fort Anne and indicates the type of measures that might promote a depositional environment and reestablishment of the salt marshes. Model runs with currents alone (no waves) indicate a depositional environment over the Fort Anne mudflat throughout the tidal cycle because the magnitudes of the currents in the Annapolis Basin are insufficient by themselves to cause erosion. An erosion zone is encountered in the Allain Creek channel on both sides of low water, but it does not extend to the mudflats because they are dry at that stage of the tide.

When surface waves are imposed on the model, the depositional environment in the shallow water near the waterline changes to a neutral or an erosional environment at all stages of the tide. Over the mudflat, stresses above the erosion threshold are caused by the presence of waves when the water is shallow, but during the high-water part of the tidal cycle, the waves are ineffective due to the depth of water, and a depositional environment again prevails in the presence of the currents alone.

The re-construction of Queen’s Wharf , or the construction of the Allain Creek jetty, have limited effect on the Fort Anne mudflats. The effects of these shoreline modifications appear to be limited to zones within about 100 m of the features themselves. The effects of widening the Allain Creek channel under the bridge appears to affect the flow velocity only in the creek bed next to the bridge.

5.7 Conclusions

Based on the results of the model simulations, the following conclusions can be drawn:

(1) Cause of erosion:

(a) Currents over the Fort Anne mudflat are not sufficiently strong to produce erosion of the of the mudflats,

(b) Surface waves are capable of causing erosion in the shallow water near the waterline at most stages of the tide. The erosion zone thus moves back and forth across the flats as the water level varies,

(c) Higher waves tend to widen the zone near the waterline where erosion occurs,

(d) Waves therefore appear to be the cause of erosion at Fort Anne, not the river or creek currents.

(2) Effects of shoreline modifications:

(a) Re-construction of the Queen's Wharf would slightly modify the pattern of erosion and deposition on the mudflats within about 100 m of the wharf over the part of the tidal cycle when the wharf is submerged,

(b) Construction of an Allain Creek jetty would alter the erosion/deposition pattern on the mudflats within about 100 m north of the jetty,

(c) Neither the re-construction of Queen's Wharf or construction of the Allain Creek jetty would appear to cause a significant reduction in erosion because neither would affect the amplitude of surface waves propagating from the Annapolis River,

(d) Widening Allain Creek under the bridges would have no measurable effect on the flow velocities over the mudflats,

(e) The shoreline modifications examined do not appear to substantially reduce erosion over the mudflat generally, or promote sediment deposition over the mudflat.

6. TIDAL1 Modeling Study

6.1 Introduction

Given the uncertainties in the wave climate prediction for the region of the inner Annapolis Basin, and given the uncertainties which still remain in the NRCC numerical simulation of the tidal flows in Annapolis Basin, a second approach has been taken to assessing the possible regeneration of the mudflats and salt marshes on the tidal flats off Fort Anne. This approach was to use the current meter data collected on the lower flats during this project as input to a numerical simulation of sedimentation/erosion of the tidal flats. The model used is a simple 1-D model (TIDAL1) that calls SEDTRANS92 to solve the combined-flow bed shear stresses, and then simulates the erosion, transport and deposition of material on the tidal flats based on this input.

6.2 Approach

S4 current meter data collected at four periods during this study were used as basic input to solve for sediment erosion, transport and deposition across the tidal flats off Fort Anne. The procedure of analysis comprised the following:

(1) primary processing of the S4 current meter data to provide burst-average mean current speed, current direction, water depth, wave height and wave period;

(2) processing of the S4 time-averaged files within SEDTRANS92 in order to compute the combined-flow bed shear stresses used in the estimation of sediment transport; and

(3) input of the SEDTRANS92 estimates of bed shear stresses to the 1-D sediment transport model TIDAL1 to compute the net sedimentation/erosion for each time-series.

6.3 Overview of TIDAL1

TIDAL1 is a QuickBasic programme written to determine the balance of sedimentation for a time-series input of combined-flow bed shear stresses. The model performs the following functions:

(1) reads the input data from SEDTRANS92,

(2) if the bed shear stress (τ_{csw}) is below the threshold for deposition ($\tau_{cd} = 0.134$ Pa) the model computes the deposition rate ($\delta M/\delta t$) according to Krone's (1962) equation:

$$\delta M/\delta t = SSC\ W_s\ (1 - \tau_{csw}/\ \tau_{cd}\ )\ P$$

where SSC is the suspended sediment concentration, W_s is the mass settling rate (0.0004 m/s), and P is a probability term for resuspension usually set to unity(P = 1). τ_{cd} has been recalculated from Sigouin and MacDonald (1994).

(3) if the bed shear stress is above the threshold for erosion ($\tau_{ce} = 0.30$ Pa) the model computes the erosion rate ($\delta M/\delta t$) according to a function derived from Sea Carousel deployed in Annapolis Basin (Amos et al. 1992):

$$\delta M/\delta t = 5.1 \times 10^{-5} \exp[1.62(\tau_{csw} - \tau_{ce})^{0.5}]$$

τ_{ce} has been determined from Sea Carousel measurements in the region reported by Daborn et al. (1995).

(4) net erosion (E) and net deposition (D) are determined by assuming that the stresses were constant during the interval between each set of recordings (Δt of 1 or 1.5 hours):

$$E = \sum(\delta M/\delta t).\ \Delta t, \text{ and}$$

$$D = (\delta M/\delta t).\ \Delta t;$$

(5) E and D (in kg) are summed for the entire duration of the time-series and binned according to water depth at 0.5 m increments,

(6) E and D are plotted against water depth and converted to accretion or erosion depths per annum assuming a dry unit weight of 500 kg/m^3.

(7) by assuming a 1-D tidal flow across the tidal flats, we can map each water depth bin to a corresponding position across the tidal flat. The difference between net erosion and net deposition yields a first-order estimate of the evolution of the tidal flat profile.

6.4 Prediction of Deposition/Erosion Using TIDAL1

The prediction of erosion and deposition across the tidal flat is based on the assumption of a constant background sediment concentration. Three concentrations have been simulated in this prediction: SSC = 5, 30, and 100 mg/L. The first two values are considered to cover the range in background levels anticipated for the region; the latter is considered to be a maximum value associated with stormy periods or high run-off.

The 90-hour (May) time-series encompasses 7 tidal cycles. Deposition dominates the major part of the time-series except for three periods of erosion associated with the low waters of tides 2, 4 and 6 (Figure 6.1). This erosion process is associated with wave motion during the last stages of

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ebb and first stages of the flood, and so takes place across the entire tidal flat in equal magnitude. Net deposition, by contrast takes place over the majority of the tidal inundation and is modulated by the tidal flows and duration of tidal inundation of the intertidal transect. The latter effect causes a reduction in net sedimentation from low to high water. The mass deposited is strongly influenced by the background sediment concentration. At levels of SSC = 5 mg/L, the deposited mass is everywhere less than the eroded mass and suggests that the profile would be erosional even in the region of observed net deposition (near low water). At levels of SSC = 30 mg/L, deposited mass exceeds eroded mass in the lowermost 3 m of the profile. Above this level, erosion dominates whereas below this level net accretion would be expected. This is close to the situation surveyed for the region. As the observed background SSC where between 5 and 30 mg/L we conclude that the model gives a reasonable agreement with field observations. At levels of SSC = 100 mg/L, the deposited mass exceeds the eroded mass at all depths and implies net accretion for the entire tidal flats, a situation which may have prevailed before construction of the causeway at Annapolis Royal. This simulation serves to indicate the dominating effect of background SSC on net deposition/erosion of the tidal flats. By changing this concentration from 5 to 100 mg/L, the tidal flat reverts from one of dominant erosion to that of overall accretion.

The May-June, 1996 time-series covers a period ranging from low springs to neaps and ultimately to high spring sets of tides (Figure 6.2). Only on the higher spring tides does erosion take place and then only during periods of shallow water. During this period of time, net deposition dominates across the tidal flat. Erosion is still prevalent for SSC = 5 mg/L, however the entire tidal flat becomes depositional at SSC = 30 mg/L.

The June, 1996 time-series shows evidence of erosion at almost every period of shallow water, with significant events taking place during the second and sixth shallow water (Figure 6.3). As a consequence of this, the predicted net erosion far exceeds predicted net deposition at all elevations and at all values of SSC. The short-lived effects of erosion during shallow water far out-weigh the effects on net deposition for the remainder of the tidal inundation.

The 1966 October-November time-series show only two major erosion events, again associated with periods around tidal exposure (Figure 6.4). Nevertheless these erosion events dominate the evolution of the tidal flats by exceeding net deposition for almost all elevations and all levels of SSC.

The predicted net erosion and net deposition for each time-series may be converted into accretion/erosion rates per annum by assuming that: (1) the dry-unit weight of sediment is 500 kg/m^3; and (2) conditions for each period to be representative of the year. The four time-series are shown in this form in Figures 6.5 and 6.6. Note that for the May time-series and the most probable SSC (30 mg/L) a net accretion of 10 cm/a would be expected. For a similar SSC during May-June, the rate is about 30 cm/a. The June time-series yields an accumulation of about 10 cm/a while the October-November time-series predicts a net erosion of 50 cm/a.

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6.5 Discussion

These simulations indicate that it is waves that cause bed erosion and that this erosion occurs immediately before tidal exposure and immediately after tidal inundation. In addition, deposition takes place at almost all stages of the tide if waves are absent. The inference of this is that a reduction in the currents are not necessary to stimulate tidal flat development, but rather a suppression of the waves, particularly during periods of shallow water, is required. If the calm-weather time-series (May-June, Figure 6.5) is used as a proxy for what might be expected if the waves were suppressed in the future, a clear picture emerges. In this case net deposition would occur across the entire tidal flat at a rate strongly dependent on the background SSC. If we assume that the SSC is 30 mg/L, then about 30 cm/a would become deposited each year on the lower flats, and about 5 cm/a on the higher flats. Thus a 2 m thick mudflat would require 40 years to generate on the upper flat, whereas such a sequence would accrete in less than 10 years on the lower flat.

If the wave effects are not removed erosion will continue on the upper flats regardless of the suppression of the tidal flows, and deposition on the lower flats will only occur above an SSC of 100 mg/L, an unlikely situation.

These results indicate the importance of SSC on the evolution of the mudflats of the tidal foreshore. It is reasonable to suppose that the historical evolution of the Fort Anne tidal flats has been controlled by long-term, historical changes in levels of SSC. The most profound influence on SSC is likely associated with deforestation and development of the Annapolis River valley. During this time, levels of SSC would be much higher than at present and this would induce the development of an extensive mudflat seawards of the Fort. In support of this is the fact that erosion began somewhere about the time of the construction of the causeway across the Annapolis River at Annapolis Royal. The causeway would have the effect of preventing sediment coming downriver from escaping seawards and hence reducing the level of SSC off the Fort Anne shoreline. The effect of this would be net erosion in the outer Annapolis Basin as we have seen in recent years. This erosion is not restricted to the region of the Fort but appears to be taking place throughout the Bay.

The most effective solution to the problem of erosion off Fort Anne is to increase SSC by (1) removal of the causeway, or (2) removal of other sites of net deposition (e.g., perhaps the breached dykelands of Allain Creek). A second effective solution would be to create suitable accommodation space for the material that is presently in suspension by removing the waves from the immediate foreshore of Fort Anne.

7. Biological Survey of Fort Anne Intertidal

7.1 Introduction

A benthic fauna survey was carried out at a series of transects within the Fort Anne intertidal zone along both the Annapolis Estuary and Allain River shorelines. The major objective of the survey was to better characterize the intertidal benthic community in terms of its species composition and abundance to determine if this site contains any unique biological characteristics that may be impacted by shoreline remediation activities.

7.2 Methods

Samples were collected on 13-14 August 1996 along 13 transects spanning the intertidal between the Queen's Wharf and the Allain River bridges (Figure 7.1). Transect 1 was located near Queens Wharf, and other transects, running perpendicular to the shoreline, were located at 40 m intervals along the high water line. The first sampling station for odd numbered transects was established at the upper edge of the muddy intertidal, while the first sampling station at even numbered transects was established 10 m seaward of this edge. Subsequent sampling stations were located at 20 meter intervals along each transect. Since the width of the Fort Anne shoreline varies, the number of sampling stations at each transect varied between two and eight. Triplicate samples were collected at each sampling station.

Samples were collected from the upper 10 cm of sediment using a 5.9 cm diameter core and were fixed immediately with formalin. Each sample was later processed by sieving through a 0.750 mm screen to separate organisms from sediment. The sieved samples were preserved in 70 % alcohol and identified and enumerated using a dissecting microscope.

7.3 Results

A total of 23 taxa were identified (Appendix 11.1), the majority of which were polycheates. *Polydora sp*. and *Nereis diversicolor* were the most abundant polycheates. An unidentified oligochaete was also relatively abundant. *Corophium volutator* was the most abundant organism and was present at a mean density of about 2,400/m^2 (Appendix 11.2). This amphipod, which is a major food source of foraging sandpipers, is one of the most abundant intertidal species around the Bay of Fundy. Densities greater than 10,000/m^2 have often been recorded within the Minas Basin intertidal. The second most abundant group were small oligochaetes (about 290/ m^2) which have not been identified to species. This group of organisms is not well studied in the Bay of Fundy, but are considered to be abundant in at least some areas. Appendix 11.2 contains the density of each taxa in each sample.

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7.4 Discussion

There is little indication that the Fort Anne intertidal is unique in terms of it biological community. By comparison with other intertidal areas in the Bay of Fundy it is relatively sparsely populated, probably as a result of the unstable sediment regime currently existing on the foreshore. The results of this and previous surveys (Daborn et al. 1995) suggest that remedial actions that impact the intertidal will not have serious biological implications and may, in fact, lead to a more biologically diverse and productive community if the foreshore were to be stabilized.

8. Literature Review of Procedures for Re-establishment of Salt Marsh Vegetation

Prior to the 1970's an extensive *Spartina alternaflora* (Smooth cordgrass) salt marsh existed within the intertidal zone of the Fort Anne site. The reason for the disappearance of a large portion of the Fort Anne marsh is not entirely clear, but seems to be related to events occurring at the time of construction of the nearby causeway. Salt marshes are known to decrease shoreline erosion by decreasing the scouring energy of currents and waves and by stabilizing deposited sediments through formation of dense root-rhizome mats beneath the sediment surface. If it were possible to develop a neutral or depositional environment on the Fort Anne foreshore through some sort of engineered structure, it may be possible to further increase the rate of sediment deposition if a *Spartina* salt marsh could be recreated within the intertidal zone. Accordingly, a literature search was carried out to determine under what conditions, and by what means, a *S. alternaflora* salt marsh could be recreated within the Fort Anne intertidal zone.

The establishment of *Spartina* salt marshes as an aid to erosion control has a long history. *S. alterniflora* has received more study and has been planted with better chance of success that any other coastal marsh species native to North America and there exists considerable documentation as to the conditions under which a *Spartina* marsh can be created or restored. There is also a great deal of information on the various procedures that can be used in restoration and the advantages and disadvantages of each.. Appendix 11.3 contains a bibliography of literature relevant to *S. alternaflora* salt marsh restoration. The following is a brief summary of the critical factors and most successful procedures involved in restoring a *S. alternaflora* salt marsh.

The elevation range within a shoreline in which *S. alternaflora* grows depends to a large extent on the tidal range of the area. Where the tidal range is small (< 2 m), *S. alternaflora* will grow from about mean low water to mean high water. As the tidal range increases there is a decrease in the lower level at which it will survive. Within the area around Fort Anne, which has a tidal range of about 9 m, it would be expected to grow between about the levels of mean tide and mean high tide. Its salinity tolerance is between 5-35 ppt, which is well within the range existing along the Fort Anne shoreline.

S. alternaflora grows well on almost all soil types, from sands to muds. However, it is easier to restore a *S. alternaflora* marsh on finer grained soils, partly because these retain nutrients and water better than sandy soils, but also because finer grained soils are usually associated with environments having low wave energies and therefore limited erosion. Although *S. alterniflora* has been transplanted with success on eroding shorelines, this has usually only been possible when breakwaters have been installed to decrease wave energy. There appears to be little quantitative information available on the wave characteristics under which transplantation efforts fail.

There are numerous approaches to planting salt marshes. Planting by broadcasting seeds collected from existing stands is the least expensive method, but is generally limited to very sheltered sites and the upper 20-30% of the intertidal zone because of problems associated with resuspension and transport of the seeds. Vegetative transplants are much more tolerant of currents and waves and is the recommended procedure in most instances. Transplanting small plants collected from other marshes is a commonly used procedure where abundant material is available. This is the preferred method since the plant material is easy to handle and limited preparation of the planting area is required. Single stems with small shoots and short pieces of rhizome collected from stands of recent origin are preferred over plants collected from older stands which tend to have smaller, poorer quality plants. In most cases the young plants can be planted into a dibbled hole. In some cases, *S. alternaflora* marshes have been created by planting pot-grown nursery seedlings, but these are expensive to produce and plant. Plugs obtained from natural marshes have also been used, but these are difficult to obtain, transport and plant and tend to be used only when other sources of plant material are unavailable. Both nursery seedlings and plugs require digging or drilling a planting hole which can be difficult and time consuming in clay soils. Materials for seeding or transplanting should be obtained from nearby areas as there appear to be geographical differences between populations in factors such as growth rates and forms, flowering times and salinity tolerances. Once a *S. alternaflora* stand is established, the predominant means of spreading is through vegetative reproduction by extensive below-ground rhizomes.

Topics currently in need of more investigation with respect to creation of *S. alterniflora* salt marsh include the degree of protection from wave action necessary to ensure survival of transplants, appropriate planting densities and how this relates to existing sediment stability, better techniques for planting by seeds and best planting times.

9. Conclusions

(1) Monitoring of pore water pressures within the intertidal zone of the Fort Anne shoreline indicated that that the intertidal sediments are in a state of continuous destabilization which maximizes at the moment of exposure during each falling tide. In order to increase the stability of the intertidal mudflat the previously eroded overburden material must be reinstated, in combination with measures to reduce wave action. Preventing wetting of fresh, intact consolidated sediment is the key to mitigating the erosion of the susceptible clay deposit.

(2) Deployment of a subtidal current meter off the Fort Anne shoreline indicated that the discrepancy between current meter data and current velocities predicted by the NRCC model is not due to errors in the original current meter measurements. However, current velocities predicted by the NRCC model within the area of the Fort Anne shoreline agree reasonably well with current velocities measured during 1996.

(3) Model predictions made by refinement of the NRCC model to incorporate the effect of wave activity indicate that:

> (a) currents over the Fort Anne mudflat are not sufficiently strong to cause erosion of the mudflat,
>
> (b) erosion is due mainly to surface waves and occurs in the area of shallow water at most stages of the tide,
>
> (c) neither re-construction of Queen’s Wharf nor construction of the Allain Creek jetty will cause significant reduction in erosion of the mudflat since neither affect the amplitude of surface waves,
>
> (d) widening Allain Creek under the bridge would have no measurable affect on flow velocities, and therefore erosion, over the mudflats,

(4) the rate of deposition on the tidal flat that would occur if wave activity could be suppressed is largely dependent on ambient suspended sediment concentrations,

(5) a biological survey of the Fort Anne intertidal zone indicated that the intertidal community is poorly developed with little evidence of any unusual biological characteristics,

(6) a survey of literature relevant to re-establishment of a *Spartina alternaflora* marsh within the Fort Anne intertidal zone suggests that this would be possible, but only if the intertidal zone were protected from severe wave action and a neutral or depositional environment was established.

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Appendix 11.1. List of benthic fauna taxa collected during biological survey.

Benthic fauna taxa collected during the biological survey of the Fort Anne intertidal zone.

- Hydrozoa
- Rhyncocoela
- Nematoda
- Oligochaeta
- Polychaeta:
  - *Polydora sp.*
  - *Nereis diversicolor*
  - *Nereis virens*
  - *Heteromastus filiformis*
  - *Nephtys neotenus*
  - *Nephtys picta*
  - *Eteone sp.*
  - *Streblospio benedicti*
  - *Chaetozone setosa*
  - *Nephtys caeca*
  - *Spio setosa*
  - *Spiophanes bombyx*
  - *Phyllodoce mucosa*
  - unid. Phyllodocidae
  - unid. Polychaeta
- Amphipoda
  - *Corophium volutator*
- Tanaidacea
  - *Leptochelia savignyi*
- Insecta
- Cirripedia
  - *Balanus balanoides*
- Pelecypoda
  - *Mya arenaria*
- Gastropoda
  - *Littorina littorea*

Appendix 11.2. Density of biological organisms collected during the biological survey.

Summary statistics of the abundance of intertidal infauna at Fort Anne (in order of decreasing abundance).

	Mean Density number/m^2	Standard Deviation	Min. Density number/m^2	Max. Density number/m^2
C. volutator	1771.38	2363.29	0.00	12210.00
Oligochaeta	289.36	1311.21	0.00	12210.00
Polydora sp.	210.44	422.42	0.00	2590.00
N. diversicolor	129.50	249.67	0.00	1110.00
L. littorea	94.81	345.32	0.00	2220.00
H. filiformis	83.25	227.10	0.00	1110.00
N. neotenus	76.31	329.63	0.00	2220.00
E. flava	74.00	184.65	0.00	1110.00
S. benedicti	41.63	190.11	0.00	1480.00
unid. Polychaeta	27.75	128.24	0.00	1110.00
Rhyncocoela	27.75	134.79	0.00	1110.00
L. savignyi	23.13	159.03	0.00	1480.00
Nematoda	11.56	64.58	0.00	370.00
C. setosa	11.56	76.76	0.00	740.00
N. caeca	11.56	76.76	0.00	740.00
Insecta	9.25	57.95	0.00	370.00
B. balanoides	6.94	87.75	0.00	1110.00
N. virens	4.63	58.50	0.00	740.00
M. arenaria	4.63	41.24	0.00	370.00
S. setosa	4.63	58.50	0.00	740.00
unid. Phyllodocidae	2.31	29.25	0.00	370.00
E. longa	2.31	29.25	0.00	370.00
N. picta	2.31	29.25	0.00	370.00
S. bombyx	2.31	29.25	0.00	370.00
P. mucosa	2.31	29.25	0.00	370.00
Hydrozoa	2.31	29.25	0.00	370.00

Polychaete Density (number/m^2)

Location			Nereis	Eteone	Polydora	Heteromastus	Nephtys	Streblospio	Nereis.	Chaetozone	Nepthys.	Eteone	Nephtys	Spiophanes	Spio	Phyllodoce	unid.	unid.
Trans.	Sta.	Rep.	diversicolor	flava	spp.	filiformis	neotenus	benedicti	virens	setosa	caeca	longa	picta	bombyx	setosa	mucosa	Phyllodocidae	Polychaeta
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	370
1	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	370
1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	3	2	0	0	370	370	0	0	0	0	0	0	0	0	0	0	0	0
1	3	3	0	0	0	0	0	0	0	0	0	0	0	0	740	0	0	0
1	4	1	0	0	370	0	740	370	0	0	0	0	0	0	0	0	0	370
1	4	2	0	0	0	370	1110	0	0	0	0	0	0	0	0	0	0	0
1	4	3	0	0	0	0	2220	0	0	0	0	0	0	0	0	0	0	370
2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	370
2	1	2	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	3	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	1	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	2	0	0	740	0	0	0	0	0	0	0	0	370	0	0	0	0
2	2	3	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	3	1	0	370	740	0	0	0	0	0	0	0	0	0	0	0	0	0
2	3	2	0	0	0	0	0	0	0	370	0	0	0	0	0	0	0	0
2	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	4	1	0	0	740	0	0	0	0	0	0	0	0	0	0	0	0	0
2	4	2	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
2	4	3	0	370	740	0	0	0	0	0	0	0	0	0	0	370	0	0
3	1	1	370	0	0	0	370	0	0	0	0	0	0	0	0	0	0	0
3	1	2	740	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	3	0	0	740	0	0	0	0	0	0	0	0	0	0	0	0	0
3	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	2	2	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	4	1	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
3	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	5	1	0	0	0	740	0	0	0	0	0	0	0	0	0	0	0	0
3	5	2	0	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0
3	5	3	0	0	740	370	1110	0	0	0	0	0	0	0	0	0	0	0

Polychaete Density (number/m^2) (con't.)

Location			Nereis	Eteone	Polydora	Heteromastus	Nephtys	Streblospio	Nereis.	Chaetozone	Nepthys.	Eteone	Nephtys	Spiophanes	Spio	Phyllodoce	unid.	unid.
Trans.	Sta.	Rep.	diversicolor	flava	spp.	filiformis	neotenus	benedicti	virens	setosa	caeca	longa	picta	bombyx	setosa	mucosa	Phyllodocidae	Polychaeta
3	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	6	2	0	0	0	370	1110	0	0	0	0	0	0	0	0	0	0	0
3	6	3	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
4	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	1	2	370	0	370	0	0	370	0	0	0	0	0	0	0	0	0	0
4	1	3	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	2	1	370	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
4	2	2	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	2	3	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	3	1	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	4	2	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	4	3	0	370	370	0	0	0	0	0	0	0	0	0	0	0	0	0
4	5	1	370	370	0	0	370	0	0	0	0	0	0	0	0	0	0	0
4	5	2	0	0	0	0	2220	0	0	0	0	0	0	0	0	0	0	1110
4	5	3	740	0	370	740	1850	0	0	0	0	0	0	0	0	0	0	0
5	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1	2	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	2	2	740	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	2	2	0	0	0	1110	0	0	0	0	0	0	0	0	0	0	0	0
5	2	3	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
5	3	1	0	0	740	0	0	0	0	0	0	0	0	0	0	0	0	0
5	3	1	740	0	740	0	0	0	0	0	0	0	0	0	0	0	0	0
5	3	1	370	370	370	0	0	0	0	0	0	0	0	0	0	0	0	0
5	4	1	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	4	2	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	740
5	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	6	1	0	0	0	1110	0	0	0	0	0	0	0	0	0	0	0	0
5	6	2	0	0	370	0	0	740	0	0	0	0	0	0	0	0	0	0
5	6	3	0	0	0	740	0	0	0	0	0	0	0	0	0	0	0	0
5	7	1	0	740	0	370	370	0	0	0	0	0	0	0	0	0	0	0
5	7	3	0	0	0	1110	0	0	0	0	0	0	0	0	0	0	0	0
6	1	1	740	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
6	1	2	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
6	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Benthic Species - Polychaete Density (number/m^2) (con't.)

Location			Nereis diversicolor	Eteone flava	Polydora spp.	Heteromastus filiformis	Nephtys neotenus	Streblospio benedicti	Nereis. virens	Chaetozone setosa	Nepthys. caeca	Eteone longa	Nephtys picta	Spiophanes bombyx	Spio setosa	Phyllodoce mucosa	unid. Phyllodocidae	unid. Polychaeta
Trans.	Sta.	Rep.																
6	2	1	740	740	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	2	2	740	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	2	3	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	3	1	0	740	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	3	2	0	370	370	0	0	0	0	0	0	0	0	0	0	0	370	0
6	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	4	1	0	370	370	0	0	0	0	0	0	0	0	0	0	0	0	0
6	4	2	0	370	370	0	0	0	0	0	0	0	0	0	0	0	0	0
6	4	3	0	0	0	370	0	0	0	0	0	0	0	0	0	0	0	370
6	5	1	0	0	1850	0	370	370	0	0	0	0	0	0	0	0	0	0
6	5	2	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
6	5	3	0	370	370	0	0	0	0	0	0	0	0	0	0	0	0	0
6	6	1	0	370	370	0	0	0	0	0	0	0	0	0	0	0	0	0
6	6	1	0	0	1480	370	0	0	0	0	0	0	0	0	0	0	0	0
6	6	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	6	3	370	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
6	7	1	740	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
6	7	2	0	370	2220	0	0	0	0	0	0	0	0	0	0	0	0	0
6	7	3	370	0	1110	0	0	0	0	0	0	0	0	0	0	0	0	0
6	8	3	0	0	1480	0	0	0	0	0	0	0	0	0	0	0	0	0
7	1	1	740	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	1	2	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	2	1	1110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	2	2	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	2	3	740	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	3	2	0	0	2590	0	0	0	0	0	0	0	0	0	0	0	0	0
7	3	3	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	4	1	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	4	3	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
7	5	1	370	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
7	5	2	0	0	0	0	0	0	740	0	0	0	0	0	0	0	0	0
7	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	6	1	740	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	6	2	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	6	3	740	0	1480	0	0	0	0	0	0	0	0	0	0	0	0	0
7	7	1	0	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0
7	7	2	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
7	7	3	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0

Polychaete Density (number/m^2) (con't.)

Location Trans.	 Sta.	 Rep.	Nereis diversicolor	Eteone flava	Polydora spp.	Heteromastus filiformis	Nephtys neotenus	Streblospio benedicti	Nereis. virens	Chaetozone setosa	Nepthys. caeca	Eteone longa	Nephtys picta	Spiophanes bombyx	Spio setosa	Phyllodoce mucosa	unid. Phyllodocidae	unid. Polychaeta
8	1	1	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	2	2	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
8	3	1	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	3	2	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
8	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	4	1	370	0	740	0	0	0	0	0	0	0	0	0	0	0	0	0
8	4	2	370	0	740	0	0	0	0	0	0	0	0	0	0	0	0	0
8	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	1	2	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	1	3	0	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0
9	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	2	3	0	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0
10	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	1	2	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	2	1	370	0	0	370	0	0	0	0	370	0	0	0	0	0	0	0
10	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	2	3	370	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	1	2	1110	0	0	370	0	370	0	0	0	0	0	0	0	0	0	0
11	1	3	0	0	370	0	0	370	0	0	0	0	0	0	0	0	0	0
11	2	1	0	0	1480	0	0	0	0	0	0	0	370	0	0	0	0	0
11	2	2	0	0	370	0	0	0	0	0	0	0	0	0	0	0	0	0
11	2	3	0	0	740	370	0	370	0	0	0	0	0	0	0	0	0	0
12	1	1	0	740	0	370	0	370	0	0	0	0	0	0	0	0	0	0
12	1	2	0	1110	0	1110	0	0	0	0	0	0	0	0	0	0	0	0
12	1	3	0	0	0	740	0	0	0	0	740	0	0	0	0	0	0	0
12	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	370
12	2	2	0	0	0	0	0	1480	0	370	0	0	0	0	0	0	0	0
12	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	2	1	0	0	370	0	0	0	0	740	370	0	0	0	0	0	0	0
13	2	2	0	0	0	370	370	1480	0	0	0	0	0	0	0	0	0	0
13	2	3	370	0	0	0	0	370	0	370	370	370	0	0	0	0	0	0

Density of Taxa other than Polychaetes (number/m^2)

Location			Corophium				Littorina	Mya		Leptochelia	Balanus	
Trans.	Sta.	Rep.	volutator	Oligochaeta	Rhyncocoela	Nematoda	littorea	arenaria	Insecta	savignyi	balanoides	Hydrozoa
1	1	1	0	0	0	370	0	0	0	0	0	0
1	1	2	0	0	0	0	0	0	0	0	0	0
1	1	3	0	0	370	0	0	0	0	0	0	0
1	2	1	0	3700	740	0	1480	0	0	0	0	0
1	2	2	0	3330	740	0	0	0	0	0	0	0
1	2	3	0	5550	370	0	0	0	0	0	0	0
1	3	1	0	0	0	0	740	0	0	0	0	0
1	3	2	1480	0	0	0	0	0	0	0	0	0
1	3	3	0	0	0	0	0	0	0	0	0	0
1	4	1	0	0	0	0	0	0	0	0	0	370
1	4	2	370	0	0	0	0	0	0	0	0	0
1	4	3	0	0	0	0	0	0	0	0	0	0
2	1	1	370	12210	0	0	1480	0	0	0	0	0
2	1	2	0	1110	0	0	0	0	0	0	0	0
2	1	3	0	1850	1110	0	740	0	0	0	0	0
2	2	1	1480	370	0	0	0	0	0	0	0	0
2	2	2	3700	0	0	0	0	0	0	0	0	0
2	2	3	1850	0	0	0	0	0	0	0	0	0
2	3	1	0	0	0	0	0	0	0	0	0	0
2	3	2	0	0	0	0	0	0	0	0	0	0
2	3	3	0	0	0	0	0	0	0	0	0	0
2	4	1	0	0	0	0	0	0	0	0	0	0
2	4	2	0	0	0	0	0	0	0	0	0	0
2	4	3	0	0	0	0	0	0	0	0	0	0
3	1	1	3700	370	0	0	0	0	0	0	0	0
3	1	2	1110	0	0	0	0	0	0	0	0	0
3	1	3	740	370	0	0	0	0	0	0	0	0
3	2	1	740	0	0	0	0	0	0	0	0	0
3	2	2	2590	0	0	0	0	0	0	0	0	0
3	2	3	8880	0	0	0	0	0	0	0	0	0
3	3	1	5550	0	0	0	0	0	0	0	0	0
3	3	2	4070	0	0	0	0	0	370	0	0	0
3	3	3	2590	0	0	0	0	0	0	0	0	0
3	4	1	1110	0	0	0	0	0	0	0	0	0
3	4	2	740	0	0	0	0	0	0	0	0	0
3	4	3	1110	0	0	0	0	0	0	0	0	0
3	5	1	0	370	0	0	1110	0	0	0	0	0
3	5	2	0	370	0	0	740	0	0	0	0	0
3	5	3	370	0	0	0	0	0	0	0	0	0
3	6	1	370	0	0	0	370	0	0	0	1110	0
3	6	2	0	0	0	0	370	0	0	0	0	0
3	6	3	0	0	0	0	0	0	0	0	0	0
4	1	1	5180	0	0	0	0	0	0	0	0	0
4	1	2	1480	2220	0	370	0	0	0	0	0	0
4	1	3	1480	0	0	0	0	0	0	0	0	0
4	2	1	3330	370	0	0	0	0	0	0	0	0
4	2	2	740	0	0	0	0	0	0	0	0	0
4	2	3	370	0	0	0	0	0	0	0	0	0
4	3	1	8510	0	0	0	0	0	0	0	0	0
4	3	1	4070	0	0	0	0	0	0	0	0	0
4	4	1	2590	0	0	0	740	0	0	0	0	0
4	4	2	1110	0	0	0	0	0	0	0	0	0
4	4	3	1110	0	0	0	0	0	0	0	0	0
4	5	1	370	0	0	0	0	0	0	0	0	0
4	5	2	1850	0	0	0	0	0	0	0	0	0
4	5	3	2220	0	0	0	0	0	0	0	0	0
5	1	1	1850	0	0	0	0	0	0	0	0	0
5	1	2	0	0	0	0	0	0	0	0	0	0

Density of Taxa other than Polychaetes (number/m^2) (con't.)

Location			Corophium volutator	Oligochaeta	Rhyncocoela	Nematoda	Littorina littorea	Mya arenaria	Insecta	Leptochelia savignyi	Balanus balanoides	Hydrozoa
Trans.	Sta.	Rep.										
5	1	3	1850	0	0	0	0	0	0	0	0	0
5	2	2	4070	0	0	0	0	0	0	0	0	0
5	2	2	0	0	0	0	0	0	370	0	0	0
5	2	3	1110	0	0	0	0	0	0	0	0	0
5	3	1	370	0	0	0	370	0	370	0	0	0
5	3	1	740	0	0	0	0	0	0	0	0	0
5	3	1	370	0	0	370	0	0	0	0	0	0
5	4	1	0	0	0	0	0	0	0	0	0	0
5	4	2	0	0	0	0	0	0	0	0	0	0
5	4	3	740	0	0	0	0	0	0	0	0	0
5	5	1	1110	0	0	0	0	0	0	0	0	0
5	5	2	370	1110	0	0	0	0	0	0	0	0
5	5	3	370	370	0	0	0	0	0	0	0	0
5	6	1	0	0	0	0	0	0	0	0	0	0
5	6	2	370	7770	0	370	0	0	0	0	0	0
5	6	3	370	3700	0	0	0	0	0	0	0	0
5	7	1	0	0	0	0	0	0	0	0	0	0
5	7	3	740	0	0	0	0	0	0	0	0	0
6	1	1	6290	0	0	0	0	0	0	0	0	0
6	1	2	5550	0	0	0	0	0	0	0	0	0
6	1	3	6660	0	0	0	0	0	0	0	0	0
6	2	1	2590	0	0	0	0	0	0	0	0	0
6	2	2	2960	0	0	0	0	0	0	0	0	0
6	2	3	5180	0	0	0	0	0	0	0	0	0
6	3	1	370	0	0	0	0	0	0	0	0	0
6	3	2	370	0	0	0	0	0	0	0	0	0
6	3	3	740	0	0	0	0	0	0	0	0	0
6	4	1	1110	0	0	370	0	0	0	0	0	0
6	4	2	2220	0	0	0	0	0	0	0	0	0
6	4	3	0	0	0	0	0	0	0	0	0	0
6	5	1	7400	0	370	0	0	0	0	0	0	0
6	5	2	1110	0	0	0	0	0	0	0	0	0
6	5	3	1850	0	0	0	0	0	0	0	0	0
6	6	1	5920	0	0	0	0	0	0	0	0	0
6	6	1	3700	0	0	0	0	0	0	0	0	0
6	6	2	2960	0	0	0	0	0	0	0	0	0
6	6	3	6290	0	0	0	0	0	0	0	0	0
6	7	1	740	0	0	0	0	0	0	0	0	0
6	7	2	1110	0	0	0	0	0	0	0	0	0
6	7	3	1850	0	0	0	0	0	0	0	0	0
6	8	3	2590	0	0	0	0	0	0	0	0	0
7	1	1	740	0	0	0	0	0	0	0	0	0
7	1	2	0	0	0	0	0	0	0	0	0	0
7	1	3	740	0	0	0	0	0	0	0	0	0
7	2	1	2220	0	0	0	0	0	0	0	0	0
7	2	2	2590	0	0	0	0	0	370	0	0	0
7	2	3	6660	370	0	0	0	0	0	0	0	0
7	3	2	1850	0	370	0	0	0	0	0	0	0
7	3	3	5920	0	0	0	0	0	0	0	0	0
7	4	1	2220	0	0	0	0	0	0	0	0	0
7	4	2	1850	0	0	0	0	0	0	0	0	0
7	4	3	1850	0	0	0	0	0	0	0	0	0
7	5	1	1850	740	0	0	0	0	0	0	0	0
7	5	2	1110	0	0	0	370	0	0	0	0	0
7	5	3	740	0	0	0	0	0	0	0	0	0
7	6	1	1110	0	0	0	0	0	0	0	0	0
7	6	2	3700	0	0	0	0	0	0	0	0	0
7	6	3	2960	0	0	0	0	0	0	0	0	0

Benthic Species - Density of Taxa other than Polychaetes (number/m^2) (con't.)

Location			Corophium volutator	Oligochaeta	Rhyncocoela	Nematoda	Littorina littorea	Mya arenaria	Insecta	Leptochelia savignyi	Balanus balanoides	Hydrozoa
Trans.	Sta.	Rep.										
7	7	1	370	0	0	0	0	0	0	0	0	0
7	7	2	1480	0	0	0	0	0	0	0	0	0
7	7	3	1850	0	0	0	0	0	0	0	0	0
8	1	1	1480	0	0	0	0	0	0	0	0	0
8	1	3	740	370	0	0	0	0	0	0	0	0
8	2	1	1850	0	0	0	0	0	0	0	0	0
8	2	2	2960	0	0	0	0	0	0	0	0	0
8	2	2	1480	0	0	0	0	0	0	0	0	0
8	3	1	740	0	0	0	0	0	0	0	0	0
8	3	2	370	0	0	0	0	0	0	0	0	0
8	3	3	0	0	0	0	0	0	0	0	0	0
8	4	1	370	1110	0	0	0	0	0	0	0	0
8	4	2	2590	740	0	0	0	0	0	0	0	0
8	4	3	7030	0	0	0	0	0	0	0	0	0
9	1	1	3700	0	0	0	0	0	0	0	0	0
9	1	2	0	0	0	0	0	0	0	0	0	0
9	1	3	740	0	0	0	0	0	0	0	0	0
9	2	1	0	0	0	0	2220	0	0	0	0	0
9	2	2	0	0	370	0	1850	0	0	0	0	0
9	2	3	0	0	0	0	1850	370	0	0	0	0
10	1	1	1480	0	0	0	0	0	0	740	0	0
10	1	2	1110	0	0	0	0	0	0	1480	0	0
10	1	3	370	0	0	0	0	0	0	1110	0	0
10	2	1	370	0	0	0	370	0	0	0	0	0
10	2	2	740	0	0	0	0	0	0	0	0	0
10	2	3	0	0	0	0	0	0	0	0	0	0
11	1	1	12210	0	0	0	370	0	0	0	0	0
11	1	2	10360	0	0	0	0	0	0	0	0	0
11	1	3	4810	0	0	0	0	0	0	370	0	0
11	2	1	0	0	0	0	0	0	0	0	0	0
11	2	2	370	0	0	0	0	0	0	0	0	0
11	2	3	0	0	0	0	0	0	0	0	0	0
12	1	1	2590	0	0	0	0	370	0	0	0	0
12	1	2	370	0	0	0	0	0	0	0	0	0
12	1	3	370	0	0	0	0	0	0	0	0	0
12	2	1	0	0	0	0	0	0	0	0	0	0
12	2	2	0	0	0	0	0	0	0	0	0	0
12	2	3	0	0	0	0	0	0	0	0	0	0
13	1	1	11470	0	0	0	0	0	0	0	0	0
13	1	2	4810	370	0	0	0	0	0	0	0	0
13	1	3	4810	0	0	0	0	0	0	0	0	0
13	2	1	0	0	0	0	0	0	0	0	0	0
13	2	2	0	0	0	0	0	0	0	0	0	0
13	2	3	0	0	0	0	0	0	0	0	0	0

Appendix 11.3. Bibliography of literature relevant to salt marsh restoration.

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