HYDRODYNAMICS AND SEDIMENT TRANSPORT IN NATURAL AND BENEFICIAL USE MARSHES

A Thesis

by

VAISHALI KUSHWAHA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2005

Major Subject: Civil Engineering

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Approved by:

Co-Chairs of Committee,	Thomas M. Ravens
	Robin Autenrieth
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ABSTRACT

Hydrodynamics and Sediment Transport

in Natural and Beneficial Use Marshes. (August 2005)

Vaishali Kushwaha, B.E., Lalbhai Dalpatbhai College of Engineering

Co-Chairs of Advisory Committee: Dr. Tom Ravens
Dr. Robin Autenrieth

Since 1970, U.S. Army Corps of Engineers, Galveston District, has been using dredged sediments from the Houston ship channel to create and restore salt marshes in Galveston Bay. Some projects have failed due to excessive sediment erosion or siltation. The research reported here applies an engineering approach to analysis of tidal creeks in natural and beneficial use marshes of Galveston Bay. The hydrodynamic numerical model, DYNLET, was used to assess circulation in marsh channels. A preliminary sediment transport model was developed to analyze erosion and deposition for the same channels. *In situ* flume experiments were conducted to determine the sediment erodibility in natural and constructed marshes. A natural reference marsh, Elm Grove, was studied to understand marsh hydrodynamics and model calibration. The model results show that DYNLET can largely duplicate the marsh hydrodynamics and the sediment transport model can provide preliminary indication of erosion in tidal creeks. Analysis of the preliminary channel layout of the beneficial-use marsh demonstrated that channels will have sufficient circulation and optimum velocities.

For Mummy & Papa, the pillars of my life.

Bhai & Bhabhi, who supported me.

ACKNOWLEDGEMENTS

Many people have contributed to this study in many different ways. It would have been difficult to complete this work without their advice, assistance and support. First, I would like to express my gratitude to Dr. Tom Ravens, whose intellect, enthusiasm and assistance has made this research successful. I would also like to thank Dr. Robin Autenrieth and Dr. Ann Kenimer for their kindness in serving as co-chair and committee member on my thesis committee. I am very grateful for the encouragement and support of Dr. Vijay Panchang of Maritime System Engineering, TAMUG.

This thesis would not have been completed without the selfless input from Tarun Bhayia. His guidance, help and support made the task easier. I am grateful to Shipra Bhabhi for her understanding, care and hospitality. I also thank my dearest friends who stayed with me through all my ups and downs.

During this research, much help came from discussions of numerical modeling with Dr. Zeki Demirbilek (of engineering research at Waterways Experiment Station) and Doncheng Li; a special thanks to them. I am thankful to Maelinda Sheperd, MASE department secretary, who has answered my every call for help. I greatly appreciate the help and assistance we received from all the high spirited TAMUG students and staff on our field trips.

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INTRODUCTION

Background

Wetlands are amongst the most important ecosystems on the Earth and are often described as “the kidneys of the landscape” for they cleanse polluted waters, prevent floods, protect shorelines, and recharge ground water aquifers (Mitsch, 1986). Salt marshes are tidal wetlands typically occurring in high salinity area along protected estuarine shoreline (Salvesen, 1990; Lester and Gonzalez, 2002). Marshes play several key ecological, biological and hydrological functions in protecting and maintaining the health of estuary ecosystem (Lester and Gonzalez, 2002). Three-fourths of the estuarine wetlands in United States are salt marshes (Dahl and Johnson, 1991).

Salt marshes of Galveston Bay, Texas, are unique environments that house indigenous coastal plants and offer a nutrient rich arena that nurtures juvenile marine organisms such as shrimp, oysters, crabs, and numerous fishes (Lester and Gonzalez, 2002). Migratory shorebirds, wading birds and waterfowl depend on these marshes for feeding, breeding and wintering habitat (Lester and Gonzalez, 2002). Pulich and Hinson (1996) accounted for approximately 33,775 acres of salt marshes in Galveston Bay. But decades of human activities and developmental pressure has destroyed or reduced much of the Bay’s tidal wetlands. The Galveston Bay salt marshes have decreased by 21% from the 1950s resource level (White et al., 1993). Subsidence due to oil, natural gas and

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This thesis follows the style of *Journal of Environmental Engineering*.

groundwater withdrawal, rise in relative sea-level, shoreline erosion and land development are foremost causes of marsh disappearance (White et al., 1993).

In the present scenario of re-establishing and restoring wetlands has become vital in maintaining Galveston Bay's economic benefits, fish and wildlife resources, and aesthetic qualities. Wetland creation is among the few options available to offset the loss of tidal wetlands. One way of creating tidal wetlands is through the use of dredge material. Marshes constructed from dredged material are often referred to as beneficial use marshes. Since 1970, the U. S. Army Corps of Engineers have used dredged material from the Houston ship channel to restore and construct salt marshes in Galveston Bay (Streever, 2000). However, until now it has not been possible to completely duplicate natural marsh habitats in terms of hydrology, geomorphology, productivity and sustainability. This inability to duplicate the natural salt marsh is due to the complexity of these ecosystems. The demonstration marsh by Atkinson Island and the West Bay beneficial use marsh by Chocolate Bayou highlighted the problems of siltation and insufficient flushing and subsequent closer of channels (Ravens, 2003).

Tidal hydrodynamics, sediment transport, geomorphology, drying and flooding patterns, water and soil salinity, and substrate condition are the driving forces for wetland development and functioning (Mitsch and Gosselink, 1993; Callaway, 2000). For any wetland creation and restoration to provide habitat support and other functions, appropriate hydrology must be established (Callaway, 2000). However, limited information is available on design criteria of tidal wetland created with dredged material. In most of the cases reported, a nearby natural marsh is compared as a reference marsh.

The marsh elevation, creek characteristics (depth, slope, density, sinuosity, etc.) and other hydrological parameters are designed purely on the basis of reference marsh survey. Mitsch and Wilson (1996) stated that the best designs encourage processes that enable the system to develop itself, rather than trying to duplicate an existing natural marsh. The outcome of a created marsh is the least predictable as its hydrology, soil and other physical parameters might not match those of natural marsh (Callaway, 2000).

Purpose of Study

The purpose of this research is to provide an engineering perspective to the design and development of marsh channels in beneficial use marshes. The tidal creeks will be evaluated on the basis of water circulation and sediment erosion/accumulation. The research will help understand hydrodynamics and sediment transport in reference as well as beneficial use marshes with the help of mathematical models.

Objective of Study

The primary objectives of this study are:

1. To perform field surveys in reference and beneficial use marsh for studying tidal creek geometry and hydrodynamics.
2. To develop and field test DYNLET, the circulation model, and sediment transport model for reference and beneficial use marsh in Galveston Bay.

3. To test sediment erodibility as a function of current strength in reference and beneficial use marsh with *in situ* flume.
4. To evaluate tidal creeks for sufficient circulation, optimum velocity and sediment stability using DYNLET and sediment transport model.

Research Procedure

This study will be conducted through several steps as follows:

Step 1

Perform bathymetry survey and develop DYNLET model for one of the tidal creek systems in the reference marshes of Galveston Bay. This model will find how closely the creek hydrodynamics can be duplicated from numerical point of view.

Step 2

Collect water level and depth average velocity data from reference tidal creek and use this field data for model calibration.

Step 3

Perform *in situ* flume experiments in reference marsh to determine sediment erodibility.

Step 4

Develop sediment transport model to predict erosion and deposition in tidal creeks. Sediment properties determined from flume experiment will be used to calculate the model constants.

Step 5

Perform *in situ* flume experiments in beneficial use marsh to determine erodibility of dredged sediments.

Step 6

Evaluate tidal creeks of beneficial use marsh and reference marsh using hydrodynamic and sediment transport model. Determine the creek stability on the basis of flow rate and sediment erodibility.

Previous Research

In the initial step of this study, attempts were made to collect as much information from the previous related research as possible in order to better understand the problem at hand and to find a better strategy to solve them. Little research has been conducted on design and development of artificial marsh hydrology. However, the researches that were most pertinent were studied in detail and used for guidance.

Callaway (2000) extensively studied the hydrology and substrate conditions in coastal wetlands. Based on this study general design and development considerations for restoring and creating wetlands were provided. The study emphasized wetland hydrology as it determines conditions for sediment erosion and/or accumulation, which in turn affects the substrate conditions at a given site. Characteristics of tidal creeks and channels were observed and were found to be a function of wetland area and local tidal regime. Tidal prism (the volume of water that flows in and out of the system on a tidal cycle) was found to be an important consideration as a reduced tidal prism decreases the velocity of tidal water at inlet causing sedimentation and hence reductions in channel cross-sectional area. It was recommended that configuration (size and cross-section) of creeks should be based on reference creek morphology, dynamics of erosion and accretion be understood and stable elevation of the marsh plain be established. Lack of research in engineering and construction methods of creeks and in evaluation of the creek networks was also mentioned.

French and Stoddart (1991) studied the north Norfolk marshes of England to investigate the fundamental processes of water movement and sedimentation as a precursor to understanding their function in relation to problems in coastal geomorphology, ecology and protection. They synthesized the understanding of Norfolk salt marsh creek hydrodynamics to generalize the ideas for universal application. They also examined the entrainment and transport of creek sediments. Finally magnitude and direction of total sediments via the creek system were measured to assess utility of this approach for estimation of material budgets in general. The study concluded that tidal channels in vegetated marsh substrates are characterized by a high degree of flow unsteadiness. Flood and ebb velocity transients differ in magnitude. Also, the combined effect of one-dimensional flow in creek and two-dimensional circulation over the marsh surface results in opposite net transports of sediments.

Christiansen *et al.* (2000) determined specific sediment transport patterns and shear stresses acting on the marsh surface as a function of time and distance from the tidal creek. They characterized the dispositional processes on surface of Philips Creek marsh, on the Atlantic coast of Virginia (U.S.A), using measurements of sediment concentration, flow velocity, turbulence, water surface elevation, marsh surface topography and particle size distributions of marsh surface sediments. Slightly higher velocities were observed during falling tides suggesting ebb dominated tidal asymmetry. Sediment concentrations were found higher on creek bank than in marsh interior. It was found that deposition occurred on the marsh surface during rising tide and was largely because of flocculation of fine sediments. They also observed that the processes controlling sediment deposition did not vary among tides. However, suspended sediment concentration near the creek banks increased with increasing tidal amplitude.

Wood and Widdows (2002) compared modeled biotic and physical effects on intertidal sediment transport, using parameterizations that were based on laboratory and field experiments. The model combined a simple one-dimensional onshore-offshore model of water movement with a semiempirical model of cohesive sediment erosion and deposition. Tidal currents were used as fundamental forcing and affect of biota on erosion response to particular tidal forcing was also considered. The studies determined that the changes in erosion or deposition caused by natural variation in biota densities were as large as those caused by changes in tidal range and currents over a spring-neap cycle. The results showed that biotic influences on transport of sediment within the intertidal zone were significant and played a significant role in determining sediment budgets over tidal to monthly timescales.

Montalto *et al.* (2002) illustrated the effect of several restoration scenarios on hydrology patterns in a tidal marsh. An analytical wetland hydrology model was used along with observations made at Piermont Marsh at New York Estuary. Given a series of physical and time-dependent inputs, the model predicted water surface elevation at points along a transect perpendicular to a tidal creek. Four critical parameters (the substrate tranmissivity, the substrate porosity, the average marsh elevation and the marsh width) were varied, one at a time, to determine the deviation from original prediction. The model predicted that the elevation of the marsh surface determines the frequency of marsh inundation, i.e. the higher the marsh surface the less frequently the marsh will be flooded and vice versa. The rate at which marsh lost water was found to be related to tranmissivity of the substrate. The model was found to be most sensitive to average marsh surface elevation. The study demonstrated various physical parameters that affect the hydrology of tidal marshes. The research provided an analytical tidal marsh hydrology model to investigate the casual relationship between limited set of tidal, topographic and climatological factors in determining the spatial and temporal subsurface hydrology characteristics of wetlands.

SITE DESCRIPTION

Galveston bay system is a 1,554-km^2 estuary situated in southeast Texas (Delaney et al. 2000). The system is composed of four bays: East Bay, West Bay, Galveston Bay and Trinity Bay, and includes numerous other small embayments. It is a wonderfully complex system and is also the largest and most biologically productive estuary in Texas (Lester and Gonzalez, 2002). Galveston Bay receives freshwater flow from the San Jacinto River, Trinity River and other local streams (Galveston Bay Information Center, 2005). Bay's inflow of tidal water comes from the Gulf of Mexico through Bolivar Roads and San Luis Pass. The bay is separated from the Gulf of Mexico by the Bolivar Peninsula, Galveston Island and Follets Islands.

The estuary is ecologically subdivided in Open-Bay Water, Open-Bay Bottom, Oyster Reef, Seagrass Meadow and Wetlands (Lester and Gonzalez, 2002). The Bay itself, its tributaries, wetlands, trees, and land all provide homes, protection, or food for a diverse wildlife community, plant species and other organisms. The mean high water (MHW) in Galveston Bay occurs at 2.70 feet MLT while the average of the mean low water (MLW) occurs at 1.65 feet MLT (Turner Collie and Braden Inc., 2002). Therefore the tidal range in Galveston Bay is 1.0-1.5 feet. The marshes under consideration are in lower Galveston Bay, northwest of Bolivar peninsula (Fig. 1).

Elm Grove: The Reference Marsh

Elm Grove is a low, inter-tidal salt marsh towards bayside of Bolivar peninsula. The 27 mile long Bolivar peninsula runs northeast. The south or beach-side of the peninsula

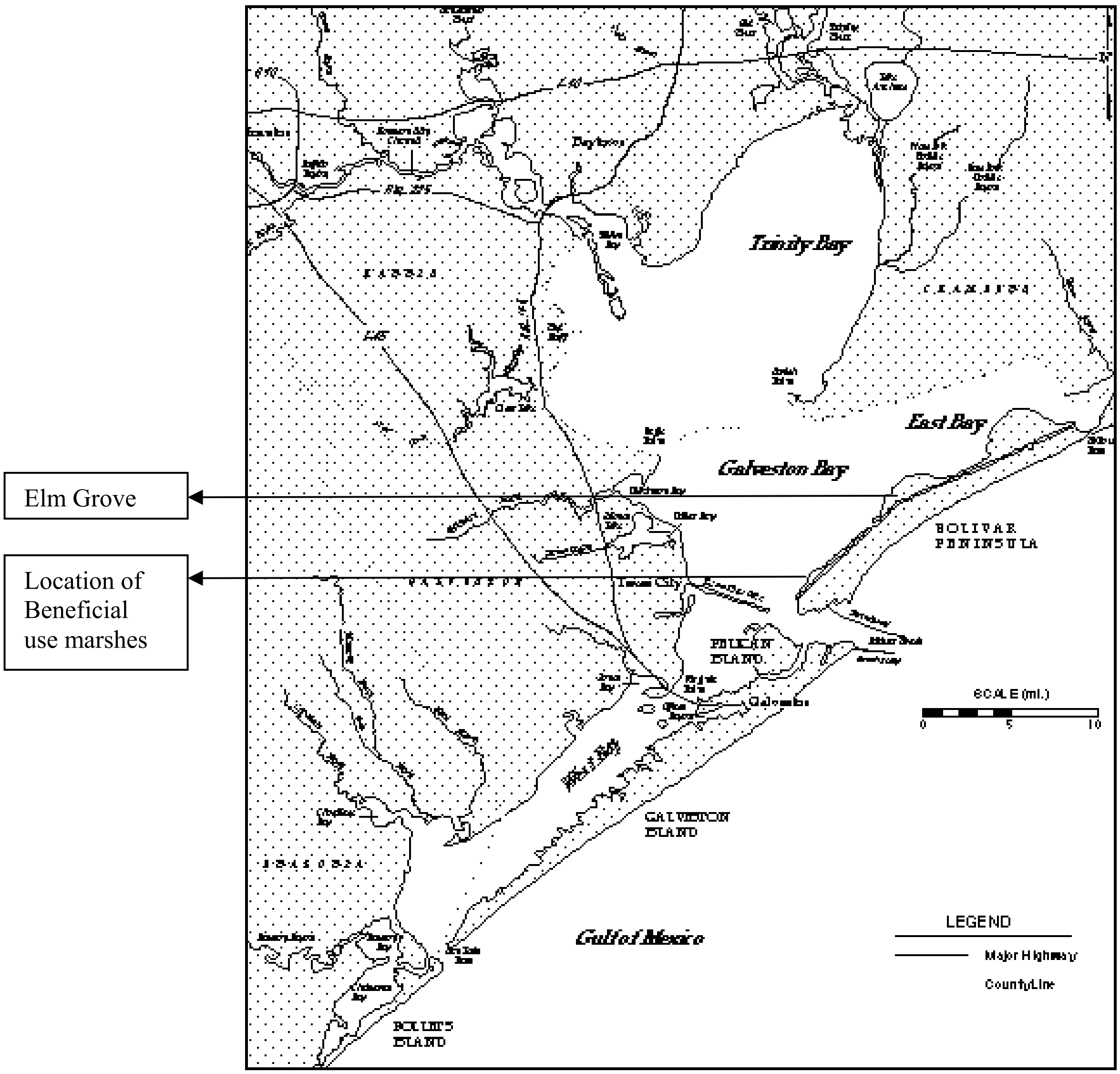

Fig. 1. Site location in Galveston Bay
(Adapted from The University of Texas
http://www.tsgc.utexas.edu/topex/buoy/pics/galvestonbay.gif)

fronts the Gulf of Mexico and the north or backside that faces Galveston Bay is protected by inter-tidal marshes. Elm Grove has a surface area of about 9km^2. The marsh surface is inundated at least once a day and reflects Galveston Bay tidal cycle. The overall creek layouts are sinuous as the channels and creeks meander through a majority of the marsh area. It is dominated by *Spartina alterniflora* and gets its name from nearby elm woods. The marsh provides critical habitat for large number of shorebirds, waders and ducks. Large number of juvenile Crabs, Redfish, Flounder and Specked Trout also occupy this marsh (Lester and Gonzalez, 2002). Elm Grove has six dominant channel systems also called reference channels. These channel systems are highly sinuous and are supported by numerous ponds. For this research one of the primary channels called "channel system I" has been characterized. The channel system I is approximately 160 acre in area and it has one main channel, 5250 feet long and 55 feet wide (Turner Collie and Braden Inc., 2002). The channel density (number of channels per Acre) is 2 and pond density (number of ponds per Acre) is 13 (Turner Collie and Braden Inc., 2002). The main channel is supported by 84 tributary creeks and the marsh to open water ratio is 2:1(Turner Collie and Braden Inc., 2002).

Around 94.59 percent of Elm grove sediments constitute of size 0.43mm or smaller (Fig. 2). The bulk density for sediments in channel system I is 0.77 g/cm^3. Research related field measurements were performed for channel cross-section, water surface elevation, velocity and turbidity. Flume test was performed at the channel entrance in order to obtain *in-situ* sediment erodibility.

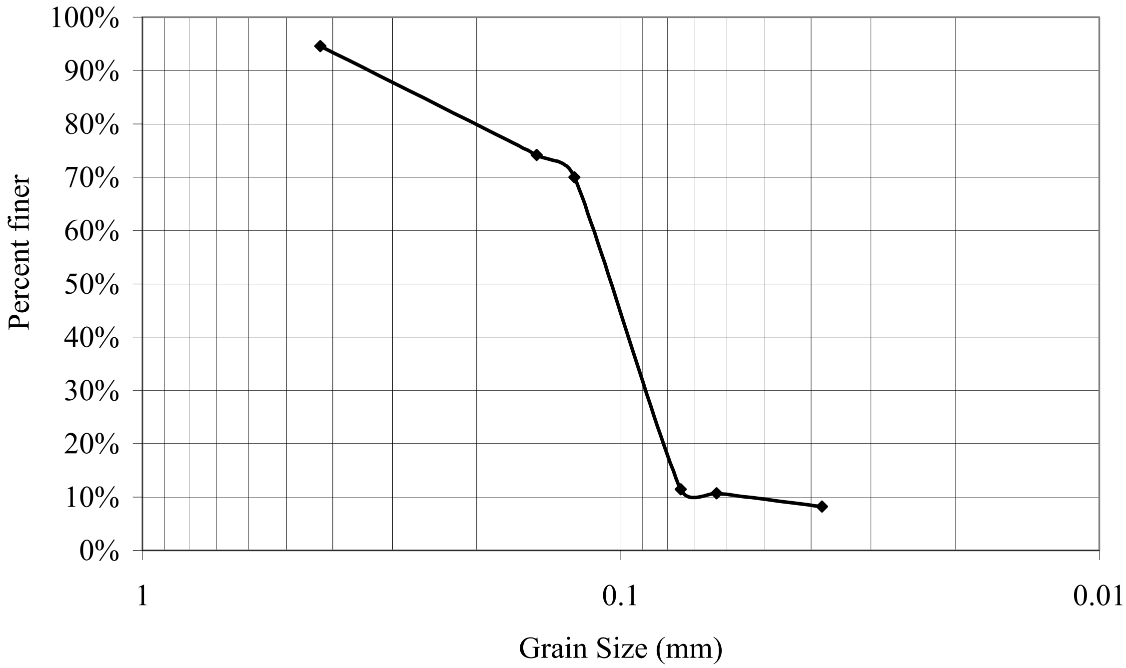

Fig. 2. Grain size distribution for Elm grove sediments

Bolivar Beneficial Use Marsh: The Constructed Marsh

The Bolivar beneficial use marsh is typically a tidal marsh constructed from dredged material of Galveston ship channel. It is getting constructed on bayside of Bolivar peninsula near the Bolivar roads entrance (Fig. 1). The marsh is constructed in form of three cells: Cell 1, Cell 2 and Cell 3. The placement of dredged material started in 1993 and till date the marsh sediments are in settling phase. The marsh sediments are supported and enclosed by exterior levee. The target marsh surface elevation is in range of 2.11 feet to 2.66 feet MLT (Turner Collie and Braden Inc., 2002). The design water depth across the average marsh surface is 0.5 to 1.5 feet deep (Turner Collie and Braden Inc., 2002). Cell 1 has two spillboxes which are closed in order to pond water and enhance settlement of the sediments. Cell 2 has an opening for maintaining tidal circulation but channels have not been constructed in either of the cells. The Beneficial Use Group (BUG) has come up with an extensive channel layout which includes primary channels, secondary creeks and ponds, for Cell 1. The design is inspired by a nearby Lower Galveston Bay reference marsh, Elm Grove. No specific design is available for Cell 2 and Cell 3, but over the past few years a natural channel (channel CC) is developing in Cell 2. Also, some initial pond developments have been observed in Cell 1. Cell 1 and Cell 2 are scarcely vegetated and work as feeding grounds for some local birds.

The subsurface materials consist of medium dense silty sands, shell and very soft clays but the profile varies depending on the location (HVJ Associates Inc.). The bulk density of sediments in Cell 2 was determined as 0.95 g/cm^3. The void ratio in beneficial use marsh was found lower than that in Elm grove (HVJ Associates Inc.). These finding are consistent with the bulk density measurement in Cell 2 i.e. the bulk density in beneficial use marsh is greater than in Elm grove (0.77 g/cm^3).

For the research purposes primary channels of Cell 1 and natural channel of Cell 2 are studied. Cell 1 is 314 acre in size and is proposed to have a channel density of 2.3 (Turner Collie and Braden Inc., 2002). The marsh will initially be supported by two 3000 (Channel BB) and 9000 (Channel AA) feet long main channels (Figure 3). The channels will be 90 feet wide at the mouth and -3 feet deep. The main channel width will taper very gradually as it extends back into the marsh (Fig. 3). There will be approximately 80 tributary creeks and 2100 ponds. The designed marsh to open water ratio is 3:1 (Turner Collie and Braden Inc., 2002).

Preliminary field survey was performed in order to study and observe the developing marsh system in Cell 2. Sediment samples were obtained from this site for determining dredged sediment properties. Flume test were performed at the opening of Cell 2 in order to test the erodibility of dredged sediments.

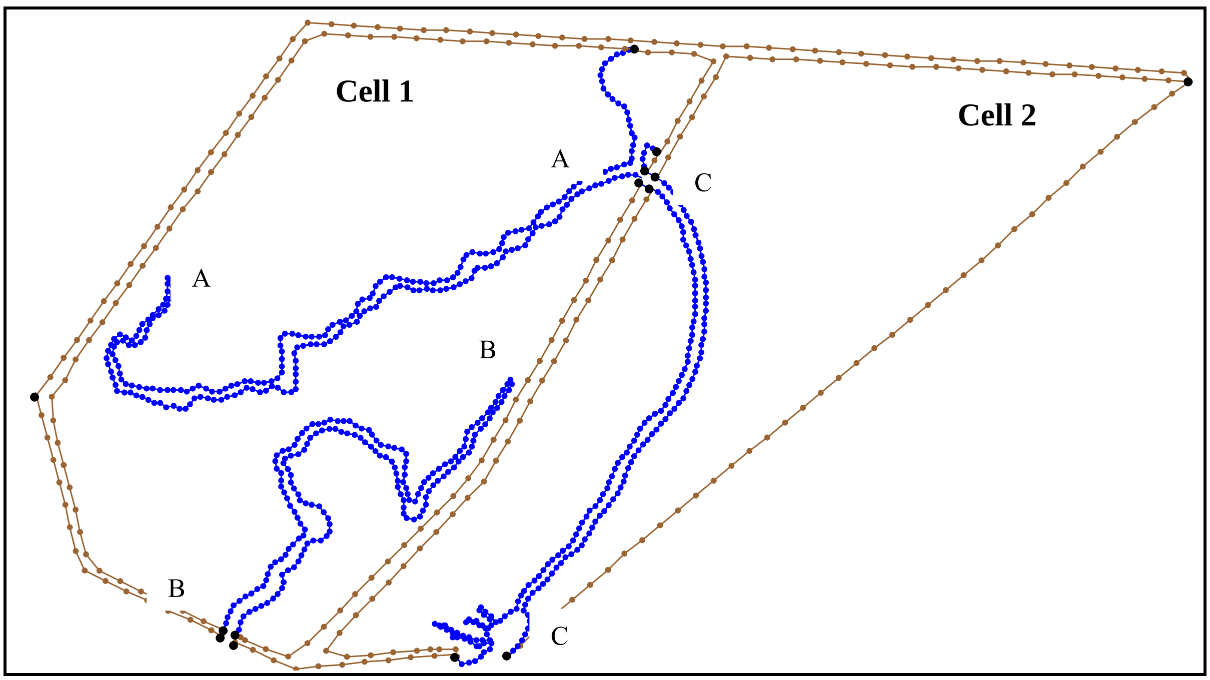

Fig. 3. Cell1 and Cell 2 of beneficial use marsh with proposed channel layout (Adapted from ADCIRC Model)

HYDRODYNAMIC MODEL (DYNLET)

DYNLET is an acronym that stands for Dynamic Behavior of Tidal Flow at Inlets (Cialone and Amein, 1993). DYNLET is one of the general engineering modules of Coastal Engineering Design and Analysis System (CEDAS). It predicts water surface level and tide dominated velocities at inlet, interior Back Bay systems, channel flow in river and estuaries. The model is applicable to tidal flow, flows in lakes and reservoirs, river flow, and wave motion where the wavelength is significantly greater than the water depth. DYNLET solves one-dimensional shallow water equations using an implicit finite difference technique and provides detailed velocity information across channels. The model is generally used for design-level studies for most inlets and provides reliable and accurate answers while requires minimal data.

In this research DYNLET was used to study circulation and determine depth average velocities in the marsh channels. The marsh under consideration has narrow marsh channels and shallow water depths. The detailed bathymetry was unavailable for the whole marsh area. Under such circumstances one-dimensional DYNLET model easily duplicated the channel system and fulfilled the need of preliminary hydrodynamic study. One of the drawbacks with one-dimensional modeling was the failure to duplicate the bends in channels. The channel bends are characterized by change in flow direction and normal stress in addition to shear stress. The normal stress would lead to enhanced erosion and this can not be easily accounted for with DYNLET. In order to reduce the error and overcome this inability the nodes (predefined cross-sections) in these areas were placed closer. Also, the energy loss accompanying the sudden change in expansion or contraction of flow area was reproduced by providing transition loss coefficients. Loss coefficient equal to 0.5 was used at the entrance of marsh channel (Cialone and Amein, 1993). Unlike marsh channels the marsh surface is densely vegetated and provides resistance to flow. This phenomenon was imitated by providing a higher Manning's coefficient (generally 0.4 for marsh surface) to stations situated on marsh surface. This increased the bottom stress and hence the resistance to flow. DYNLET is also inadequate for calculating effect of time varying wind on tidal currents. But a wind drag coefficient can be provided to the model for including the wind effects.

Model Equations

The shallow-water hydrodynamic equations used for one-dimensional depth-averaged flow consist of the equations for the conservation of mass, momentum, and energy. For most applications, the conservation of momentum and conservation of energy equation produce identical results. The momentum and mass equations used for describing flow at tidal inlets are written as

$$\frac{dQ}{dx}+\frac{d}{dx}\frac{Q^2}{A}=-gAS_f+aB\tau_z-gAS_c-gA\frac{dz}{dy} \quad (1)$$

$$\frac{dQ}{dy}+\frac{dA}{dt}-q=0 \quad (2)$$

where

Q = volume flow rate

t = time

y = horizontal distance (along a channel)

A = cross-sectional area

g = acceleration due to gravity

S_f=friction slope

B = width of top of channel cross section

τ_z= surface shear stress due to wind

S_c = transition loss rate with distance

z = water surface elevation

q = lateral inflow or outflow per unit channel length per unit time.

Eqs. (1) and (2) are also known as the one-dimensional shallow-water equations or the one-dimensional long-wave equations (Cialone and Amein, 1993). The equations constitute a system of nonlinear first order hyperbolic partial differential equations that are solved numerically for arbitrary bathymetry and forcing conditions.

Numerical Solution

To solve a DYNLET model of a complex inlet consisting of interconnecting channels and bays, three type of information is required:

a. Identification of interior points.

b. Specification of external boundary conditions.

c. Specification of junction conditions.

The components of numerical model involving interior points of channels are obtained by replacing partial derivatives in Eqs. (1) and (2) with finite differences. Known water surface elevation and/or flow rates at external points work as boundary conditions. A junction is created if two or more channels meet. A two-channel junction need not be specified while a three-channel junction provides three equations for the inlet system.

Each node has two unknowns, the flow rate Q and the water surface elevation z. For N nodes in an inlet system, the total numbers of unknowns are 2N, thus, 2N equations are needed to determine values of the unknowns. The finite difference representations of the shallow-water equations with the boundary conditions and the junction conditions constitute a system of 2N nonlinear algebraic equations. To solve these equations DYNLET uses the generalized Newton-Raphson iteration method (Cialone and Amein, 1993). Iteration is continued until the differences in water surface elevation and discharge between successive iterations at any node fall below specified tolerance values.

Data Collection

The first bathymetry survey for channel system I in reference marsh was carried out in August 2004. The depths along the length of channel were measured using GPS and depth sounder system. Measurements were made for initial one-third length of marsh channel as the water beyond was too shallow for boat maneuvering. Also the depths across the section were not measured as the channel was not wide enough to accommodate transverse boat movement. The horizontal measurements were made in UTM NAD83 (zone 15) and the vertical measurements were referenced to local water level. On October 2004 depth measurements were made at nine cross sections along the initial one-third length of the channel (Fig. 4). The measurements were carried out manually on a crude basis. Another bathymetry survey was conducted in May 2005 using GPS and depth sounder system which measured the cross sectional depths along the last two-third section of the marsh channel.

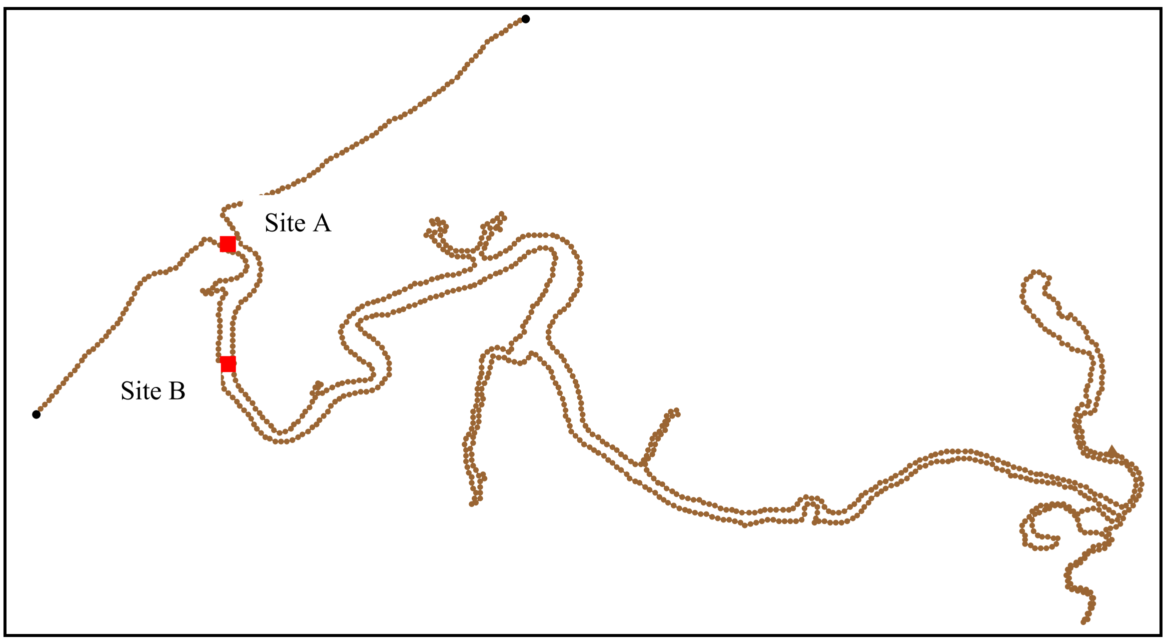

Fig. 4.Channel system I in reference marsh: Elm grove
(Adapted from ADCIRC Model)

Water velocity, pressure and turbidity measurements were made during a 24 hour period in October 2004 at site A (Fig 4). A Norteck 3D acoustic doppler velocity-meter

(ADV) recorded velocity at 1Hz at every second for 24 hours. The East(X), North(Y) and Vertical (Z) velocity, pressure and turbidity measurements were made using three beams. An optical backscatter (OBS) meter was used for measuring turbidity and suspended solids in the marsh creek. Water samples were taken along the experiment for comparison and calibrations. Another velocity meter was deployed at site B on May 2005 for 26 hour period. This time a Norteck acoustic doppler current profiler (ADCP) was used. The measurements were taken at every 5 sec at a sampling rate of 1Hz. In order to obtain the vertical distribution of velocity the channel was divided vertically in 10 cells of 10cm each. The first bin started at 21cm above bottom.

The bathymetry data collected for reference marsh channel was used to develop model grid. The turbidity measurement along with velocity magnitude was used to observe sediment erosion in channel bottom. The water elevation and depth averaged velocity were compared with model results and were used for model calibration.

Model Development

The DYNLET model for reference marsh included the Galveston Bay and Channel system I. The bay and marsh area hydrodynamics was replicated with help of 9 channels and 4 junctions (locations where channels meet). The model consisted of 67 nodes (locations where cross-sections are defined) out of which 44 were in Bay and the rest 23 were used to define the Channel system I of Elm groove. The geometry/cross-section was defined at each node with help of closely packed stations. Numbering of the nodes was done by assuming the initial flow direction at beginning and end of each channel. Nodes 1, 9, 21, 32, 40 and 67 served as exterior nodes (nodes at which data are introduced to drive the model). Node 1 was placed at the entrance of Bolivar road/Galveston ship channel entrance because a tide gauge is installed at this location (Fig. 5). This tidal gauge reading of water surface elevation served as boundary condition and was used to drive the model. Node 45, defines the channel system I entrance, was used as a representative node for understanding the marsh hydrodynamics. Node 49 was placed in the marsh channel at the location where velocity sensors were dropped for water elevation and velocity measurements (Site B). This node's output is used to compare and calibrate the DYNLET model with field measurements.

The model grid was developed using a coordinate system (x,y) with the x-coordinate defining the channel cross-section and the y-coordinate defining distances in longitudinal direction i.e. in direction of flow. A hydrographic map of Galveston bay was used to determine locations of cross-sections. Variable distances x and y were used to obtain realistic representation of the system and closely spaced distances were used where significant changes in geometry occurred.

Every grid point on the map represents a node and a cross-section is defined at each node. Inlet geometry (distance and elevation) and bottom friction coefficients were provided at each cross-section. The depth data for Galveston bay was obtained from National Oceanic and Atmospheric Administration (NOAA). The geometric data for the marsh channel was obtained from the preliminary field surveys. Manning's friction coefficient was specified at every point on a cross section. Previous studies, experience and judgment was used to determine the friction coefficient as 0.025 for water channels and 0.4 for marsh surface. (Publications by the U.S. Geological Survey and U.S. Army

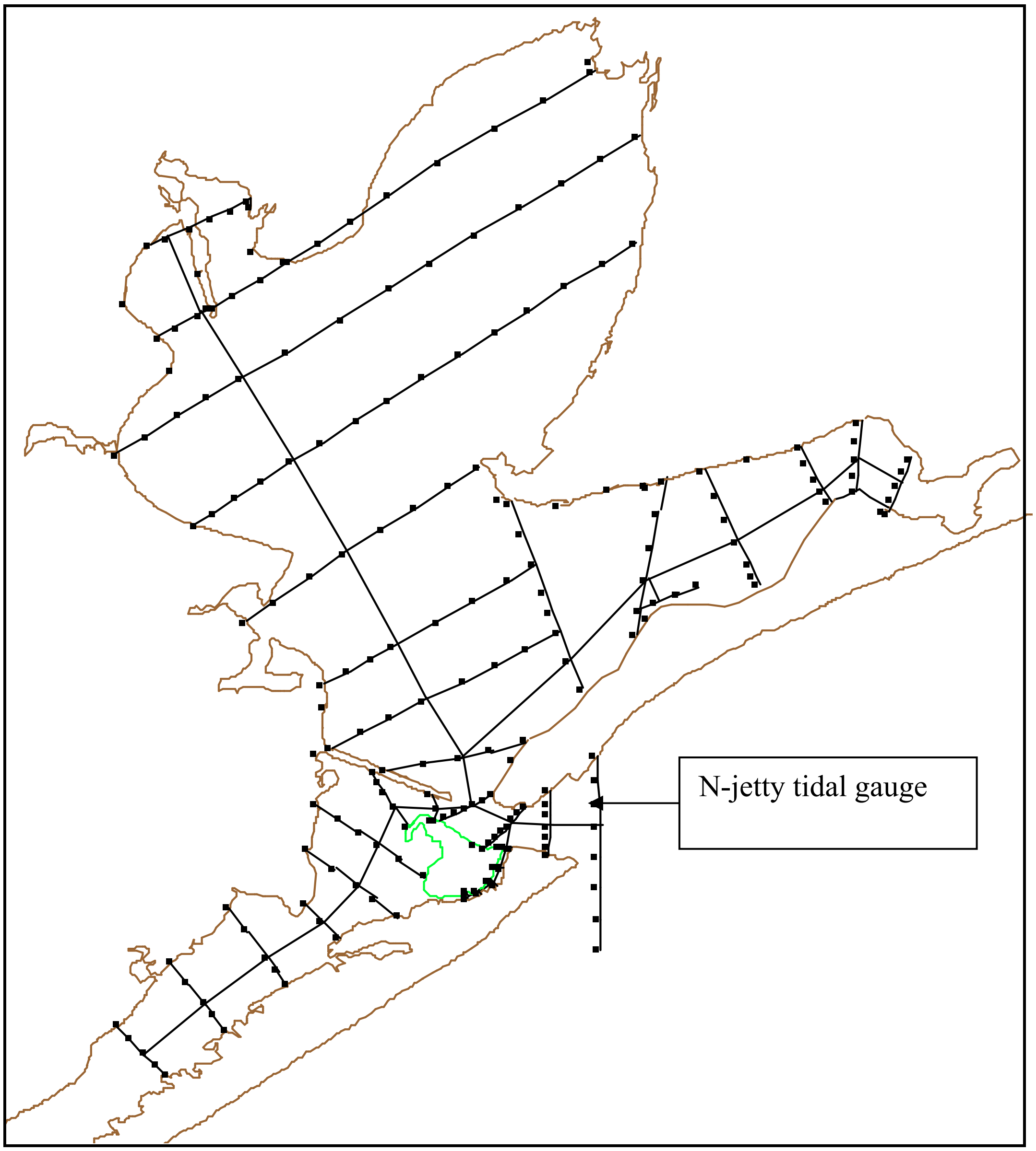

Fig. 5. Location of nodes in Galveston Bay
(Adapted from ADCIRC Model)

Corps of Engineers provided excellent guidelines). Time varying water surface elevation from N-jetty tidal gauge was used as external boundary condition to drive the model.

A similar model was developed of beneficial use marsh at Bolivar. The preliminary channel layout prepared by Turner Collie and Braden Inc. (2002) for BUG was used to develop DYNLET model. The channel BB entrance of cell 1was designed as 90 feet wide and 3 feet deep. The channel CC of cell 2 was 100 feet and 4 feet deep at entrance. The constructed marsh hydrodynamics was replicated using 11 channels and 5 junctions. The model consisted of 82 nodes with 40 nodes defining the Bay area and 42 defining the beneficial use marsh. Nodes 1, 9, 21, 32, 52, 72 and 82 served as exterior nodes with water elevation specified at node 1. As the design parameters for beneficial use marsh are influenced from Elm grove marsh and the final performance criteria is also based on reference marsh characteristics, the DYNLET model parameters were the same as used for reference marsh model. Also, DYNLET model represents the future of beneficial use marsh which assumes vegetation on marsh surface and designed tidal creeks. Hence the Manning's coefficient and transmission loss coefficient used were also same as that for reference marsh model. N-jetty data was used to drive the model.

Results

Field Measurements

The pressure data from both the site A and B of reference marsh channel demonstrated a smooth, well formed, diurnal tide with approximately 24 hour tidal cycle (Fig. 6 and 7). The measured water surface elevation showed fluctuations which can be the result of wind. Further research is needed in order to understand this phenomenon. Higher tidal elevations were observed in the month of May than in October. This represents the influence of seasonality on tides. Also, the velocity-meter deployed in October 2004 was near a channel bend and sank considerably in marsh bottom. Therefore the velocity-meter was measuring velocity close to the bottom resulting in lower measurements. The depth average velocities varied corresponding to water elevation. A sudden jump in velocity was accompanied by sudden changes in water elevation. Eighty-five percent of the velocity at site-A lay between 0.02-0.2 m/s and occasionally were higher than 0.25 m/s (Fig. 8). Elevated velocities were observed at site-B in month of May. The maximum velocity was approximately 0.55 m/s while sixty-five percent of velocities were in the 0.07-0.2 m/s range (Fig. 9). The exceptionally high velocities were supported by increased wind speed measured at Eagle point in bay area (National Data Buoy Centre, 2005). These simultaneous events indicate the influence of wind on tidal currents in marshes.

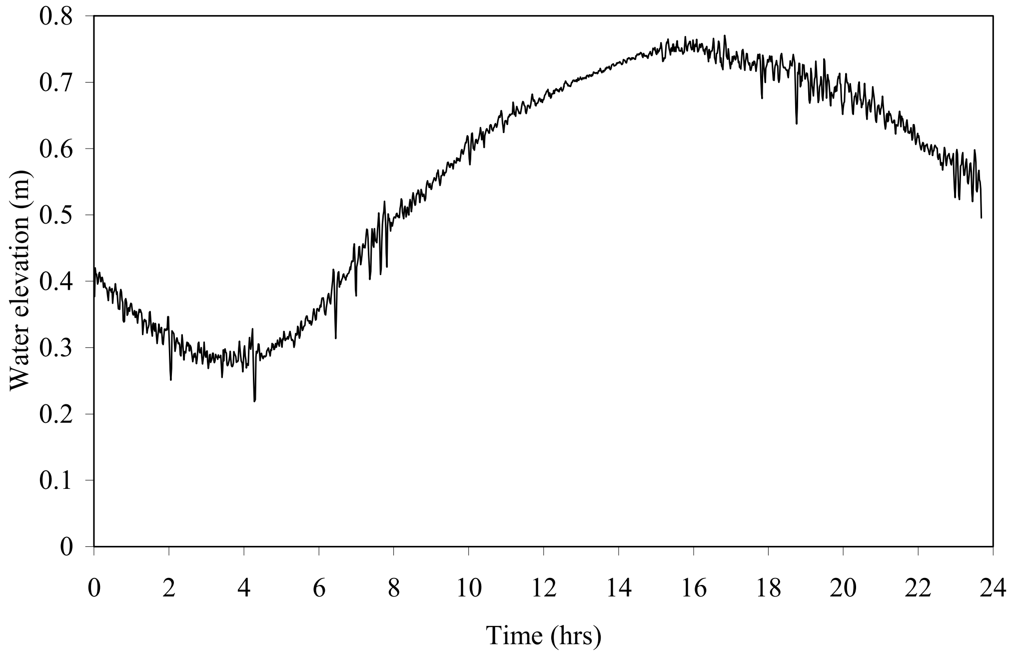

Fig. 6. Water surface elevation at site A (October 2004)

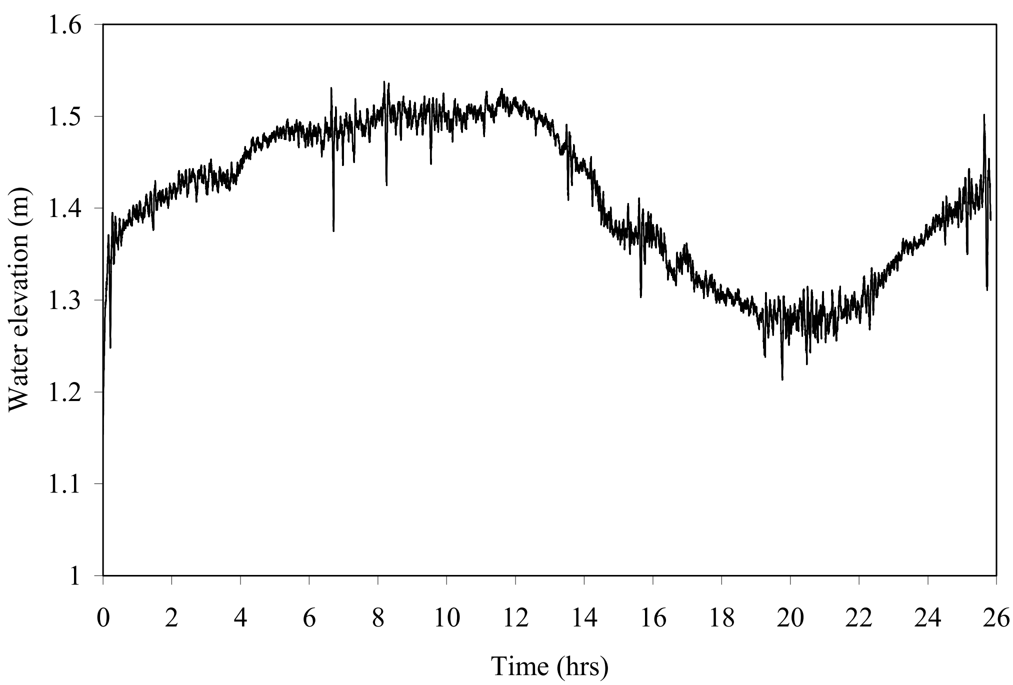

Fig. 7. Water surface elevation at site B (May 2005)

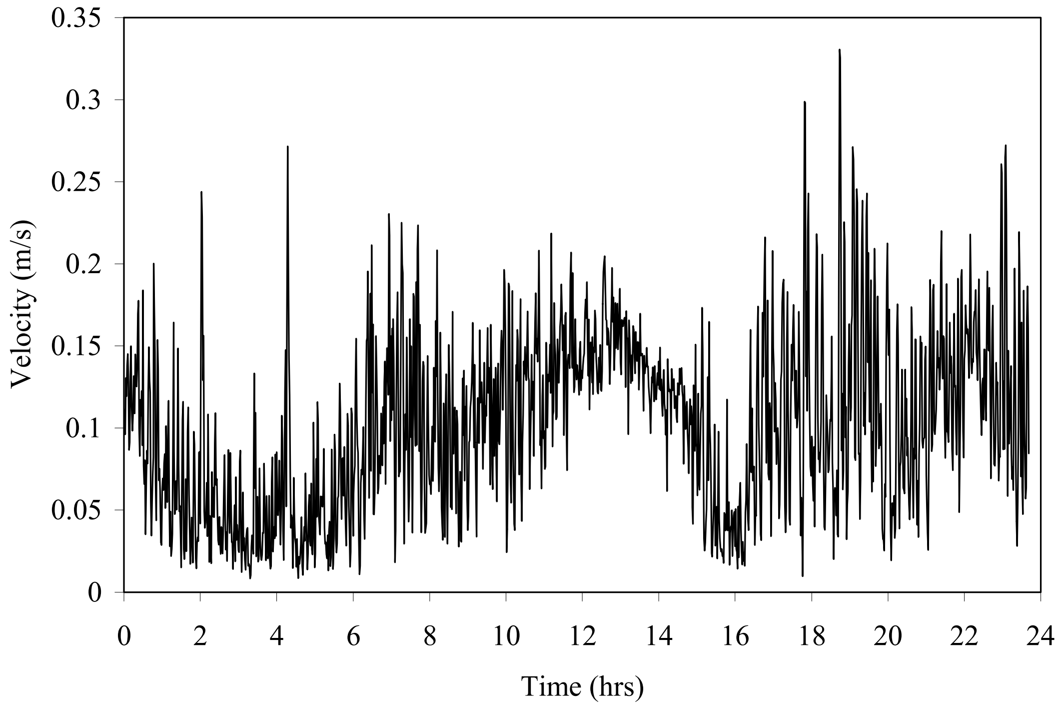

Fig. 8. Depth average velocity at site A (October2004)

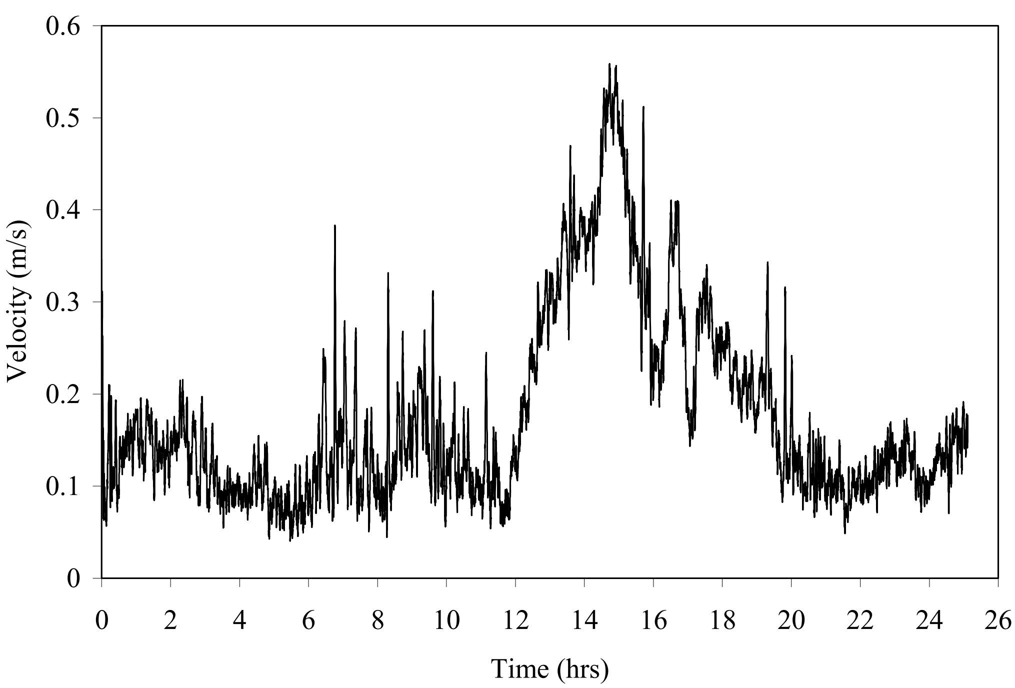

Fig. 9. Depth average velocity at site B (May 2005)

Model Results

The DYNLET model for the reference marsh was simulated for the same duration of time as the field measurements at site B in May 2005. The resultant water elevation and velocity were then compared with field data (Fig. 10; Fig. 11). The water level comparison showed a close resemblance between DYNLET results and field measurements (Fig. 10). Although the model did not produce similar oscillations as observed in the field, the average water elevations were comparable. When compared to field measurements, the DYNLET velocity demonstrated a similar pattern but lower magnitude (Fig. 11). The magnitudes of ebb velocities were higher than those of flood stage. The exceptionally high velocities, in the range of 0.4-0.55 m/s, observed in the field were not reproduced by DYNLET. The DYNLET model is limited in generating rapid changes in velocity magnitude and the instantaneous velocity spikes. This limitation can be attributed to the inability of DYNLET to consider time varying wind data in calculation of velocity. The percentage error in water elevation results was found to be 2.07%. Where as the error in velocity result was higher and was equal to 12.54%. Considering the limitations of DYNLET these errors are reasonable. The velocity calculations are satisfactory for preliminary studies and analysis. These results demonstrate the success of DYNLET model in duplicating reference marsh hydrodynamics.

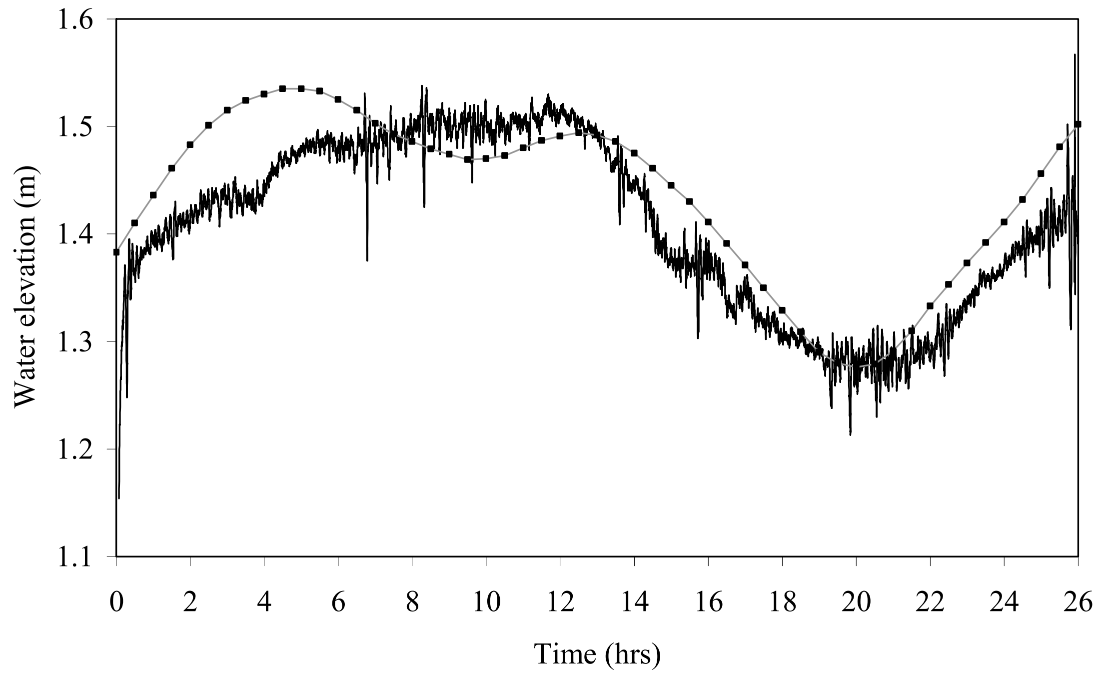

Fig. 10. Water level comparison at site B: (—) Field measurements, (■—) DYNLET

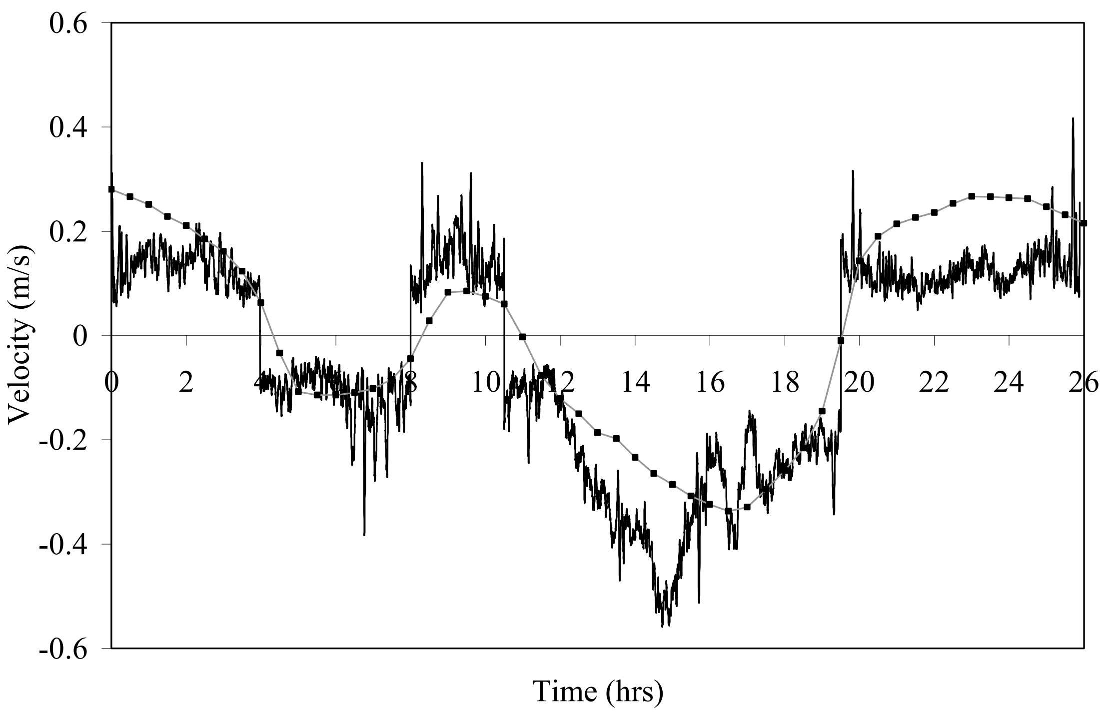

Fig. 11. Velocity comparison at site B: (—) Field measurements, (■—) DYNLET

The DYNLET model of the reference marsh was simulated for a three year period to observe the trends in velocity (Fig. 12). The results revealed that 88% of the velocities observed were less than or equal to 0.25m/s. Approximately 11.% of the velocities were higher, between 0.25-0.3m/s. Barely 1.3%, approximately 14 hours in three year time period, velocities were above 0.3m/s. This concludes that reference marsh channel rarely witnesses extreme velocities. For this time frame the model velocities did not exceed 0.4m/s, although the field measurements showed velocity peaks with higher magnitude. (This difference is due to the inability of DYNLET to produce wind influenced velocities.). Only intense velocities can cause significant erosion of bed sediments. In absence of wind the reference marsh observes intense velocities for only 5-6hrs per year; hence chances of heavy erosion are less.

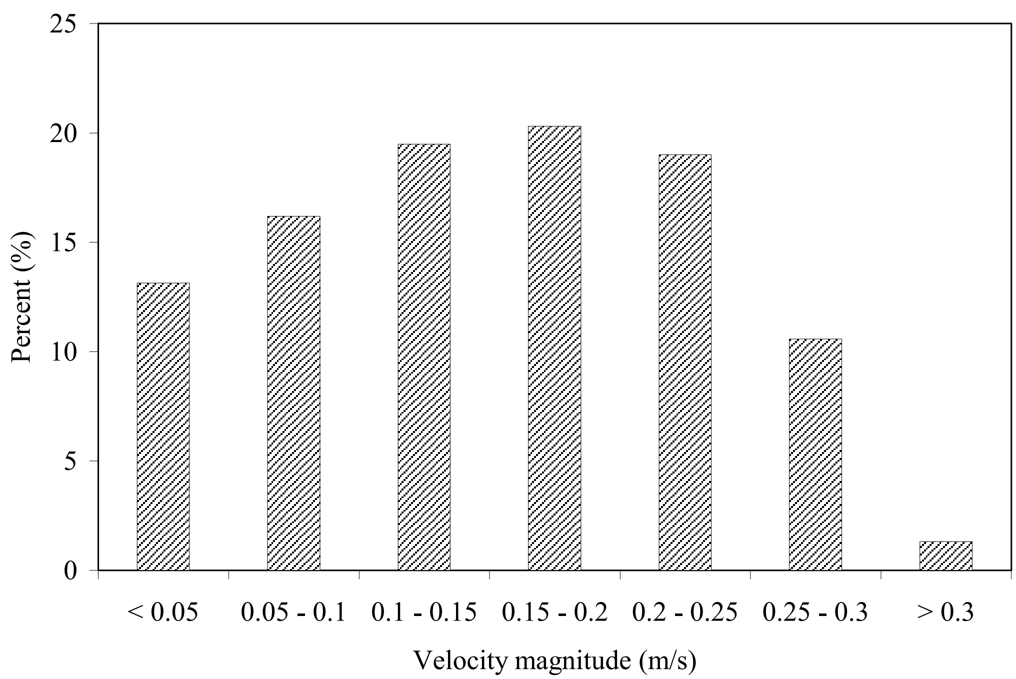

Fig. 12. DYNLET velocity analysis for year 2002-2004

After observing and analyzing the reference marsh hydrodynamics and DYNLET results, the DYNLET model of the beneficial use marsh was simulated for the same time period from 2002 to 2004. The resultant velocities were analyzed at two locations; one at the entrance of channel BB in cell 1 and in the developing channel of cell 2. The velocity magnitudes were similar for cell 1 and for cell 2 (Fig. 13; Fig. 14). The channel velocities were occasionally recorded higher than 0.3m/s. The beneficial marsh model also displayed stronger ebb velocities than flood, especially in channel CC, cell 2. The velocity results are much similar to those observed in the reference marsh. None of the velocities in the beneficial use marsh were higher than the maximum velocity observed in the reference marsh. These observations suggest that the beneficial use marsh will not be subjected to heavy erosion if their sediments are as strong as the Elm Grove sediments..

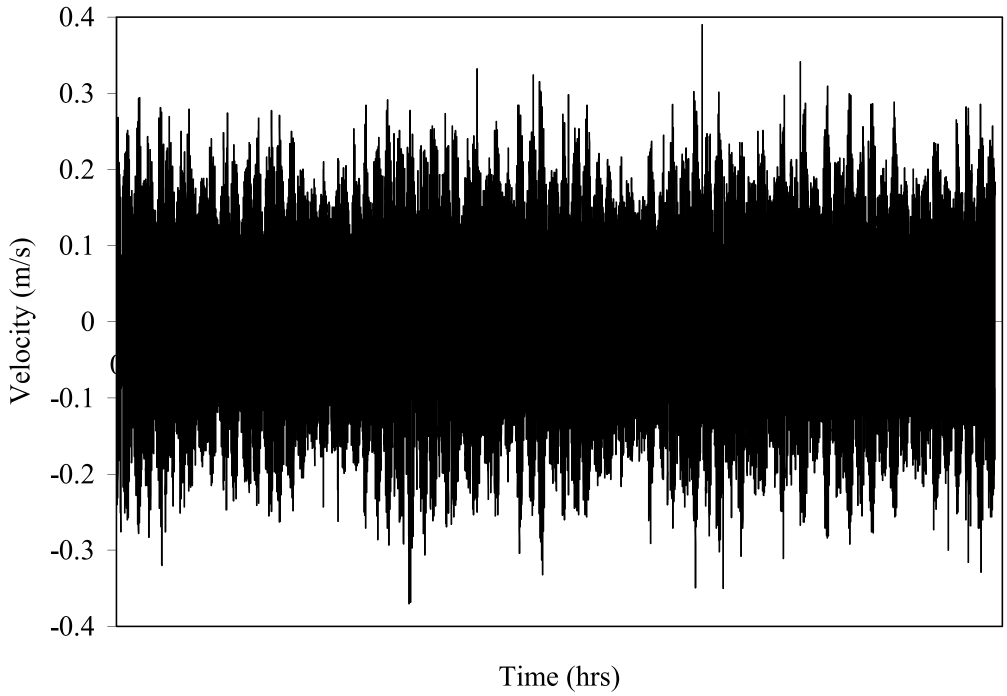

Fig. 13. Velocity distribution at channel BB of beneficial use marsh, year 2002-2004

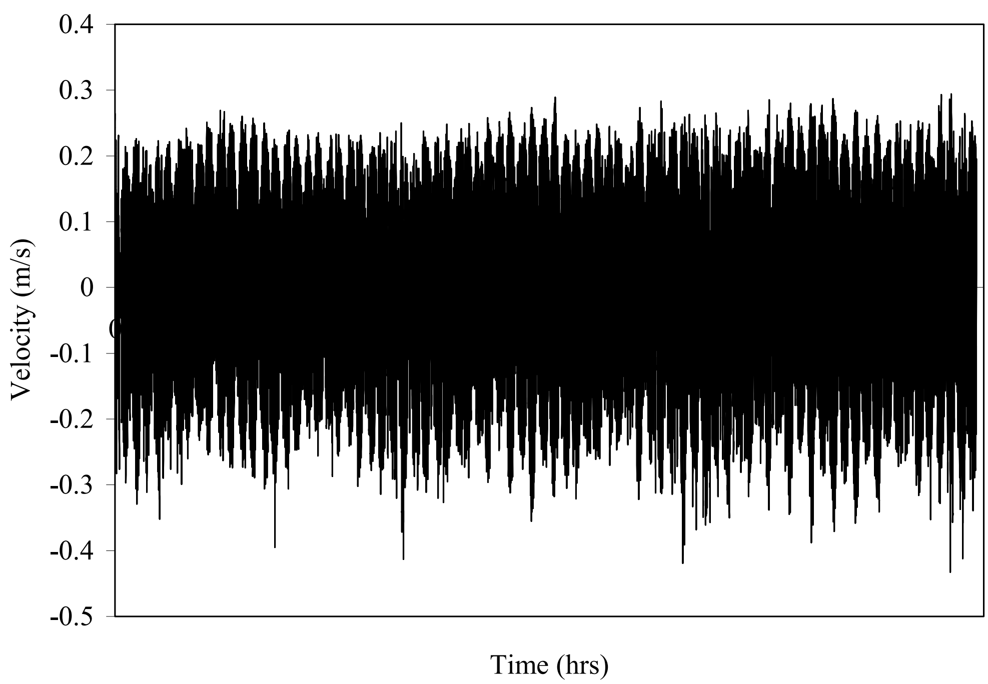

Fig. 14. Velocity distribution at channel CC of beneficial use marsh, year 2002-2004

SEDIMENT TRANSPORT MODEL

Tidal flows and sediment availability determine the balance of sedimentation and erosion that occurs across a coastal wetland. Sedimentation rates from tidal inputs vary across a marsh with the highest and most dynamic conditions in tidal creeks (Callaway, 2000). The erosion, transport, and sedimentation in tidal creeks are the result of the interaction between bottom sediment processes and tidal circulation (Eisma 1997). Understanding of the dynamics of erosion and accumulation is required for creek designs and excavation details.

Tidal marshes generally consist of sandy, silty, muddy sediments and mixtures of these. These cohesive sediments are almost always transported in suspension and their erodibility is fairly uncertain (Ravens, 1997). The cohesive sediment erodibility cannot be readily predicted from environmental parameters like sediment grain size, water content and organic carbon content (Ravens, 1997). As a result, this thesis focuses on combined use of *in situ* flume studies and sediment erosion model.

Sediment Erodibility Measurements

Research shows that for a given kind of sediment, erodibility is affected by physical, chemical and biological attributes. As a result of many uncertain influences (bacteria and algae bind sediments, worms increase erodibility) predicting sediment erodibility is difficult. Duplicating the reference conditions like flora, fauna, and a representative benthic community in lab is extremely difficult. Hence, sediment erodibility was measured in the field with the help of a flume. A flume is often employed because nature cannot be relied upon to provide the conditions of interest at a given time and it also yields data on erosional processes without having to consider other complicated sediment transport phenomenon present under reference conditions (Ravens, 1997). For this research a straight flume was deployed in tidal creek and a known bottom shear stress was applied on the sediment bed, the erosion rates were observed, and the erosional properties were then inferred using sediment erosion model.

Methods

A straight flume (240cm X 12cm X 6cm) made of acrylic plastic along with Doppler anemometer, to measure velocity within flume, was used (Fig. 15). A gasoline powered, 3.5 hp, Teele pump was used to pull water through the flume. The pump was connected to the flume via a 12 m, 7.6cm ID thick walled, rubber hose. Ball valve downstream of the pump and pump throttle were used to control the flow in the flume. Flow rates were measured manually using a bucket. Just downstream of the pump, a small portion of flow was diverted through a turbidimeter.

The experiment was conducted on February 2005 at a location near site A. The flume was lowered to the sediment bed of channel system I in reference marsh. Then, Lead weights were placed on the flume's feet to ensure its stability during the experiment. The flow was stepwise increased in at ten-minute interval, and the turbidity of water passing through the flume was measured every 30 seconds. Flow rates of up to 5 L/s were used to determine the erosion rates. Water samples were collected throughout the experiment and were later used for calibration of turbidimeter.

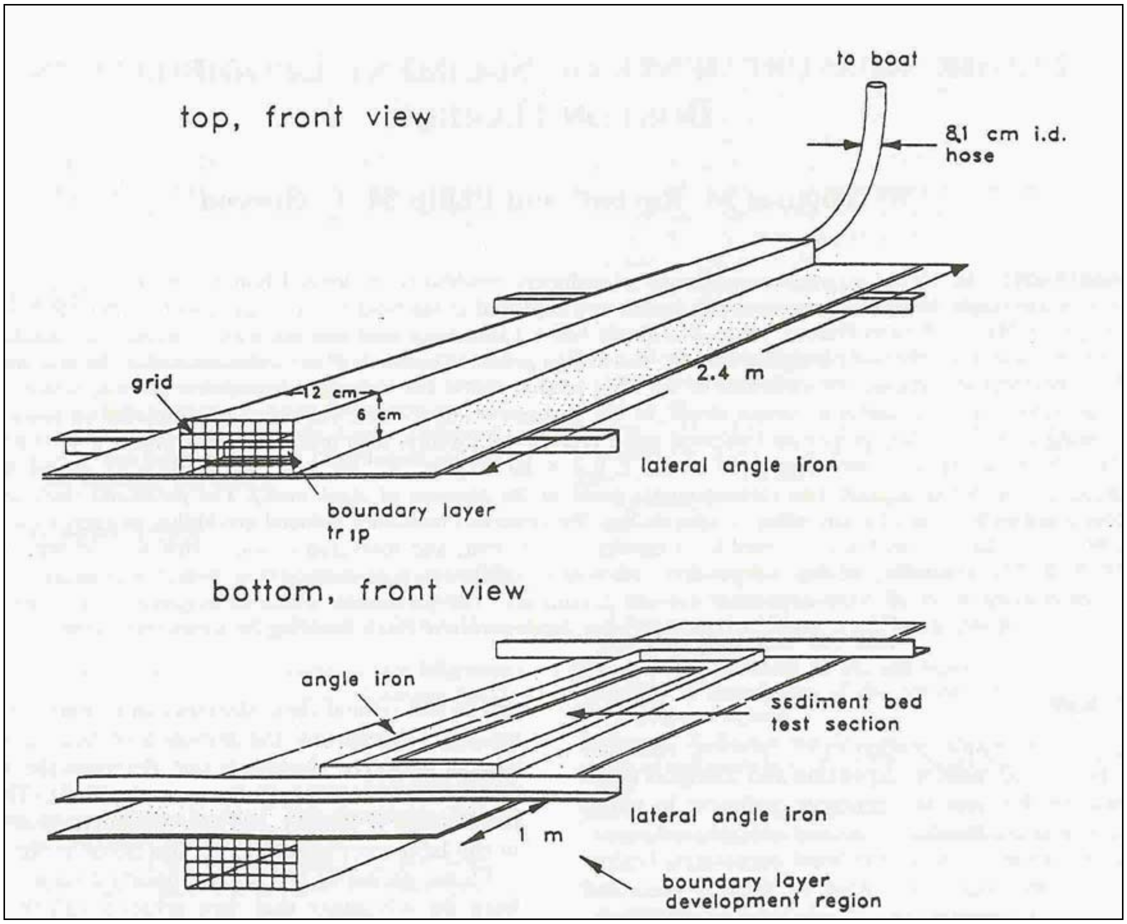

Fig. 15. Flume layout

The *in situ* field experiment for beneficial use marsh was carried out in March 2005. The flume was deployed at the entrance of the naturally developing channel CC in cell 2. The flume test was largely unsuccessful as no specific trend in erodibility was found during the experiment. The developing nature of channel, shallow and irregular depths, frequent change in current direction, presence of small boats in the vicinity of the test area, and the enormous disturbances caused by manual maneuvering of the boat might have accounted for this failure. Also, discharge of the flume water in to the stagnant enclosed embayment suspended particles and made data interpretation difficult. Though no well defined trend was observed in sediment erodibility, the sediments were found similar to those in reference marsh. The sediments were subjected to bottom stress of around 0.5Pa and no significant increase in turbidity was observed. On manual inspection the top layer of sediment was found loose and fluffy than the lower layers. The dry bulk density of dredged sediments at this location was 0.95 g/cm^3. Despite the failed flume test, the sediments in the beneficial use marsh can be characterized similar to those in reference marsh. This assumption is based on the fact that, in a given body of water, erosion rates are simple function of bulk density and shear stress (Lick and McNeil, 2001). The greater the bulk density, lower the sediment erodibility. The high bulk density of beneficial use marsh sediments can be attributed to the fact that the dumping of dredged sediments took place few years back and since then the sediments have consolidated. Also, the regular circulation of bay water in this particular channel and the creek dynamics has resulted in steady equilibrium. These sediments are not the ones that would be contacted by flowing water if a channel were to be dug. Hence, the strength of sediments in this channel entrance might not be a correct representation of dredged sediments in rest of the marsh. The more appropriate way to determine sediment erodibility will be a laboratory flume experiment on dredged sediment samples collected from constructed marsh. In absence of a lab flume and related equipments the sediment strength was assumed same as that of reference marsh sediments. However, it is noteworthy that geotech data indicate that the void ratio of the beneficial use marsh is less than that of the Elm grove marsh (HVJ Associates Inc., 2003). Hence, it is likely that the sediments of the beneficial use marsh have a higher bulk density and are more resistant to erosion than the Elm grove marsh.

Principle

The important principle behind this flume experiment is relationship between flow rate through the flume (Q, L/s) and the shear stress (τ, Pa) applied to the sediment bed:

$$\tau = \rho \frac{f}{8}\left[\frac{Q}{A}\right]^2 \quad (3)$$

where

ρ = water density (kg/m^3)

f = Darcy-Weisbach friction factor

A = bottom surface area of flume (m^2)

The Moody diagram (Mironer, 1979), modified for flow through rectangular channel, provides the friction factor as a function of relative roughness (R) and Reynolds's number (R_e).

$$R = \frac{k_a}{4R_h} \quad (4)$$

$$R_e = \frac{4R_hU}{\nu} \quad (5)$$

where,

k_a= median sediment grain size (m)

R_h= hydraulic radius (area/perimeter)

U= area average velocity (Q/A)

ν= kinematic viscosity (m^2/s)

Erosion rates were determined using measured turbidity and flow rate. Suspended solid concentration along with flow rates were used to estimate erosion rates. Following equation is used to determine erosion rates (E, $mg/s/cm^2$) from flume measurements:

$$\text{Erosion rate} = \frac{\left[\text{Moving average turbidity (NTU) - Background turbidity (NTU)}\right] \times \text{calibration constant (mg/L/NTU)} \times \text{Flow (L/s)}}{\text{Flume area (cm}^2\text{)}} \tag{6}$$

The background turbidity equal to 18 NTU was determined by revising the turbidity measurements of the flume test. The calibration constant was determined by calibrating sediment concentration (mg/L) and respective turbidity (NTU). With the help of water samples collected during the flume tests, the calibrating constant was found equal to 2.985 mg/L/NTU. Bulk density measurements were performed using the sediment samples taken from field. The erosion rate E ($mg/s/cm^2$) was divided by the dry bulk density to get erosion E (cm/s) which was then added to get net erosion z (cm) for given duration. The erosion rates reported here reflects the net amount of sediment eroded during experiment. The redeposition of sediments was not accounted in this study. Sediment that is mobilized when the bottom stress is 0.1 Pa or less was characterized as weak. The sediment that requires a bottom stress of 0.3 Pa or more to move was assumed strong.

Sediment Transport Analysis

Knowledge of erosional properties of marsh sediments is essential for sediment transport modeling. Cohesive sediment erodibility has been quantified on the basis of models which specify the rate of erosion as a function of bottom skin friction stress (i.e. shear stress exerted on the sediment grains). A combination of Krone's (1976) model based on laboratory flume experiments and Lavelle et al. (1984) model based on current-induced erosion in field was used. The model states that the rate of erosion (E, mg m^{-2} sec^{-1}) is proportional to the stress (τ, Pa) with power η, where η generally lies between 1 and 2.

$$E = \alpha \, \tau^{\eta} \tag{7}$$

where

α, erosion rate constant (mg m^{-2} min^{-1} $Pa^{-\eta}$) = ($\alpha_0 + \alpha_1$*z)

τ = shear stress (Pa)

z = depth/amount of sediment eroded (m)

$\alpha_{0,}$ α_1 = component of erosion rate constant

From the flume data shear stress τ, erosion rate E and amount of sediment eroded z were calculated. η was assumed as 2 (Ravens, 1997). Using these values the constant α was determined. $\alpha_{0,}$ α_1 were calculated as 0.949 and -0.869 respectively. Using these values the following equation was derived:

$$E = (0.949-0.869*z) \, \tau^2 \tag{8}$$

The above equation was then applied to velocity results from DYNLET model and the amount of sediment eroded in one typical tidal cycle was calculated. These results helped understand the erodibility of bottom sediments in reference and artificial marsh. The behavior of bottom stress corresponding to the model velocities was also determined and studied.

During the field survey (October 2004) abrupt increases in velocity were supported by increased turbidity (Fig. 16). This implies that high velocities play a critical role in the erosion of bed sediments. Exceptionally high turbidity in the second and third hour can be result of sediment disturbance caused by boat maneuvering. The peaks in turbidity were followed by gradual decreases demonstrating that the top layer of sediments was easy to erode but the lower layers were stable (Fig. 17). During the field survey the top layer of sediments was generally found oxic and fluffy, while the deeper sediments were more consolidated. Bottom soil often contained plant roots, small organisms and shells which bonded the sediments together.

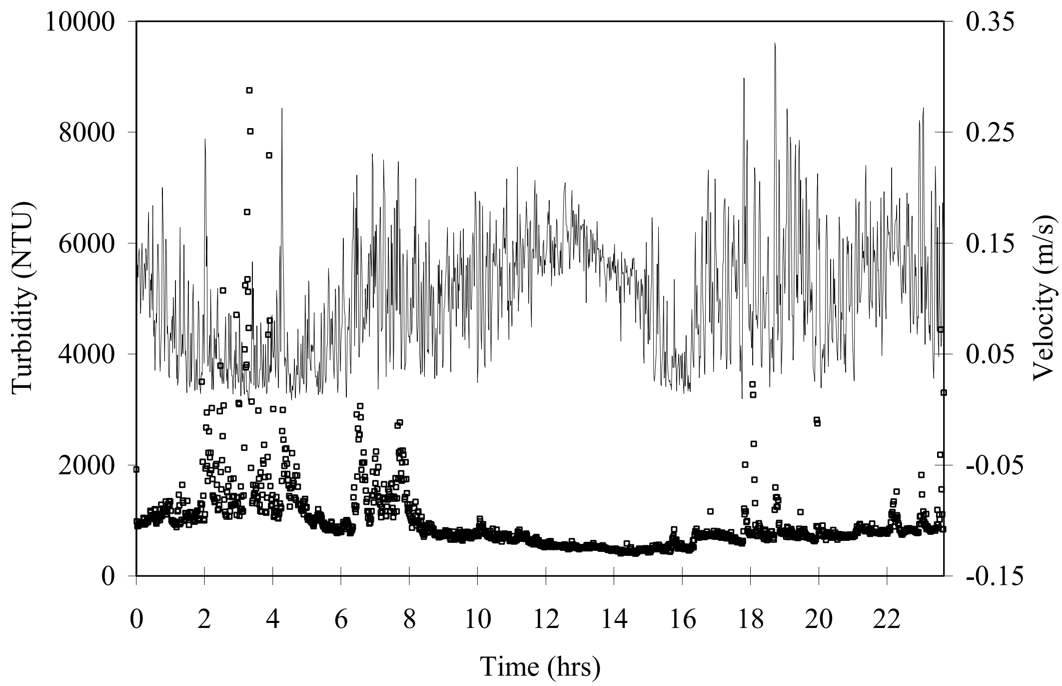

Fig. 16. Velocity magnitude (—) and turbidity counts (□) at site A (October 2004)

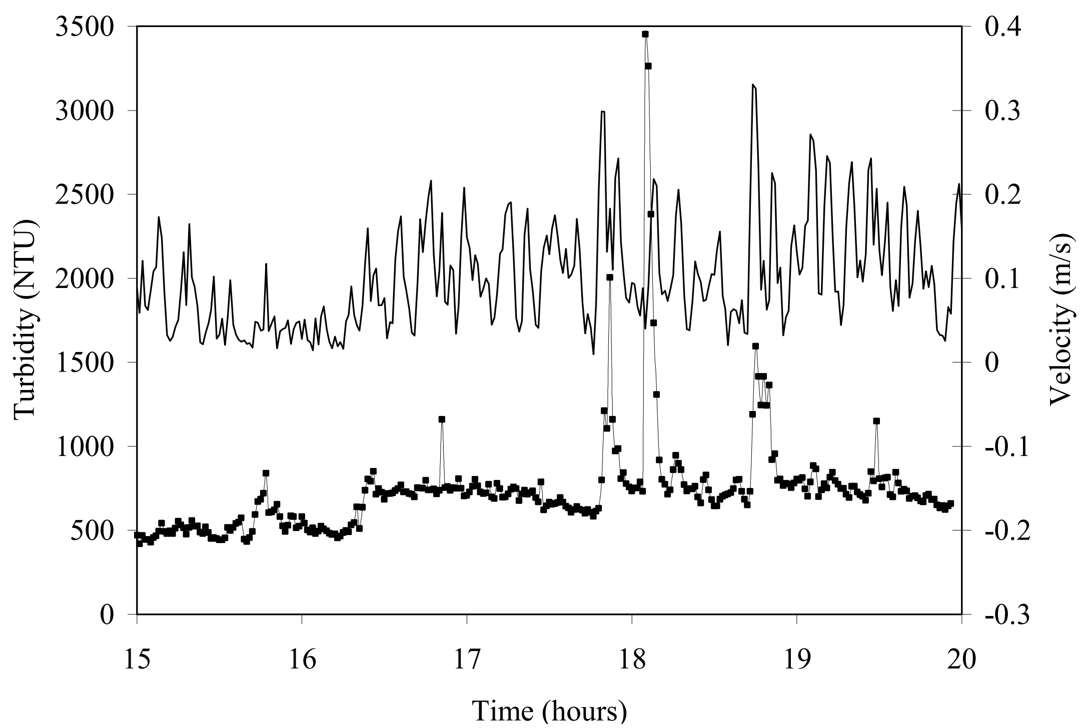

Fig. 17. Plot of velocity magnitude (—) and turbidity counts (■—) for 15th to 20th hour

The suspended solid concentration (C_s) determined from water samples was used to calibrate OBS (Fig. 18). The turbidity counts measured in field (October, 2004) were converted to suspended solid concentration (C_s) using the calibration equation.

$$\text{Turbidity} = 11668C_s + 584.69 \quad (9)$$

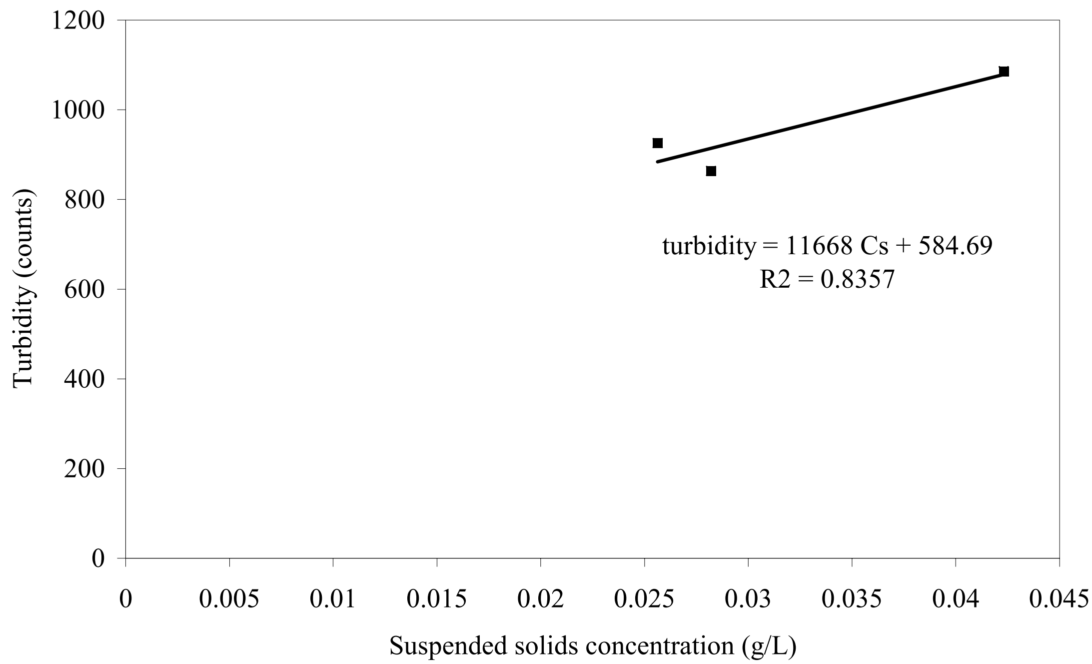

Fig. 18. *In situ* calibration of OBS

The Rousse equation determines sediment concentration at any depth z for non uniform distribution of sediments in water channel (Ravens, 1997). It assumes open channel flow with a logarithmic velocity profile, and a single class of particle. According to the equation, the sediment concentration is greater near the bottom of the water column. The equation uses sediment concentration at a particular vertical position to determine the concentration profile through the water depth.

$$C_z = C_a\left[\left(\frac{z}{a}\right)\times\frac{(h-a)}{(h-z)}\right]^{\left(\frac{-w_s}{\kappa u*}\right)} \qquad (10)$$

where

C_z = concentration at any elevation z (g/cm^3)

C_a = suspended solids concentration at elevation a (g/cm^3)

z= water elevation (cm)

a = depth of measuring suspended solid concentration (cm) = 20cm

H = water column depth (cm)

w_s = fall velocity (cm/s)

u* = friction velocity (cm/s) = (bottom stress/water desntiy)^0.5

K = Karman constant = 0.4

The erosion rate in field was then determined by taking the product of the average sediment concentration and the depth of water. The erosion rates calculated from flume model [Eq. (8)] were compared to erosion rates calculated on the basis of measured suspended solid concentration. This comparison provided a confidence in applicability of flume test for determination of sediment erodibility.

The complete sediment transport study of this research focuses on erosion. Depositional processes are not taken into consideration as it makes the study more complex. But a general rule given by Bruun (1966) was used to determine the inlet stability. The flume helped determine the upper limit of velocity while the Bruun's model provided the idea of lower limit for channel velocity. This model helped determine the stability of channel entrances for DYNLET model velocities. The researchers found that the ratio of tidal prism (W) to littoral drift (Q) determined inlet stability as follows:

$$W/Q > 300, \text{ stable inlets} \tag{11}$$

$$W/Q < 100, \text{ unstable inlet, with shoaling} \tag{12}$$

After the review of alongshore transport studies in the area, the regional littoral drift was assumed to be 50,000m^3/year. Tidal prism was calculated as volume of water that flows in the channel during the flood tide. For calculation purposes the calibrated velocities of May 2005 were used.

Results

Flume Test

The turbidity and flow rate data from the field (Fig. 19) indicated that increase in flow rate was usually accompanied by increase in turbidity followed by a gradual decrease to initial value. At sufficiently high flow rates (e.g. 5 L/s in Figure 19), the turbidity peak was high (e.g. 40 NTU in Fig. 19) indicating erosion. The initial peaks in turbidity may have resulted from the erosion of weaker surface sediments. The subsequent fall in turbidity shows existence of stronger sediments in lower layers. Also, there is a possibility that at each level of sediment there are two classes of sediments; one set that is easily eroded in the new shear environment and the other set that is removed slowly (Ravens, 1997). After the removal of both these classes of sediments, equilibrium was achieved for the particular shear environment. These results were in accordance with the observations made in the field on October 2004.

The plot of bottom shear stress corresponding to velocity displayed an exponential increase in shear stress (Fig. 20). This indicates that beyond a certain velocity (often called critical velocity) sediments are subjected to high shear stress (>0.4Pa) causing substantial erosion. From this study the critical velocity was deduced to be approximately 0.35 m/s. From the hydrodynamic analysis of reference marsh, only 1.3% of velocities were found greater than 0.3 m/s. This predicts that the channel system I of reference marsh is stable and the sediments will not be washed away. Though these results neglect wind they are in accordance with the observations and the fact that the reference channel successfully exists for number of years in equilibrium with the surroundings.

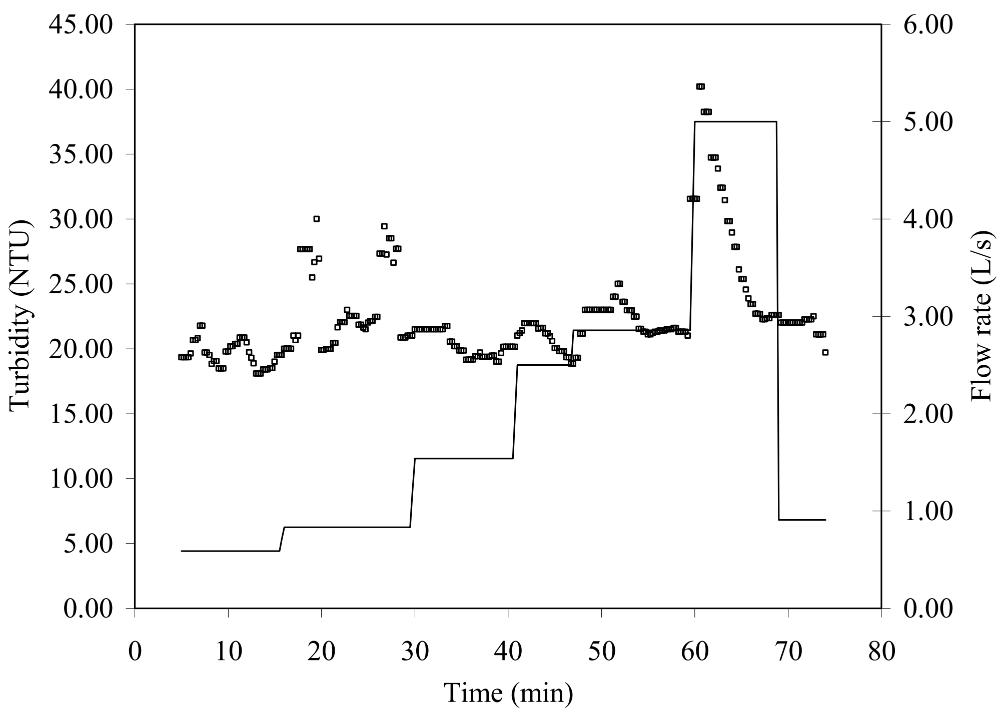

Fig. 19. Flow rate (—) and turbidity (□) measurements from flume test in reference marsh, February 2005

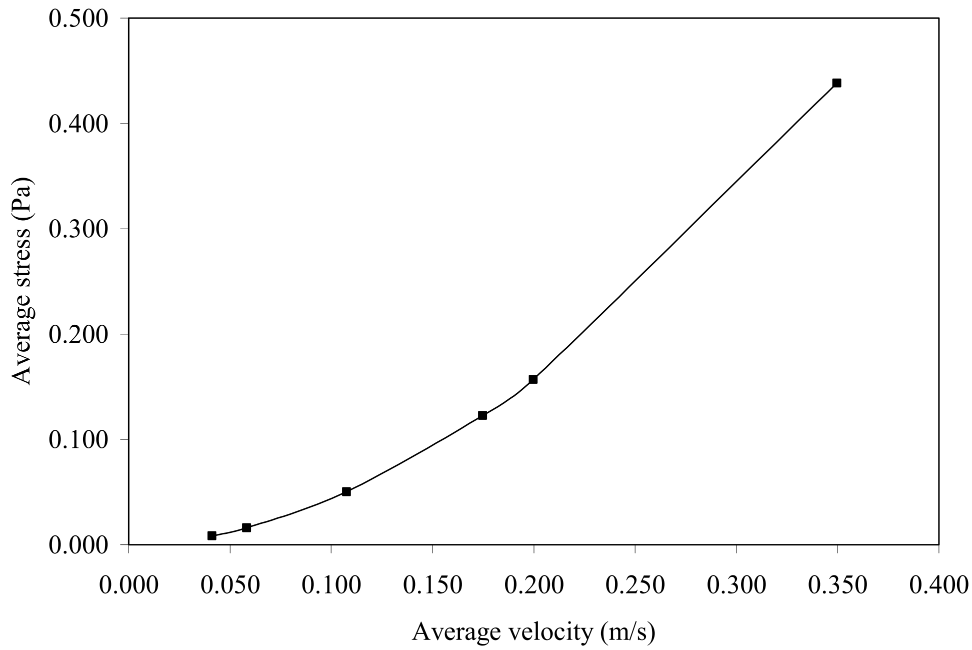

Fig. 20. Velocity and bottom stress plot for flume test in reference marsh, February 2005.

The total depth of sediment eroded during the experiment was calculated to be 0.13cm (Table 1). The duration of experiment was approximately 1 hr 7 minutes in which flow through flume was increased from 0.59 L/s to 5 L/s.

Table 1. Amount of sediment eroded during flume experiment

Time (minutes)	Average Velocity (m/s)	Average Bottom stress (Pa)	Average Erosion rate (cm/min)	Average Depth (cm)
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10.5	4.11E-02	8.54E-03	1.48E-04	8.88E-04
13.5	5.83E-02	1.62E-02	7.29E-04	6.30E-03
10.5	1.08E-01	5.02E-02	5.85E-04	1.55E-02
5.75	1.75E-01	1.23E-01	1.18E-03	2.22E-02
12.5	2.00E-01	1.57E-01	2.00E-03	3.77E-02
8.75	3.50E-01	4.38E-01	8.77E-03	1.03E-01
5	6.36E-02	1.89E-02	5.68E-04	1.33E-01

Sediment Transport Model

The amount of sediment eroded was calculated for channel system I using DYNLET results. The velocity results at the entrance of the channel were used as representative values. The analysis was performed for single tidal cycle of 24 hrs. The calibrated tidal cycle of May 2005 was used specifically so as to infer better comparisons with flume results. The net erosion was calculated as the difference between the sediment eroded by ebb and flood velocities. The Reynolds's number and channel roughness was calculated using cross-section as 30m X 1.5m. For the typical tidal cycle of May 2005, the ebb velocities were found more dominating than flood velocities. This phenomenon resulted in net removal of sediments from the marsh channel. Approximately 0.07cm of bottom sediment was washed out during this typical tidal cycle (Table 2; Table 3).

In order to understand the ebb or flood dominance on reference marsh, above erosion model was applied to a tidal cycle of October 2004. The results displayed flood dominance with approximately 0.18cm of sediments being deposited in the marsh channel. These inconsistencies in results infer extremely dynamic behavior of the marshes. Characterizing a marsh channel as erosional or depositional seems difficult. Also the dominance of flood and ebb is greatly variable. This randomness is the result of numerous reference variables like wind, seasonal and daily tidal variations. Also, it is possible that our simple 1d model is limited in its ability to determine conclusively the ebb or flood dominance.

Table 2. Amount of sediment eroded during flooding (May 2005)

Average Velocity (m/s)	Average Bottom stress (Pa)	Average Erosion rate (cm/min)	Average Depth (cm)
2.80E-01	1.25E-01	1.93E-05	0.00E+00
2.66E-01	1.14E-01	1.55E-05	3.48E-02
2.51E-01	1.02E-01	1.21E-05	6.27E-02
2.28E-01	8.52E-02	8.30E-06	8.45E-02
2.11E-01	7.38E-02	6.13E-06	9.94E-02
1.85E-01	5.78E-02	3.72E-06	1.10E-01
1.61E-01	4.47E-02	2.21E-06	1.17E-01
1.23E-01	2.72E-02	8.16E-07	1.21E-01
6.30E-02	8.01E-03	7.06E-08	1.23E-01
2.80E-02	1.85E-03	3.78E-09	1.23E-01
8.30E-02	1.32E-02	1.93E-07	1.23E-01
8.50E-02	1.38E-02	2.10E-07	1.23E-01
7.50E-02	1.10E-02	1.33E-07	1.23E-01
6.00E-02	7.33E-03	5.91E-08	1.24E-01
1.43E-01	3.59E-02	1.42E-06	1.24E-01
1.90E-01	6.07E-02	4.04E-06	1.26E-01
2.14E-01	7.57E-02	6.24E-06	1.34E-01
2.26E-01	8.38E-02	7.55E-06	1.45E-01
2.36E-01	9.08E-02	8.74E-06	1.58E-01
2.53E-01	1.03E-01	1.11E-05	1.74E-01
2.67E-01	1.14E-01	1.33E-05	1.94E-01
2.66E-01	1.14E-01	1.28E-05	2.18E-01
2.64E-01	1.12E-01	1.21E-05	2.41E-01
2.62E-01	1.10E-01	1.15E-05	2.63E-01
2.47E-01	9.89E-02	8.97E-06	2.84E-01
2.31E-01	8.73E-02	6.85E-06	**3.00E-01**

Table 3. Amount of sediment eroded during ebbing (May 2005)

Average Velocity (m/s)	Average Bottom stress (Pa)	Average Erosion rate (cm/min)	Average Depth (cm)
3.40E-02	2.63E-03	8.54E-09	0.00E+00
1.08E-01	2.14E-02	5.69E-07	1.54E-05
1.14E-01	2.37E-02	6.93E-07	1.04E-03
1.14E-01	2.37E-02	6.93E-07	2.29E-03
1.10E-01	2.22E-02	6.07E-07	3.53E-03
1.02E-01	1.93E-02	4.60E-07	4.63E-03
8.40E-02	1.35E-02	2.26E-07	5.45E-03
4.50E-02	4.35E-03	2.34E-08	5.86E-03
3.00E-03	3.64E-05	1.63E-12	5.90E-03
7.70E-02	1.15E-02	1.64E-07	5.90E-03
1.21E-01	2.64E-02	8.59E-07	6.20E-03
1.50E-01	3.92E-02	1.89E-06	7.74E-03
1.86E-01	5.84E-02	4.18E-06	1.11E-02
1.98E-01	6.56E-02	5.23E-06	1.87E-02
2.34E-01	8.94E-02	9.65E-06	2.81E-02
2.65E-01	1.13E-01	1.51E-05	4.55E-02
2.86E-01	1.30E-01	1.95E-05	7.26E-02
3.08E-01	1.49E-01	2.49E-05	1.08E-01
3.24E-01	1.64E-01	2.87E-05	1.53E-01
3.37E-01	1.77E-01	3.15E-05	2.04E-01
3.29E-01	1.69E-01	2.69E-05	2.61E-01
2.95E-01	1.38E-01	1.68E-05	3.09E-01
2.59E-01	1.08E-01	9.96E-06	3.40E-01
2.16E-01	7.70E-02	4.95E-06	3.58E-01
1.45E-01	3.68E-02	1.12E-06	3.67E-01
1.00E-02	2.97E-04	7.23E-11	**3.69E-01**

Flume Test Applicability

The cumulative erosion calculated using flume model [(Eq. (8)] and suspended solid concentration in field [Eqs. (9) and (10)] showed comparable results. Three resuspension events (11^{th}-24^{th} min; 30^{th}-40^{th} min and 50^{th}-60^{th} min, Fig. 21) from October 2004 survey were used for these calculations. The velocity measurement was used to determine the bottom shear stress and erosion from the Eq. (8). The turbidity measurement was used to determine suspended solid concentration and erosion using the Eq. (10). Erosion rate calculation was performed assuming uniform distribution of sediments along the depth and non uniform distribution. The erosion rate calculation for the three resuspension events showed good similarity between cumulative erosion calculated based on flume experiments and those based on sediment concentration. The erosion rate values suggest that assuming non uniform distribution, higher sediment concentration at bottom and lower at top, represents a better scenario (Table 4). Though these results neglect the accumulation of sediments, they do provide crude yet developing sediment transport model. The good comparison is a sign of successful applicability of flume test to tidal creeks.

The comparison in figure 21 shows increase in suspended solid concentration with increase in bottom stress. The suspended particle plot also shows presence of small concentration of sediments in water channel at all times.

Table 4. Erosion rates corresponding to three resuspension events

Events	Based on flume experiment	Based on sediment concentration	
		Uniform distribution	Non uniform distribution
I: 11th-24th min	8.62 mg/cm^2	4.36 mg/cm^2	9.55 mg/cm^2
II: 30th-40th min	5.34 mg/cm^2	1.7 mg/cm^2	3.75 mg/cm^2
III: 50th-60th min	4.89 mg/cm^2	1.74 mg/cm^2	3.83 mg/cm^2

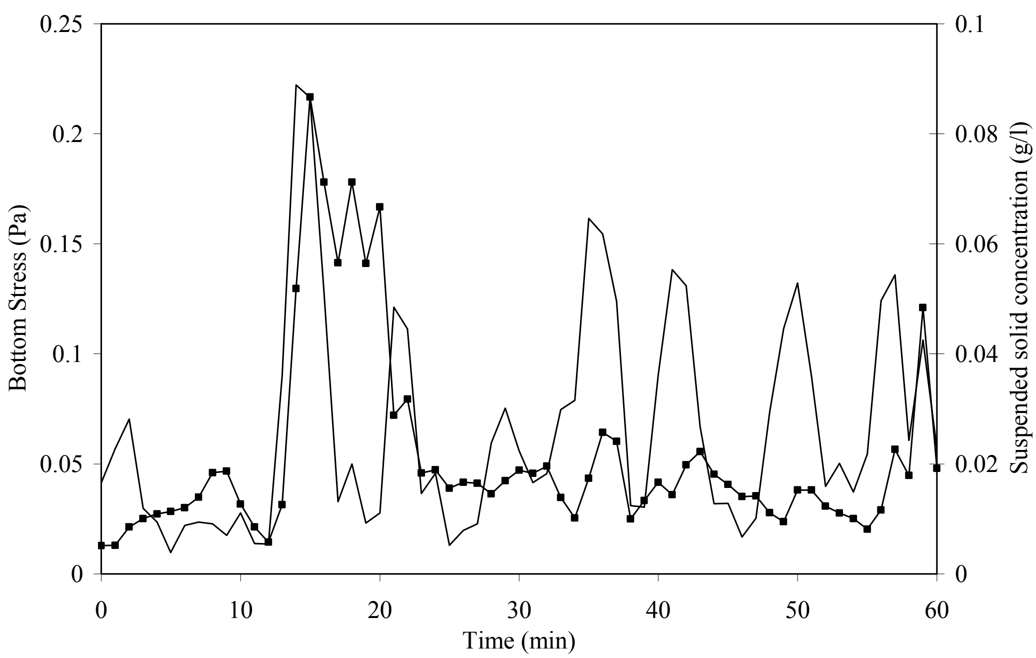

Fig. 21. Bottom stress (—) and suspended solid concentration (■—), October 2004

Inlet Stability

The overall inlet stability of channel system I, from depositional aspect, was analyzed using equation 9 and 10. The tidal prism for channel system I of reference marsh was found to be 8.17E+07m^3 over the period of one year. The ratio of tidal prism to littoral drift was then calculated as 16.34E+02(>300) which makes the inlet stable. This concludes the velocities in this channel are high enough not to cause excess deposition. Similarly the tidal prism to littoral drift ratio for channel BB, Cell 1, of beneficial use marsh was found to be 415.31. The smaller W/Q ratio for channel BB represents lesser tidal prism. In order to make the channel more stable, the length of channel was increased by approximately 200m. The new ratio was found to be 820.62. The same ratio for channel CC, Cell 2 was calculated as 19.88E+02. These results illustrate that channel CC as well as channel BB are stable. These calculations are based on the representative velocities of May 2005 they are mere approximations.

CONCLUSION

Coastal wetlands are very dynamic; they are highly sensitive to natural processes and human alterations. Understanding these sensitive ecosystems with field surveys and mathematical modeling can help in the effective design of artificial marshes. In this study, a one-dimensional hydrodynamic model and preliminary sediment transport analysis was used to understand marsh hydrodynamics. The study of reference and beneficial use marsh shows good results, especially for the channel system I of reference marsh Elm Grove. The key success to modeling the marshes lies in:

1. The availability of detailed bathymetry and wave data that can reproduce marsh channel and hydrodynamics.
2. Long term field data of velocity, water elevation, sediment erodibility and turbidity for understanding marsh behavior and model calibration.

The DYNLET model was capable of determining velocity and water elevation approximately similar to those measured in the field. The minor fluctuations in field velocity and water elevation were not duplicated, but the average values were similar. In the absence of wind data and with the inability of DYNLET to model time varying wind stress, the high velocities (>0.4m/s) caused by wind were not reproduced. These exceptionally high velocities measured in field surveys can be critical to sediment transport in tidal creeks.

The turbidity measurements in field showed increase in sediment concentration with increase in flow rate. This is the effect of the upper layers of sediments getting eroded under increased bottom stress. The turbidity peaks were followed by a gradual decrease which is accounted as decrease in sediment erodibility with depth. Similar results were obtained from the flume test in natural channel. A flow rate of 5L/s was observed to produce enough bottom stress to cause significant erosion rates. But even under these stress conditions, the erosion rate quickly decreased showing presence of stable sediments. The significant strength of reference marsh sediments is attributed to organic matter (plat roots, shells, algae, microbes etc.) and the fact that these sediments have become stable under the impact of regular flooding and drying.

The sediment erodibility of marsh sediments was successfully determined from *in situ* flume test and erosion model. The critical velocity for channel system I sediments was found to be 0.35m/s And the corresponding bottom stress was 0.42 Pa. The velocity analysis of DYNLET results for same channel showed 1.3% chances of velocity being higher than 0.35m/s. These results infer that the natural channel will not be subjected to excessive erosion. But the velocities calculated by DYNLET are lower than that in field, the erosion rates calculated using these values are under-predicting the extent of erosion. The inlet stability calculations of same displayed no signs of extreme siltation. Hence, the hydrodynamic and sediment transport model illustrates that the channel system I observes proper circulation, has optimum velocities and will not be subjected to heavy erosion and/or siltation.

A similar study of the beneficial use marsh described the proposed channel layouts as stable. In the absence of any reliable flume experiment data and considering the bulk density measurements, the dredged sediment erodibility was assumed similar to reference marsh sediment. The DYNLET model velocities in the channel entrances are comparable to velocities measured in reference marsh. Also the inlet stability ratio was greater than that required for stability. But for avoiding any chances of sedimentation in channel BB of Cell 1, lengthening of the channel is recommended. The results suggest the designed cross sections of beneficial use marsh will witness sufficient circulation and safe velocities. Considering the assumptions made for sediment erodibility, use of preliminary channel designs of BUG poses no future problem of excessive erosion or siltation.

This study confirms the dynamic and unpredictable nature of marshes. But it also gives an overview of how these complex systems can be analyzed. It further ascertains the significance of studying a reference marsh for designing and developing a constructed marsh. Use of two-dimensional hydrodynamic models (e.g. RAM2) supported by detailed bathymetry and field measurements is recommended for further studies. As a result of complex situations, this research emphasized only on erosion while studying sediment transport, whereas, sedimentation is also equally important phenomenon. Understanding and modeling these complex processes needs use of well developed sediment transport models like RAM4. *In situ* flume test can not be performed successfully at all locations. In such scenario a laboratory flume test needs to be developed in order to determine the erodibility of sediments from soil samples.

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