EFFECTS OF REGULARLY REVERSING ENERGY GRADIENTS ON SEDIMENT TRANSPORT IN A TIDAL WETLAND SYSTEM

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INTRODUCTION

During the past two decades, people have become much more aware of the biological importance of tidal wetlands. This awareness has led to a dramatic increase in the number of tidal wetland restoration projects being planned and constructed around the United States. In planning and constructing these projects, engineers and geomorphologists often design or predict the morphology of the channel networks that exist in the wetlands. These channels are critical to the habitat zones that will develop in the restored wetlands because they control the depth and frequency of inundation of the different areas of the wetlands and thus control the types of plant communities that can survive in those habitat zones.

Tidal wetland restoration projects frequently begin with ecological goals based on an optimum mix of habitat zones. The habitat zones usually progress out from the wetland channels, with the channel bottoms supporting subtidal or intertidal plant species and the areas farthest away from the channels supporting transitional or upland plant species. The types of species that can survive in an area of the wetland are determined by the depth and frequency of tidal inundation of that area. As an example, a tidal wetland in New England may be designed to support *Zostera marina (*eel-grass, a subaquatic species) habitat in the wetland channels, to support *Spartina alterniflora* (cord grass, an intertidal species that typically colonizes an area between mean sea level (MSL) and mean high water (MHW)) habitat in the zone immediately adjacent to the wetland channels and on the marsh surface, and to support a zone of mixed *Juncus gerardii* (black grass) and *Distichlis spicata* (spike grass) (both upper high marsh species that typically colonize an area between MHW and mean spring high water (MSHW)) habitat between the *alterniflora* zone and the upland (non-tidal) zone.

Unfortunately, due to insufficient understanding of the physical processes involved in shaping tidal wetlands, many of these projects fail to meet their habitat restoration goals. One manner of failure is excessive erosion or deposition of sediments in various areas of the wetlands. If the wetland channels are not properly designed or if their morphology is not properly anticipated, zones that were planned to be intertidal may end up actually becoming subtidal or upland habitat. Current methods of designing wetland channels and anticipating morphologic characteristics such as channel width and depth are commonly based on empirical relationships (Coats, 1995) with high levels of uncertainty. This paper presents the initial methods, along with some preliminary results, of a physics-based approach to describing how reversing tidal flows affect erosion and deposition in tidal wetland channels. Since this paper describes what is, at this point, work in progress, it is somewhat incomplete. The conference presentation and subsequent papers will provide more detail and more results, based on the data collected and additional analysis.

Within this paper, tidal wetlands are defined as wetlands that are subjected to regular inundation by salt or brackish water due to astronomical tides. Wetlands which are normally unaffected by astronomical tides, but which are periodically inundated by meteorological tides (surges) are not included in this definition or in this paper.

TIDAL WETLAND MORPHOLOGY AND DESIGN

Tidal Wetland Morphology: Tidal wetlands can take many forms, depending on the percent area of emergent land, the tidal range, and the depth and frequency of submergence of the subtidal and intertidal areas. Wetlands with a relatively small (percentage) emergent area, and with a relatively large (percentage) subtidal area often take the form of lagoons interspersed with connected and unconnected islands. Wetlands with a relatively large (percentage) emergent or intertidal area and a relatively small (percentage) subtidal area often take the form of marshes interlaced with a dendritic network of channels. Flooding of the marsh surface in these types of wetlands may be by transmission of water through the wetland channels to interior areas or by submergence of the marsh and transmission of tidal waters over the entire marsh surface at higher tide stages. Channels in these types of wetlands are often highly sinuous (Fagherazzi, 2004) with widths and depths that usually decrease as distance from the channel mouth increases.

Influencing Factors: Channel morphology in tidal wetlands is influenced by many of the same factors that influence upland rivers and streams, but is complicated by the varying and dynamic nature of tides. Tidal range, regime (diurnal, semidiurnal, or mixed), and asymmetry determine the depths, durations, and frequencies for which various land-surface elevations are submerged. Tidal range and regime can be partially characterized by tidal datums, such as mean lower low water (MLLW), mean low water (MLW), mean tide level (MTL), MHW, mean higher-high water (MHHW), and mean spring high water (MSHW). These datums are determined and published by the National Ocean Service (NOS) for tide gauge locations around the United States. Tidal asymmetry can be estimated by comparing the relative times of high tides and low tides or by examining the tidal harmonic constituents calculated by NOS for various tide gauge locations.

The topography and elevation of the marsh surface (with respect to the local tidal datums), the marsh size, and the type of vegetative cover on the marsh surface all affect the boundary shear stresses in the wetland channels. These boundary shear stresses, and the marsh surface and channel bed and bank material characteristics, govern the potential for erosion and sediment transport throughout the wetland system.

Tidal Wetland Channel Design: In areas where tidal wetlands have been completely eliminated or severely degraded, the restoration (or creation) process involves designing, or at least anticipating, the locations, widths, depths, and sinuosities of the wetland channels. The wetlands may be designed and constructed to their planned final form prior to reintroducing tidal action or they may be only partially restored with the final wetland form shaped by the erosion and deposition of sediments that will occur after reintroducing tidal action. In the case of the tidal wetland that is constructed to its final or near final form prior to reintroducing tidal action, the channel design is critical to ensuring the wetland system is successful and does not dramatically change from its desired (and constructed) form. In the case of the tidal wetland that is only partially restored prior to reintroducing tidal action, understanding how the wetland channels will evolve and being able to accurately predict which areas of the wetland will experience significant erosion or deposition of sediments is also critical to a successful restoration project. For each of these cases, understanding how to design or predict the form of the wetland channels is essential.

General Assumptions: Several assumptions related to tidal characteristics, tidal currents, tidal prism, channel velocities and channel form are common, though not necessarily accurate, in tidal wetland channel design. Some of these common assumptions are:

- Horizontal tidal currents can be anticipated based on the rate of rise or fall of the tides and used to estimate the direction of net sediment transport (Walker, 1988),

- Peak velocities in a channel are uniform along the entire channel length for both ebb and flood flows (Pestrong, 1965; Myrick, 1963; Fagherazzi, 2004).

Ebb/Flood Dominance: Determining whether a tidal wetland is dominated by ebb or flood tides by comparing the rates of tidal rise to tidal fall assumes that the velocity of horizontal tidal currents is primarily due to the rate of change of the water level. While this may initially seem reasonable, analysis of measurements taken by NOS indicates it is not necessarily true. In its published tidal current tables, NOS (2005) explains that "the relation of current to tide is not constant, but varies from place to place" and that "the time of maximum speed of the current [does not] usually coincide with the time of most rapid change in the vertical height of the tide." Assuming flood or ebb dominance, based on predicted tides for a given location, can thus lead to incorrect conclusions that a wetland system experiences a net loss or gain of sediment due to tidal currents.

Empirical Relationships: Channel characteristics, such as width and depth, are sometimes designed based on empirically-derived relationships between tidal prism and channel width and depth (Coats, 1995). These relationships are similar to those developed in early work on upland rivers and streams that related drainage area or discharge to channel width and slope (Leopold, 1964 and Julien, 1995). Many of these relationships, however, fail to include such critical factors as bed material and bank material characteristics and the elevation of the wetland surface with respect to the local tidal datums. The result is that many of these relationships have extremely high levels of uncertainty associated with them and can, at best, only be used for very crude estimations of channel width and depth (Knuuti, 2000).

Application of Fluvial Hydraulics Methods: Stable channel design for stream and river restoration projects is often based on calculations of sediment transport over a channel's full range of discharges (Watson, 2005; Copeland, 2001; and Soar, 2001). This method involves using the channel bed material characteristics, the discharge hydrograph, and the physical features of the channel to design a stable cross section and planform. This method may also be applicable in tidal wetland channels, but is significantly complicated by the fact that the energy grade line of the water in the channels is constantly changing and reversing. Channel beds in tidal wetlands almost always slope down toward the channel mouths, but the energy grade line only slopes in this direction during an ebbing tide. During a flood tide, the energy grade line slopes is in the opposite direction. The result of this varying and reversing energy gradient is that bed material in a tidal wetland channel is alternately transported into (during a flood tide) and out of (during an ebb tide) the wetland channel. Stable design of a tidal wetland channel must take this into account in order to be effective.

ONGOING WORK

Background: Designing tidal wetland channels using a physics-based approach that is similar to the approach used in traditional fluvial hydraulics may allow designers to be more certain of their results than they would be using empirical relationships and general assumptions. This type of approach requires a thorough understanding of the hydraulic processes in tidal wetland channels. Various previous studies have examined suspended sediment processes (Ward, 1981), discharge asymmetries (Boon, 1975 and Reed, 1987), and velocity surges (Pethick, 1980) in tidal wetlands. None of these studies, however, have comprehensively examined the full range of physical processes, based on wetland characteristics and tidal range and regime, involved in tidal wetland channel hydraulics and stability. A new effort, under the U.S. Army Corps of Engineers' System-Wide Water Resources (research) Program (SWWRP), is beginning to study this range of physical processes in an attempt to better guide tidal wetland restoration projects.

Approach: Initial work involved collecting data for use in documenting and explaining the hydraulic processes in the wetland channels by measuring channels characteristics, water stage and water velocities at several locations, simultaneously, in several different tidal wetland channels. Tidal wetland channel planform was measured and recorded using newly collected, high-resolution, digital ortho-rectified aerial photographs. Tidal wetland topography was mapped using a combination of differential global positioning system (DGPS) and traditional (total station and optical level) surveying methods. Tidal wetland channel cross sections were surveyed at numerous locations and tied into the wetland topographic mapping. Vegetation types, within the wetland channels and on the marsh surface, were recorded and measured. Sediment characteristics, to include grain-size distributions for bed material, thickness of peat layers on the marsh surface, and organic content of bed and bank materials were recorded at each surveyed channel cross section. Water stage was monitored using both traditional staff gauges and acoustic water-level meters. Water-velocity profiles were recorded using bed-mounted acoustic Doppler current profilers (ADCPs). Some channels in the study areas were only surveyed, while others were surveyed and monitored for water stage and velocity. Each channel that was monitored for water stage and velocity had staff plates and ADCPs mounted at several locations simultaneously. ADCP time clocks were synchronized so both the temporal the spatial variations in the water levels and velocities could be determined. Tide and weather (wind speed and direction and barometric pressure) conditions were monitored at each location using newly installed weather stations and tide gauges.

Study Sites: Initial data collection efforts have been completed in four different tidal wetlands, all within New England. The wetland locations are in Wells, Maine; Seabrook, New Hampshire (Figure 1); Revere, Massachusetts; and Duxbury, Massachusetts. In each of these wetlands, numerous measurements of wetland topography and channel geometry have been made. More detailed data collection, to include water stage and water velocity profiles, has been completed in four of the surveyed wetland channels in Wells, Maine and Seabrook, New Hampshire. Although many of the tidal wetlands in New England have undergone severe ditching over the past century, as part of hay farming and mosquito-control efforts, the four wetland channels selected for detailed study are in areas that have never been ditched or otherwise altered by unnatural influences.

Figure 1 Tidal wetland in Seabrook, New Hampshire

<u>Methods</u>: After collecting aerial photographs and examining the wetland sites in person, the wetland areas were surveyed and sediment samples were collected. Several channels were selected and ranked in order of priority for more detailed data collection. Water levels and velocity profiles were monitored for periods of time varying from thirteen hours to five days, depending on how the times of high and low tide coincided with daylight hours. Each period of data collection closely coincided with a full moon, in order to obtain the highest tides and the best variation in successive high tides possible, in the shortest amount of time. With the sites all being in New England, detailed data collection efforts were also planned to avoid the extreme low temperatures that occur between December and March, due to equipment limitations and freezing water in the channels.

Tide gauges in the estuaries, but near the mouths of the channels, were used to measure the tide stage outside the wetlands. The varying tide stage at these locations is what drives the hydraulics in the wetland channels and can be used to examine water surface slope. After installing staff gauges at the desired channel cross sections, low-profile ADCPs were installed on the channel beds at low tide. Each channel studied had three to four ADCPs installed, at various locations successively farther up the channel from the mouth. ADCPs were installed in channel locations that appeared to be dominated by one-dimensional flows, along the channel axis, with minimal secondary circulation effects. These locations were determined by considering channel planform, channel cross-sectional geometry, and channel bed-form orientation. After installation, the ADCPs were surveyed to record their elevations and the staff gauges were monitored throughout the tidal cycle. ADCPs were removed during another low tide, at the end of the sampling period.

Data Collection: For each channel with detailed data collection, basic parameters such as wind speed, wind direction, and estuarine tide stage were recorded. Within the channels, water level, water-velocity profiles and water temperature were continuously recorded. In order to be able to assess the quality of the data collected with the ADCPs, the signal strength, acoustic backscatter, standard error, and flow direction were also collected and examined. ADCP data were sampled at a rate of 1 Hz and were later averaged over continuous 60-second periods to remove small-scale turbulent fluctuations and wind-wave effects.

Data Analysis: Prior to beginning field data collection, it was anticipated that the hydraulics in the channels would be driven by the long-wave mechanics associated with tidal propagation. For each of the channels studied, however, it was apparent that the time of slack water coincided almost exactly with the time of high tide. One possible reasons to explain this was that the small tidal channels may have attenuated the propagating tide wave enough to allow the time of slack water to coincide with the time of high tide. Because the channels were relatively short and because this attenuation and phase lag was not seen in the estuary near the mouth of each channel, an alternative explanation was considered. That explanation was that flow in the wetland channels was driven primarily by the head difference between the channel mouth and the upper reaches of the channel. If that was the case, it might be possible to consider the flow in the wetland channels to be steady, uniform flow and to apply the methods commonly used to examine sediment transport in rivers and streams to the wetland channels.

Considering the flow in the wetland channels to be steady and uniform seemed somewhat far-reaching, at first. The channels are not prismatic since they have horizontal banks and sloping beds and taper from wide mouths to narrow upper reaches in only a few thousand meters. Flow in the channels includes velocities that regularly change and water depth is constantly cycling from low tide to high tide. Still, the velocity changes, depth changes, and channel narrowing were gradual so quasi-steady, gradually-varied flow seemed possible. To test this assumption, the hydraulic grade line along a channel reach was assumed to be parallel to the energy grade line. The slope of this measured line, as it varied throughout a tidal-day in one-minute increments, was used along with the measured water depths to predict the mean water velocity in the channel, using Manning's equation. This series of one-minute velocity calculations was compared to the measured mean velocities, also in one-minute increments, in the same reach of channel. The agreement between measured and calculated velocities was quite good so the assumptions of head-driven, quasi-steady, gradually-varied flow were considered reasonable for basic analysis.

Data were then analyzed to determine how the constantly changing and reversing energy grade line affected boundary shear stress at the bed (bed shear stress) and sediment transport potential throughout a tidal cycle (one flood and one ebb). Bed shear stress τ_o was calculated using

$$\tau_o = \gamma R_h S_f \qquad (1)$$

where γ is specific weight of water, R_h is channel hydraulic radius, and S_f is energy slope. The median bed-material particle diameter was determined from the bed material grain size distribution and converted to a dimensionless particle diameter d_* using

$$d_* = d_{50}[(G-1)g/\upsilon^2_m]^{1/3} \qquad (2)$$

where d_{50} is the median grain diameter for the bed material, G is specific gravity, g is gravitational acceleration, and υ_m is kinematic viscosity of water. Shields parameter τ_* was then calculated using

$$\tau_* = \tau_o/[(\gamma_s-\gamma)d_{50}] \qquad (3)$$

where γ_s is the specific weight of a sediment particle. Shields parameter values were calculated for every minute of the measured tidal cycle and compared to the critical value of the Shields parameter to determine if the boundary shear stress was great enough to mobilize the median grain size of the bed. The critical value of the Shields parameter τ_{*c} was approximated using

$$\tau_{*c} = 0.25 d_*^{0.4} \tan\varphi \qquad (4)$$

where φ is the angle of repose for the median bed material size. The total time durations of the median bed material being mobilized during flood and ebb tides were then compared in order to provide a very quick estimate of whether the net time of transport was into or out of the wetland channels. This method is, admittedly, fairly crude but provided a relatively quick method for initial assessment and for assessing the feasibility of more rigorous methods.

INITIAL RESULTS

Velocities: Velocities in the tidal channels were generally asymmetrical about high tide for each cross section. All velocity plots were significantly different, in terms of asymmetry and surges, than the plots of predicted tidal currents in the estuaries near the mouths of the tidal channels. One important aspect of the channel velocities was the obvious surge in velocity corresponding to the time when the rising tide overtops the upper limit of the channel banks and begins to flood the marsh surface. A corresponding, though less intense, velocity surge occurs on the falling tide. This velocity surge can be clearly seen in Figure 2. In this figure, the thin horizontal line represents the channel bank elevation and the vertical red lines show how the time when the tide level meets the bank height corresponds to the surges in velocity. The intensity of this overbank velocity surge varied with maximum depth of water above the bank at high tide, and with location of the channel cross section. Initial analysis indicates the overbank velocity surges are less dramatic closer to the mouths of the channels. Mean channel velocities varied slightly with location along the channel axis, but not dramatically.

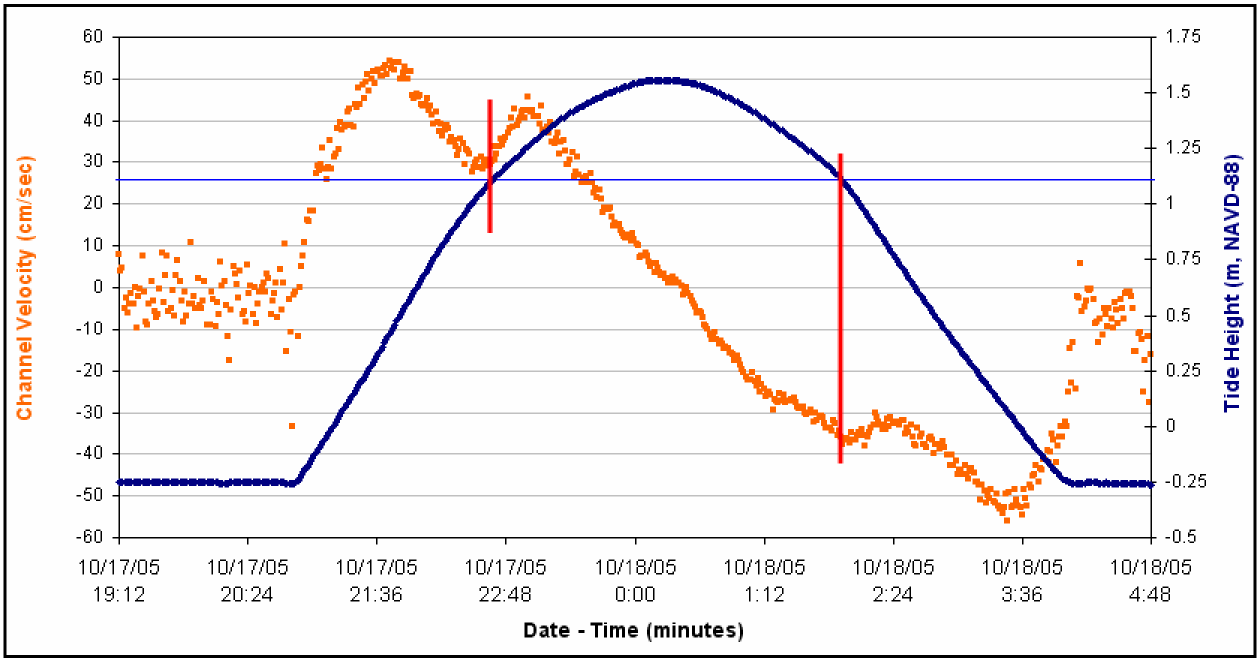

Figure 2 Mean channel velocity variations with time (Seabrook XS-B7)

Water Levels and Energy Gradients: Water levels varied both spatially and temporally throughout each wetland channel. With only small variations in velocity, the energy grade line closely paralleled the hydraulic grade line. Figure 3 shows the variation in the energy grade line at one channel cross section measured in the wetland in Seabrook, New Hampshire. Horizontal portions of the energy grade line, at the beginning, in the middle, and at the end represent times when the channel was dry or the water level was low enough that it could not be accurately measured. Short-term variability in the energy grade line, and spikes immediately adjacent to the horizontal portions of the plot, are due to noise in the data

Shear Stress and Sediment Transport: Preliminary calculations of bed material transport potential in the tidal wetland channels were based only on the median bed material grain size. Times of flood and ebb transport were used as a quick estimate of the direction of net sediment transport and were determined by comparing the total number of minutes when the Shields parameter exceeded the critical Shields parameter for the flood and ebb portions of the tide. For the two low-high-low tidal cycles recorded and presented in Figure 3 and Figure 4, the first cycle indicated a possible net sediment export from the channel with the time of sediment export exceeding the time of sediment import by 44 minutes. The second cycle of this series, however, indicated a possible net sediment import to the channel, with the time of sediment import exceeding the time of sediment export by 36 minutes. Together, the two low-high-low cycles had a net time of sediment export from the channel of only eight minutes, or very close to equilibrium. It is important to remember that the net volume of sediment transport may or may not be similar to the net time of transport into or out of the channels. To properly estimate net sediment transport volumes, sediment transport rates and distances would have to be considered, along with lengths of time for slack water periods, and transport would have to be calculated for much longer tidal cycles, such as the 365-day solar year or the 4.4-year lunar perigee modulation cycle. It is also important to note that the channels chosen for this study were selected, in part, due to their apparent long-term stabilities (based on aerial photo analysis and interviews with local residents) and equilibrium natures.

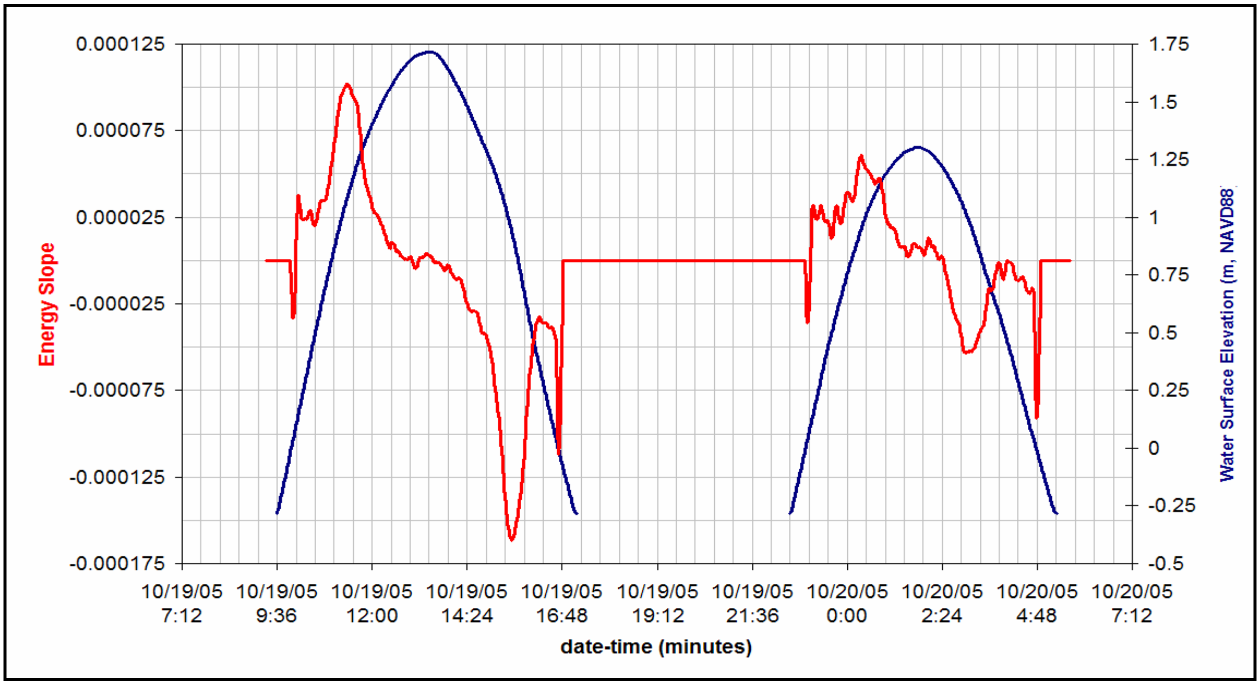

Figure 3 Energy grade line variations over two successive tidal cycles (Seabrook XS-A2)

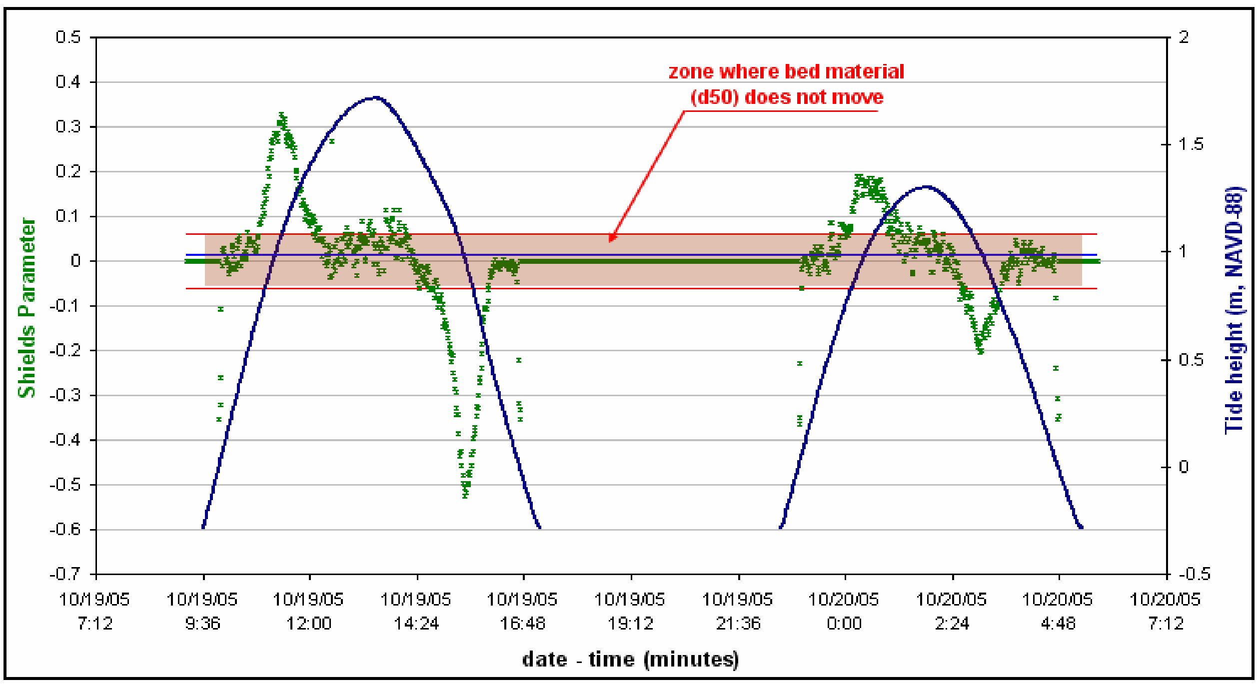

Figure 4 Calculated Shields parameter values compared to critical Shields parameter (Seabrook XS-A2)

FUTURE WORK

Data Analysis: Work on this topic should continue, under the SWWRP, for at least the remainder of this fiscal year and possibly throughout fiscal year 2007, as well. Initially, additional work will focus on continuing to analyze the existing data from the three study sites but using much more rigorous methods. In particular, the effect of tidal range (between different tidal datums) on velocity and shear stress will be examined as will the effect of changing bedforms (throughout the tidal cycle) on velocity profiles. Net sediment transport calculations will be expanded to include transport of the full range of sediment sizes present in the bed material. In order to improve on some of the geomorphic relationships between tidal prism and channel width and depth that have been developed by others, detailed calculations of tidal prism will be made and compared to several different channel cross sections.

Numerical Modeling: Numerical models of tidal wetlands are most commonly developed using estuarine circulation and water level models. Many of these models have difficulty modeling the processes in tidal wetlands due to rapid land surface variations and severe wetting and drying. Two numerical models have already been developed for the estuary in Seabrook, New Hampshire and will be modified in an attempt to see how well they can model the processes occurring in the tidal wetland channels. A third numerical model, which is currently under development at the U.S. Army's Engineer Research and Development Center, will be modified and used in an attempt to improve on the results currently possible with existing numerical models.

Use of Remote Sensing Data: Part of the data collection effort that has already been completed included collecting topographic and bathymetric LIDAR data for each of the study sites. The LIDAR data will be compared to the DGPS and traditional survey data collected at each site to determine how accurate the LIDAR system is for mapping ground elevations in densely vegetated coastal wetlands. If the LIDAR data proves to be reasonably accurate, it will be used to develop topographic maps of the wetland sites which will then be used for tidal prism calculations and numerical model development.

REFERENCES

Boon, J.D. (1975). "Tidal discharge asymmetry in a salt marsh drainage system," Limnology and Oceanography, 20(1), pp 71-80.
Coats, R.N., et. al. (1995). Design Guidelines for Tidal Channels in Coastal Wetlands. Unpublished report prepared for the U.S. Army Corps of Engineers Waterways Experiment Station.
Copeland, R.R., et. al. (2001). Hydraulic Design of Stream Restoration Projects. U.S. Army Corps of Engineers Report ERDC/CHL TR-01-28, Vicksburg, Mississippi.
Fagherazzi S., et al. (2004). "The effect of bidirectional flow on tidal channel planforms," Earth Surface Processes and Landforms, (29), pp 295–309.
Julien, P.Y. and Wargadalam, J. (1995). "Alluvial channel geometry: theory and applications," Journal of Hydraulic Engineering, ASCE, 121 (4), pp 312-325.
Julien, P.Y. (1998). Erosion and Sedimentation. Cambridge University Press. New York.
Knuuti, K. (2000). "Assessment of using hydraulic geometry relationships to estimate channel characteristics in San Francisco Bay coastal wetland restoration projects," U.S. Army Corps of Engineers internal report.
Leopold, L.B., Wolman, M.G., and Miller, J.P. (1964). Fluvial Processes in Geomorphology. Dover Publications, Inc., New York.
Leopold, L.B., Collins, J.N. and Collins, L.M. (1993). "Hydrology of some tidal channels in estuarine marshland near San Francisco," CATENA, Cremlingen, 20, pp 469-493.
Myrick R.M, Leopold L.B. (1963). "Hydraulic geometry of a small tidal estuary," U.S. Geological Survey Professional Paper 422-B.
National Ocean Service (2005). Tidal Current Tables 2005. International Marine. Camden, Maine.
Pestrong R. (1965). "The development of drainage patterns on tidal marshes," Stanford University, Publications in Geological Science (10).
Pethick, J.S. (1980). "Velocity surges and asymmetry in tidal channels," Estuarine and Coastal Marine Science, (11), pp 331-345.
Reed, D.J. (1987). "Temporal sampling and discharge asymmetry in salt marsh creeks," Estuarine, Coastal and Shelf Science (25), pp 459-466.
Soar, P.J., and Thorne, C.R. (2001). Channel Restoration Design for Meandering Rivers. U.S. Army Corps of Engineers Report ERDC/CHL CR-01-01, Vicksburg, Mississippi.
Walker, J.R., et al. (1988). "Hydraulic aspects of wetland design," Proceedings of the Twenty-first Coastal Engineering Conference, American Society of Civil Engineers, pp 2666-2680.
Ward, L.G. (1981). "Suspended-material transport in marsh tidal channels," Marine Geology (40), pp 139-154.
Watson, C.C., Biedenharn, D.S., and Thorne, C.R. (2005). Stream Rehabilitation. Cottonwood Research LLC, Fort Collins, Colorado.