CHARACTERIZATION OF SEDIMENT MOVEMENT IN TIDAL CREEKS ADJACENT TO THE GULF INTRACOASTAL WATERWAY AT ARANSAS NATIONAL WILDLIFE REFUGE, AUSTWELL, TX: STUDY OF NATURAL FACTORS AND EFFECTS OF BARGE-INDUCED DRAWDOWN CURRENTS

A Thesis

by

JOHN BRYAN ALLISON

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

May 2005

Major Subject: Geology

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Approved as to style and content by:

Christopher C. Mathewson (Chair of Committee)	Stephen E. Davis, III (Member)
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ABSTRACT

Characterization of Sediment Movement in Tidal Creeks Adjacent to the Gulf
Intracoastal Waterway at Aransas National Wildlife Refuge, Austwell, TX: Study of
Natural Factors and Effects of Barge-Induced Drawdown Currents. (May 2005)
John Bryan Allison, B.S., Western Carolina University
Chair of Advisory Committee: Dr. Chris Mathewson

The coastal wetlands at Aransas National Wildlife Refuge near Austwell, Texas, support the last migrating population of whooping cranes during the winter months (October through April). With a population currently at 216 individuals, these are the rarest cranes in the world. The wetlands in which they winter are a part of the San Antonio Bay system, a bay that receives constant fresh water flow from the Guadalupe River. Currently there is a plan for using water diverted from the Guadalupe River just before it enters San Antonio Bay as a water supply for the greater San Antonio metropolitan area located 200 km to the northwest. The Guadalupe River delivers nutrients and sediment into the estuary along with fresh water. Because of the importance of sediment within a tidal wetland ecosystem, it is imperative to understand the sediment budget and underlying forces that drive it if one is to ultimately grasp how this ecosystem functions. To document natural and anthropogenic factors exerting control over sediment movement in this system, three sites on tidal creeks near the boundary between marsh and bay were chosen. The Gulf Intracoastal Waterway parallels the marsh edge. Over six, non-consecutive weeks water level and velocity were automatically monitored in the tidal creeks. Automated water samplers extracted water samples that were analyzed for suspended sediment. In addition, bedload traps were deployed in one creek to monitor sediment movement along the channel bottom. Inflow exceeded outflow during the study. As a result there was a net influx of suspended sediments into the marsh. Bedload material also moves with current direction, and it appears to move in response to barge induced outflow currents. Barges passing on the Gulf Intracoastal Waterway exert influence on water level, flow direction, and velocity within tidal creeks. Natural factors such as winds, tides, and freshwater input from upland runoff or river discharge also impact suspended and bedload sediments.

TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

TABLE Page

1. INTRODUCTION

Coastal wetlands worldwide are in need of protection because they are diverse ecosystems that have been recognized for their value as estuaries, fisheries, endangered species habitat, etc. The coastal wetlands at Aransas National Wildlife Refuge (ANWR) near Austwell, Texas, are no exception as they support the last migrating population of whooping cranes during the winter months (October through April). With a population currently at 216 individuals, these are the rarest cranes in the world. The wetlands in which they winter are a part of the San Antonio Bay system, a bay that receives a constant discharge of fresh water from the Guadalupe River.

As is common in many estuaries, pulses of freshwater inflow are an important part of the subsidy and maintenance of the bay and marsh ecosystems. Currently there is a plan for diverting water from the lower Guadalupe River (just below its confluence with the San Antonio River) as a water supply for the greater San Antonio metropolitan area located 200 km to the northwest of the river's mouth (The Lower Guadalupe Supply Project, 2003). This interest has helped launch an ecological study at ANWR that will gather data pertaining to many aspects of the marsh ecosystem and ultimately model the ecology of the wetlands in response to environmental drivers such as riverine inflows, tides, wind, etc. Special emphasis will be given to the factors affecting food sources of the whooping crane, such as blue crabs and wolfberry.

This thesis follows the style and format of *Estuarine, Coastal, and Shelf Science*.

The Guadalupe River is a source of materials for the San Antonio Bay system. Sediment is a major component of coastal wetland substrate structure and its continued input maintains the elevation of coastal wetlands relative to regional subsidence and sea level rise (Callaway et al., 1997; Christiansen et al., 2000; DeLaune et al., 1983). To fully understand how this ecosystem works as a whole, it is imperative to understand the characteristics of sediment movement and the drivers of it. Natural factors (such as tides, winds, storms, etc.) controlling movement of sediment within the marsh ecosystem need to be documented (Leonard, 1997; Davis, et al., 2004). The effect of passing barges in the nearby Gulf Intracoastal Waterway (GIWW) is an unnatural driver that needs to be understood (Maynord, S.T. and Siemsen, T.S., 1991). The drawdown currents associated with barges have some influence over materials exchange between the tidal creeks and adjacent bays (Stockstill, R.L. and Berger, R.C., 2001).

Much sediment research done within coastal wetlands is focused on accretion rates and processes, such as mineral deposition in relation to flow and turbulence (Christiansen, et al., 2000; Leonard and Luther, 1995; Leonard, 1997; Wang, et al., 1993). Such studies have found that most suspended sediment enters a marsh from the adjoining bay via tidal creeks with high tide inflow (Davidson-Arnott, et al., 2002) or during spring tides (Leonard, 1997) when water volumes and velocities are often at their highest. Those who have monitored sediment movement within a tidal channel have found that most suspended sediment is in highest concentration during initial tidal inflow (Davidson-Arnott et al., 2002) or during spring tides (Leonard, 1997). Bryce et al. (2003) found tidal currents to be the primary control on suspended sediments. Storm events have also been found to be major contributors to sediment movement (Leonard et al., 1995).

All of these studies dealt with the natural drivers of suspended sediment movement within a tidal creek and marsh system. It is known that suspended sediment movement is facilitated (or affected) by the tides and other means of water motion such as wind (Leonard et al., 1995; Sutula et al., 2003). This should also be the case in ANWR tidal creeks because they are subjected to tides, winds, etc.

Unnatural means of water movement, such as barge-induced currents, can also affect sediment movement (Stockstill, R.L. and Berger, R.C., 2001). Barge-induced currents observed in this research can create tidal-like oscillations over short time intervals (i.e. minutes), with velocities and water level changes that are comparable if not exceeding natural velocities and water level changes. This activity results in an unnatural movement of sediment within the system, both as suspended and bedload sediments.

The effects of barges and boats on sediment movement and erosion have been studied within main canals such as the Intracoastal Waterway or navigable rivers like the Mississippi (Maynord and Siemsen, 1991; Stockstill and Berger, 2001), but not within the tributaries or associated tidal creeks of those canals or rivers. Trimbak, et al. (2001) published a method for estimating vessel-induced sediment suspension that discusses barge drawdown, but mainly focuses on the effects of waves. Many vessel studies such as Trimbak et al.'s (2001) find wake to be a major factor in sediment mobilization and erosion. At ANWR, wake cannot be a major factor in sediment movement because the tidal creeks are too far removed from the GIWW either by obstructions, alignment, or stretches of shallow water.

Drawdown and its ecological effects are mentioned by Stockstill and Berger (2001), but their work is mainly focused within the main channels of dug canals like the GIWW and major rivers like the Mississippi. It was established that barges create currents and drawdown of the water level that affect the surrounding waters outside the channel. Stockstill and Berger (2001) have modeled these effects at locations along the Mississippi River, the Illinois Waterway, and coincidentally, in Sundown Bay at ANWR, Texas. The latter is a narrow shallow embayment between the GIWW and coastal wetlands along the lower Blackjack Pennisula of Texas (Fig. 1).

The objectives of this study were to 1) quantify the spatial and temporal variability in total suspended sediment (TSS) exchange and bedload sediment movement in tidal creeks at ANWR and 2) to understand the roles of various environmental drivers (tides/water levels, wind, inflows, barges, etc.) in shaping this variability.

It was hypothesized that water and TSS movement would be controlled by drivers such as wind, tide, storms, and barge-induced currents. Bedload transport was hypothesized to be influenced by the barge-induced changes in creek current direction and velocity.

1.1. Site Description

The marsh surface at ANWR is infrequently inundated as diurnal tides typically reach insufficient heights to flood the marsh. Instead, spring tides, wind tides, and intra-annual high water periods in the Gulf of Mexico are largely responsible for flooding

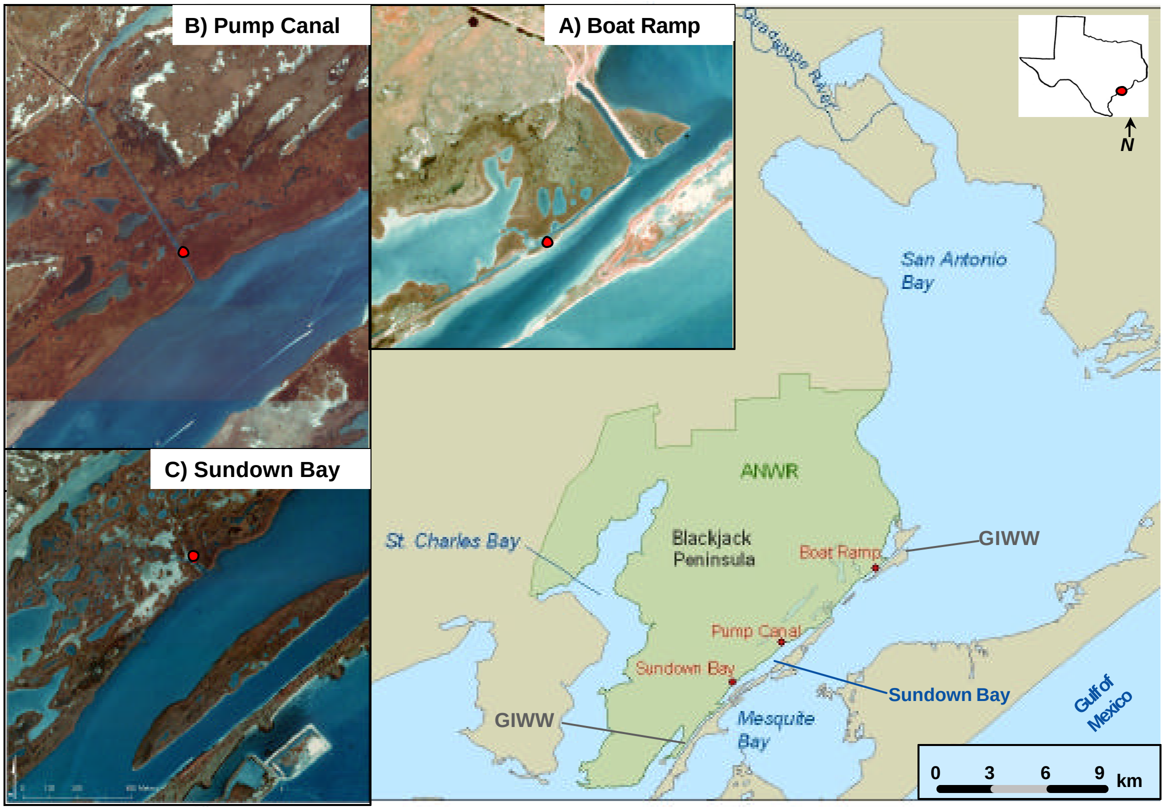

Fig. 1. Location.
Location of study area within the state of Texas as well as in relation to features such the Guadalupe River mouth, San Antonio Bay, Sundown Bay, Blackjack Peninsula, and the Gulf Intracoastal Waterway (GIWW). Each of the three sites studied are shown in the aerial photographs. A) Boat Ramp is very close in proximity to the GIWW. The dead end canal to the northeast accesses the Aransas National Wildlife Refuge boat ramp. B) Pump Canal is a man made canal whose mouth is separated from the GIWW by a shallow expanse of water that makes up Sundown Bay. The visible boat traffic in the image defines where the GIWW is. C) Sundown Bay Creek site is named for the bay in which it is located, and its mouth is separated from the GIWW by the bay and a long narrow island paralleling the GIWW. The creek itself is the shortest of the three, and its tributaries/distributaries branch out quickly into the marsh and the various ponds.

these wetlands (personal observation). Tidal creeks are therefore the primary source of water and materials exchange between the marsh and bays (water does not typically enter the marsh directly from the bay side along the marsh edge). Most of the saltwater wetlands on the southeast side of Blackjack Peninsula are in close proximity to the GIWW. Three sites in the marsh along tidal creeks are the focus of this research. Each site is along the main stem of the creek near the mouth with no tributaries/distributaries occurring between the site and the confluence with the bay. The sites are spread over a space of approximately 10 km (Fig. 1). Matagorda and San Jose Islands separate San Antonio Bay and the adjacent bays from the Gulf of Mexico.

Boat Ramp is a natural creek that runs parallel to the GIWW with a general northeast-southwest orientation (Fig. 1). Boat Ramp's creek connects two large water bodies – the bay system and GIWW to one side, and a large inland lake to the other. Boat Ramp is the site furthest north and closest to the mouth of the Guadalupe River (approximately 26 km to the north). This creek is a part of a long linear feature of water probably marking the inland side of a historic beach front or overwash deposit.

The other sites are perpendicular to the GIWW (northwest-southeast orientation) and are located within the water body of Sundown Bay. Pump Canal is a man-made, straightened canal that is separated from the GIWW only by shallow open water (Fig. 1). It represents an area of marsh that historically (i.e., prior to the 1930's) had no connecting creek. This is the longest of the three creeks and it does not branch out into the marsh or serve as a direct connection for a large inland water body with the bay.

Sundown Bay Creek (SB Creek) is a natural creek that is separated from the GIWW by the same shallow open water (as was Pump Canal) and a narrow island. The creek is less than a hundred meters in length before it splits into many tributary arms that branch into the marsh (Fig. 1). The marsh surrounding SB Creek has a higher density of ponds relative to the other sites. SB Creek is furthest south and the furthest from the mouth of Guadalupe River (approximately 35 km distant).

In ANWR creeks, there is often a 5-20 cm layer of unconsolidated floc-like material (the bedload) along the bottom of the channels that mobilizes with the flow of water without entering suspension. This material is both organic and inorganic in character and seems to be composed of detritus from algae and submerged aquatic vegetation in addition to mineral sediment. Little is known about the specific sources and fate of this material in ANWR tidal systems. However, others have considered the importance of flocculated material as a source of biotic energy and nutrients in other wetland ecosystems (Hildrew and Townsend, 2002).

2. METHODOLOGY

These three sites were the focus of study for multiple, seven-day samplings conducted between May and September, 2004 (Table 1). Sampling platforms were built along the creek bank at each site to hold the equipment used. Pump Canal was the only site sampled during the first week. SB Creek was added beginning at week two. All three sites were incorporated into the study for the final three weeks (Table 1).

2.1. Flow

An American Sigma 910 area-velocity (A/V) flow meter was used to measure water level and velocity instantaneously at one-minute intervals at each site. Based on channel dimensions, water depth and water velocity were used by the flow meter to automatically calculate discharge at 1-minute intervals as well. Water level on the A/V meter was depth calibrated before each use.

At the conclusion of each sampling period, the data were downloaded to a computer and imported into a spreadsheet. Flow data were summed over four-hour periods in order to correspond with the suspended sediment samples that were collected every four hours. Each four-hour block of flow data was composed of the values collected two hours before and after a suspended sediment sampling. Cumulative flows were calculated for each of these four-hour blocks. Flux values were calculated as the product of a cumulative flow value and the TSS concentration corresponding to that period and location.

To compare outflow and inflow over the course of the study, all raw flow data taken by the flow meters every minute were arranged by site and by week. The data

Table 1.
Dates and sites represented by each of the six sampling events. Salinity, wind speed, and Guadalupe River discharge are given as mean values. Weather is as reported in field notes.

Date	Site	Salinity	Range of Water Level	Wind TCOON[1]	Guadalupe Discharge USGS[2]	Weather
5/17 to 5/21	PC	02ppt	34cm	SE 5.8m/s	2840cfs	Immediately following a rainy period.**
6/06 to 6/12	SB	09ppt	28cm	SE 7.4m/s	2563cfs	Dominated by tropical depression sitting in the Gulf for the first half of the week.
	PC	08ppt	40cm			
6/24 to 7/01	SB	10ppt	20cm	SE 4.2m/s	2980cfs	Frequent strong thunderstorms.
	PC	08ppt	--			
7/13 to 7/19	SB	13ppt	23cm	S 4.1m/s	2749cfs	Clear.
	PC	12ppt	19cm			
	BR	08ppt	33cm			
8/12 to 8/18	SB	07ppt	19cm	N-NE 3.3m/s	2624cfs	Clear. High pressure dominating.
	PC	05ppt	20cm			
	BR	04ppt	33cm			
8/27 to 9/03	SB	14ppt	--	E-NE 2.8m/s	2668cfs	Frequent rain showers and thunderstorms.
	PC	12ppt	17cm			
	BR	11ppt	25cm			

1. TCOON is the Texas Coastal Ocean Observation Network. (http://lighthouse.tamucc.edu/wiki/TCOON/HomePage)
2. USGS is the United States Geological Survey. (http://water.usgs.gov/)

** Large quantities of fresh water were entering from the marsh. This is the only sampling week in which water was out of the confined creek channel.

were then separated into positive and negative groups representing outflow and inflow respectively at each site for each week. Instantaneous flow values were multiplied by 60 to estimate flow over one minute. A sum was determined for each group. The sums of positive and negative flow values were compared for each site during each week in order to see whether outflow or inflow dominated during a sampling period.

To check the A/V meter's accuracy, the cross-sectional discharge of one creek was determined using a calibrated hand-held electromagnetic Marsh-McBirney velocity meter. Pump Canal was chosen for the test because of ease of access. Velocity measurements were taken at regular intervals across the channel. The measurements were made in the center of 122 cm subsections at approximately 0.6 of the subsection depth. A mean velocity was determined for the channel and its subsequent discharge calculated. This was compared with the discharge calculated by the stationary flow meter. The handheld measurements to determine cross-sectional discharge were taken six times over the two-day period of November 3 and 4, 2004, after the six weeks of sampling were complete.

2.2 Suspended Sediment

2.2.1. Field

An automated water sampler (American Sigma 900) was used to retrieve water samples from the tidal creeks for TSS analysis. A length of tubing that reached 8 m into the channel was attached to the sampler. The intake end of the tubing was kept in a fixed position in the water column. Samples were integrated across a 180 cm section of channel through an attachment made from 1.3 cm diameter perforated PVC pipe.

The automated water sampler was programmed to draw two 1 L samples every four hours (8 pm, 12 am, 4 am, 8 am, 12 pm, and 4 pm) for each week-long sampling period. Prior to each sampling, the automated water sampler was programmed to purge and rinse itself. Duplicate samples were taken for analytical replication and for quality assurance. The samples were retrieved twice each day, once after the 8 am sampling, and once after the 4 pm sampling. Arrival at the site for collection did not occur prior to the 8 am or 4 pm automated sampling in order to keep from artificially mobilizing sediments by boat and foot traffic.

2.2.2. Laboratory

In the laboratory, bottles were organized by site and time, and salinities were measured with a portable refractometer. For the first two weeks of sampling, duplicates were processed every three to four samples. Later, duplicate determinations were reduced to one out of every eight samples because originals and duplicates were in agreement. A measured volume of each sample was filtered through pre-rinsed, ashed, and weighed 47 mm GF/F filters. Filtration was done at a constant vacuum pressure via vacuum pump. The filter was stored in an air and water tight Petri dish until it could be dried. After drying at 70°C until the weight became constant, each filter was weighed, and the weight of the suspended sediment was obtained after subtracting the initial filter weight. The TSS concentration was calculated by dividing the weight of the suspended sediment by the volume of water that had been filtered. Bottles were acid washed before returning them to the automated water sampler.

To account for residual salt on each filter, ten filters were tested for water retention. The same pre-rinsed, ashed, and weighed 47 mm GF/F filters were soaked with deionized water and then subjected to the constant vacuum until no standing water remained on top of the filter (same treatment as TSS samples). These wet filters were then weighed to obtain the mean weight of water retained. A correction factor based on this water weight and the salinity of each sample was subtracted from each TSS value, reducing the initial TSS concentration recorded by the proportional amount of salt.

2.3. Bedload Sediment

2.3.1. Field

Bedload movement was measured during the last four sampling periods. This sampling protocol was only carried out at one site because of available time and equipment. Pump Canal was chosen because of its uniform dimensions and straightness. The channel area studied for bedload movement was a few meters upstream from the research platform and TSS sampling in order to minimize disturbance.

The method and equipment were adapted from ongoing research currently being conducted in the Florida Everglades by Dr. Daniel Childers of Florida International University (Childers, 2004). It involved deploying four traps on the bottom along the width of the channel. One was placed near each bank, and two were nearer the middle. Each trap was a box 13 cm square and 30 cm long (Fig 2). The box opened at each end via a vertical sliding door. Each time a trap was set, it was submerged, filled with water, and placed firmly on the substrate with its length parallel to the flow direction. The

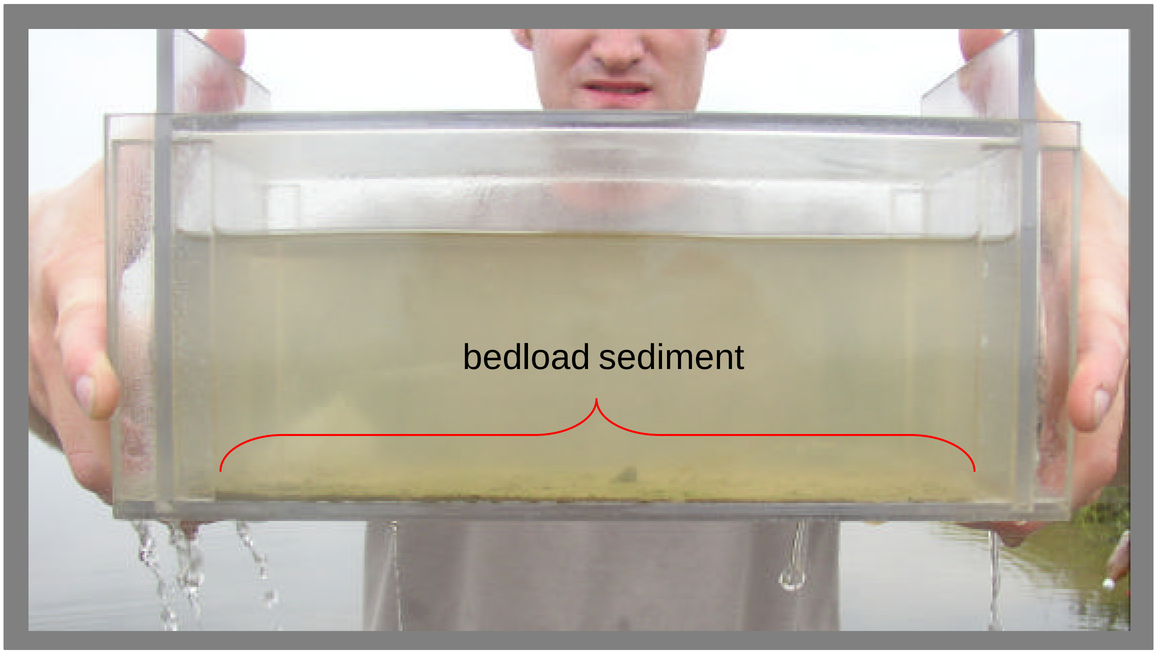

Fig. 2. Bedload.
A bedload trap after several hours of deployment. The sediment layer is visible along the bottom. Water can be seen draining around the doors of the trap with no effect on the trapped sediment.

doors were then removed. Over time, moving bedload and flocculated material entered the box with flow.

To retrieve the trap, the doors were closed and the box, containing trapped water and bedload, was removed from the water. Water would slowly drain from the box around the doors, allowing the sediment to remain stationary on the trap floor (Fig. 2). When the water had mostly drained, the contents of the box were poured into a plastic bag. This was done by sloshing the remaining water until the sediment was in suspension and then pouring it from the trap. Any remaining sediment on the box floor was rinsed into the bag with Pump Canal creek water. If suspension of sediment in the box accidentally occurred while handling the trap, the entire contents were immediately put into a plastic bag in order to minimize sediment loss.

Traps were deployed over any one of four basic time intervals throughout a week of study. In general, the intervals coincided with the TSS samplings. Traps would be deployed during the day between the 8 am collection and the 4 pm collection. They would also be deployed overnight from the 4 pm collection to the 8 am collection the following morning. Occasionally, they were left for a full 24 hours. Effort was made to minimize disturbance of sediment during trap set-up and retrieval.

There were also seven occasions where the boxes were deployed over five minute intervals in order to capture sediment movement from the influence of a specific barge that was passing. Most of these 5-minute samplings took place outside of the May to September sampling time and only one box was used at a time. It was deployed in the center of the channel for five minutes prior to barge arrival and then for another five minutes during barge outflow. Only outflow currents were measured because of the time frame in which the influence of a barge occurs and the number of hands available to deploy and retrieve traps. None of the bedload measurements can account for sediment that moved all the way through the trap before collection.

To accompany bedload data taken from the traps, measurements of bedload thickness were taken across a single transect at the Pump Canal site during each sampling trip (except for the first sampling) in order to monitor any changes that may have occured over time. A measuring tape was stretched across the channel, and measurements were taken every 60 cm. A section of 1.3 cm diameter PVC pipe was used as a probe and pushed through the bedload sediments until it made contact with the original, cohesive clays that comprise the surrounding marsh. Because Pump Canal is an artificial channel, this boundary was distinct and easy to determine. An average was taken if differing thicknesses were measured at one point. Thickness measurements were taken by measuring the portion of the PVC pipe that had penetrated the bedload material. Water depth (surface of water to surface of sediment) was also recorded. These transects were plotted as cross-sections of the channel showing channel shape and sediment thickness.

2.3.2. Laboratory

Bedload sample masses needed to be corrected for the mass of salt because salinity varied among sampling periods as well as within them. The amount of water accompanying each sample was also not consistent. The method used to remove salts from the bedload samples was adopted from Rivers et al. (1982) where gypsum was removed from soil samples placed in dialysis tubing and immersed in fresh water.

Each bedload sample was transferred from the plastic bag to a length of dialysis tubing cut to fit. One end was sealed with a watertight clip while the upper end was clamped to the inside rim of a 19 L bucket filled with deionized water. Several dialysis tubes were clamped to one bucket and the water was changed daily until the salinity in the bucket consistently read zero on a handheld refractometer. Zero salinity was typically reached after only about three days.

Bedload sediments were then transferred from the dialysis tubes into individual preweighed aluminum pie pans. Samples were dried at 105ºC for 24 hours once all standing water had evaporated. Once dry, the pans were weighed and the initial weight of the pan was subtracted to obtain the dry mass of bedload that had accumulated in the trap. Total mass of bedload trapped was used for analysis. The mass values were grouped first by location in the stream channel and then by amount of time the trap was deployed. The data were also normalized to one hour by dividing each value by the number of hours it represented to estimate the amount of sediment accumulated in one hour.

3. RESULTS

3.1. Flow

Water level data collected by the A/V meter clearly showed changes in water depth at one minute intervals. On the other hand, the velocity data collected by the A/V meter were noisy, and variations were not typically visible at small scale (Fig. 3). A regular rise and fall in the water level data that occurred over approximate 24 hour intervals was interpreted as a diurnal, lunar tide. These tidal fluctuations were easily visible in the water level data (Fig. 3). A tidal range of about 10 cm was common at each site with a maximum water level range of 20 to 40 cm per site, per sampling period. Numerous fluctuations in water level at Boat Ramp and Pump Canal were also observed. These occurred over the scale of minutes, sometimes exceeding the diurnal tidal range. These were later found to be barge-induced drawdown currents through comparison of corresponding field observations and water level data. Over the course of this study, inflows (negative flow values) predominated at each of the three sites.

The impact that a single barge had was different at each site. The magnitude of impact was also variable with bay-wide water levels. Boat Ramp, the site closest and most exposed to the GIWW, experienced water level fluctuations on the order of 10 cm anytime a barge passed and at any water level. Pump Canal typically experienced fluctuations on the order of 5-6 cm. During the week of July 13 to 20, bay water levels were 20 to 30 cm less than they had been during other sampling trips. Barge-induced water level fluctuations at Pump Canal were reduced to 2 or 3 cm. No barge impact was perceptible in the A/V data at SB Creek (Fig. 3). Except for SB Creek, water

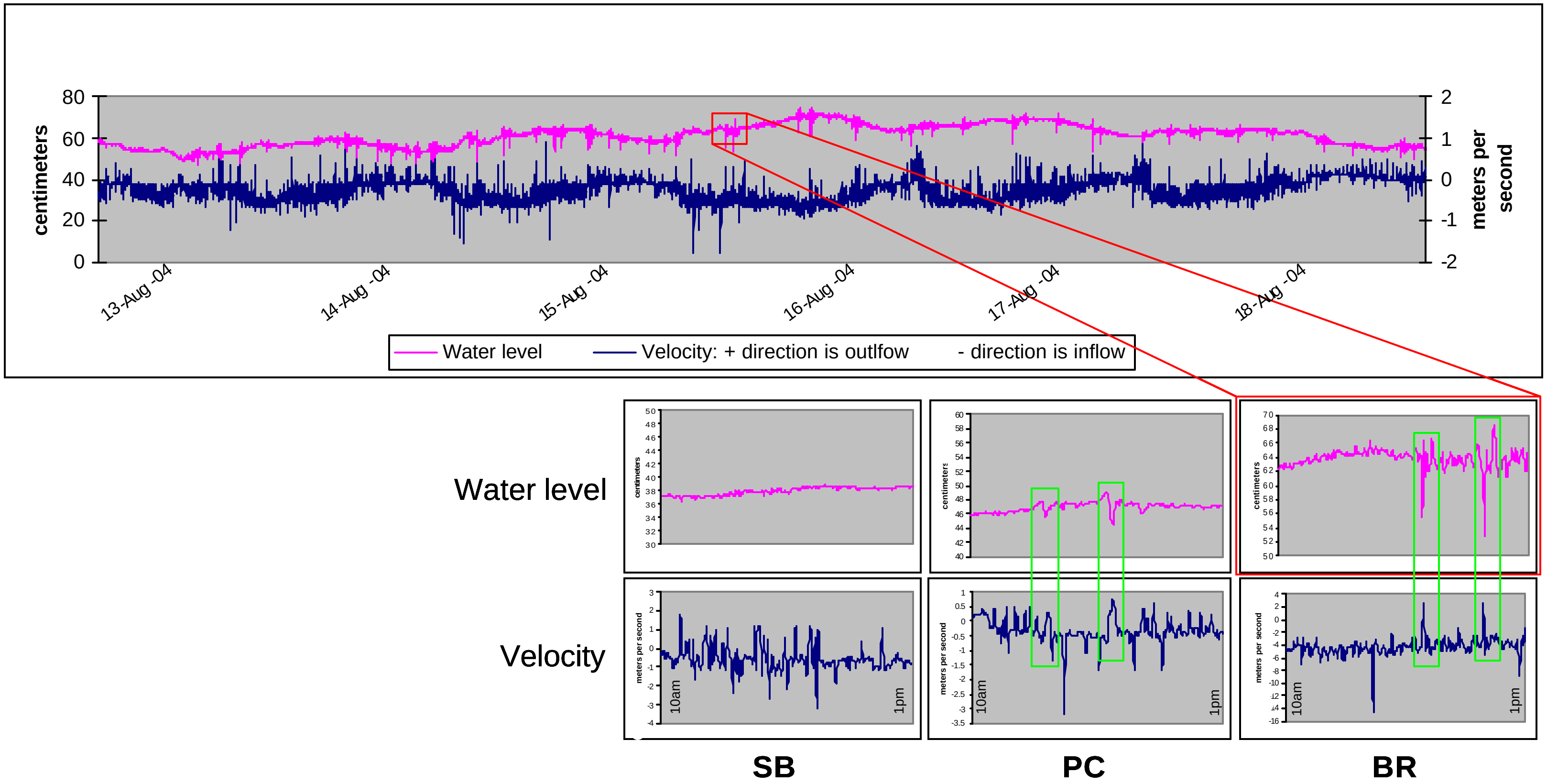

Fig. 3. Barge impact.

Water level (in red) and current velocity (in blue) collected at the Boat Ramp site from August 12 to 18, 2004 show natural tidal variation and barge influences on the creek hydrograph. A pair of passing barges was selected from the data and identified at each of the three sites, beginning with Sundown Bay Creek. The barge signature was most discernable in the water level data.

displacement from an individual barge passing was of comparable magnitude with tidal fluctuations. Tidal range was consistently around 10 cm during this study.

During five of the six samplings the number of barges passing the study areas ranged from a high of 69 to a low of 25 per sampling period. No data from which the number of barges could be counted were recorded during the third week of study.

Negative flow typically exceeded positive flow in the creek discharges measured during the six weeks of study (Fig. 4). Water level and magnitude of flow rose and fell with tidal cycles, but inflows dominated these samplings. There were only two instances where measured positive flow totaled more than negative flow at a given site for a week of sampling. These were from the first sampling at Pump Canal (Pump Canal was the only site monitored during the first week) and the fourth sampling at Boat Ramp. The other two sites exhibited greater negative flow than positive flow during the fourth week (Fig. 4).

For the purpose of scale, mean inflows over the entire course of study were 221,000 m^3/week at Boat Ramp (representing three weeks of data), 163,000 m^3/week at Pump Canal (representing five weeks of data), and 117,000 m^3/week at SB Creek (representing four weeks of study). Mean outflows at were 86,000 m^3/week at Boat Ramp, 41,000 m^3/week at Pump Canal, and 13,000 m^3/week at SB Creek. These were calculated from the all instantaneous A/V flow data estimated to the minute, and grouped into negative and positive flow by site.

A test conducted at Pump Canal of the accuracy of the A/V meter used in this study found that it underestimated flow by nearly 50% (Table 2). The greater the flow

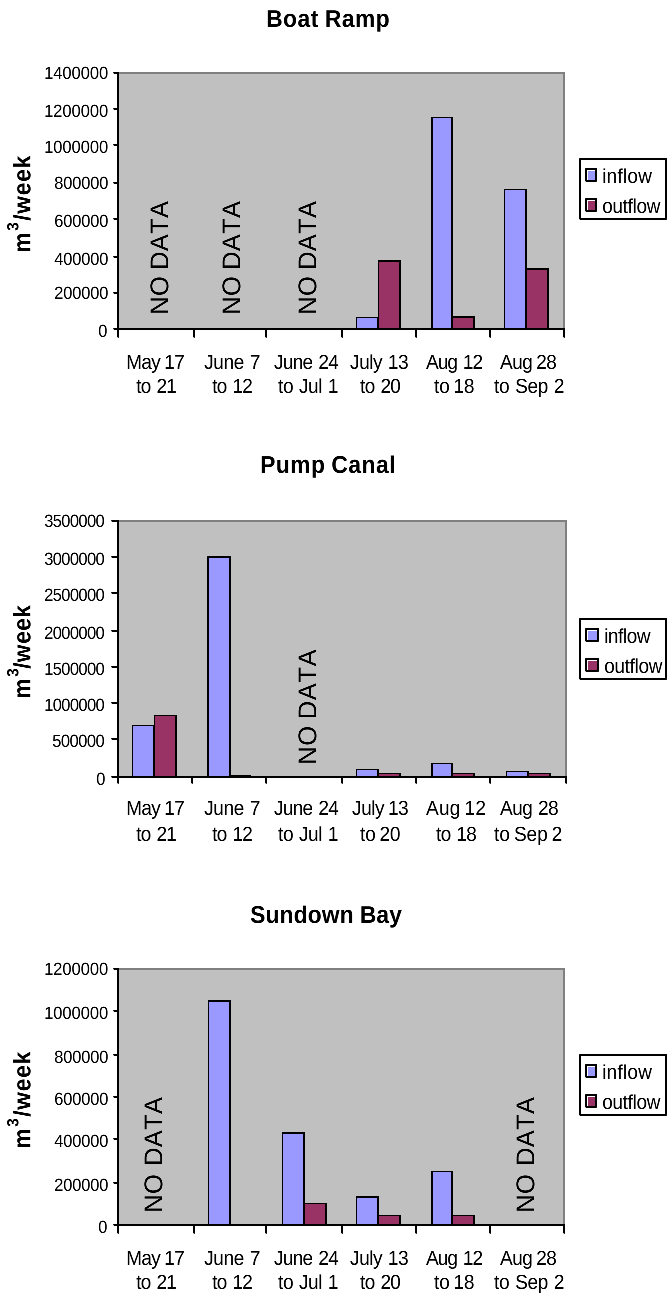

Fig. 4. Inflow versus outflow. The bars represent the total of all estimated inflow (negative flow) and outflow (positive flow) data recorded every minute at each site over the duration of the study. “No Data” indicates no flow/discharge data collected at that site during that particular sampling period. Inflow typically exceeded outflow during the six weeks of study.

Table 2.
A/V meter versus hand-held velocity meter.
Comparison of cross-sectional discharge measurements taken from Pump Canal with a hand-held Marsh-McBirney velocity meter and calculated discharge from an American Sigma 910 A/V meter. Hand-held measurements were better able to take channel geometry variability into account where the automated flow meter must assume the channel to be of uniform dimensions and flow rates.

Date	11/3/2004	11/3/2004	11/3/2004	11/4/2004	11/4/2004	11/4/2004
Time span	2:05 to 2:20pm	3:43 to 3:57pm	4:00 to 4:14pm	11:47 to 11:59am	12:00 to 12:10pm	12:11 to 12:21pm
Hand-measured discharge (m^3/s)	**1982**	**1506**	**1536**	**860**	**681**	**712**
Flow meter measured discharge (m^3/s)	**850**	**597**	**724**	**430**	**410**	**413**

recorded by the A/V meter, the greater the error. There is likely similar error at the other sites. Flow rates and channel depth were variable across the width of the creek and not uniform as the flow meter must assume to make its calculations. Flow values are still relatively representative of each site. No correction factor was applied because there is not data from the other two sites to verify that the A/V meter also underestimates by 50% at them as well.

3.2. Suspended Sediment

It was discovered after completion of the six weeks of study that the filters used to obtain TSS concentrations retained a mean water weight of 0.46 g. This meant that the weight of salt left in a filter could range from around 0.5 mg to about 7 mg depending on the salinity at the time an individual sample was collected. Therefore, a correction factor was applied to each sample's TSS value reducing it proportionately according to the mean water weight and their respective salinity.

There were rain events of greater than 3 cm prior to weeks one and three. No significant rain occurred after the end of June, 2004 till the end of the study on September 2, 2004 (Fig. 5). However, mid June through mid July was a period of high discharge from the Guadalupe with two peaks over 566 m^3/s. Typically the Guadalupe River remained under 283 m^3/s between March and mid June, then under 140 m^3/s after mid July (Fig. 6) (USGS, 2005). Compared with the 24 previous years, the summer of 2004 experienced higher than normal inputs to San Antonio Bay from the Guadalupe River (Fig. 7) (USGS, 2005).

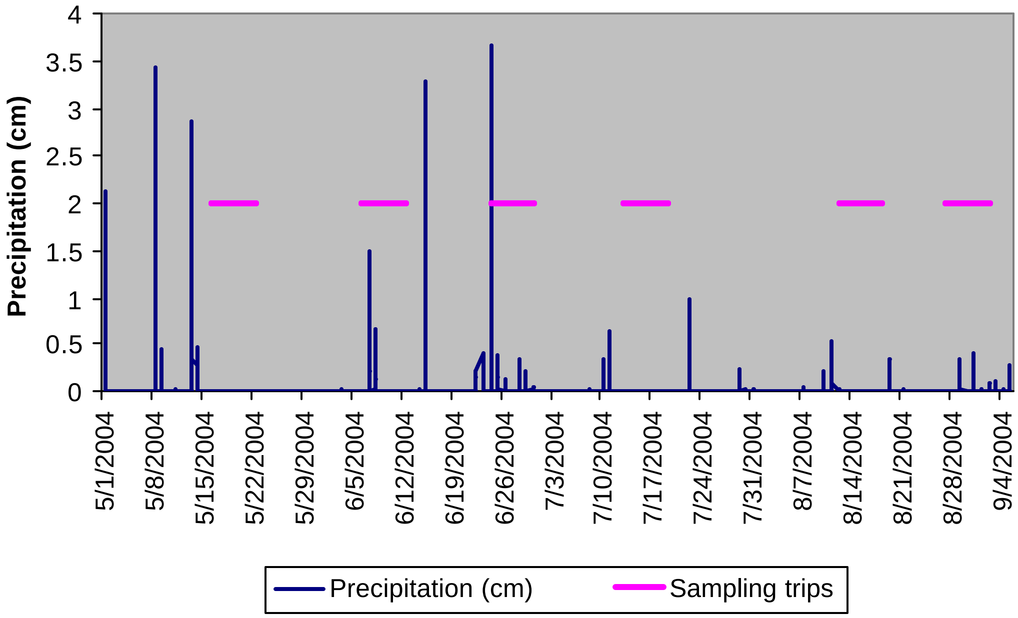

Fig. 5. Precipitation.
Hourly precipitation measured at the Aransas National Wildlife Refuge headquarters (Austwell, TX) from May 2004 to September 2004.

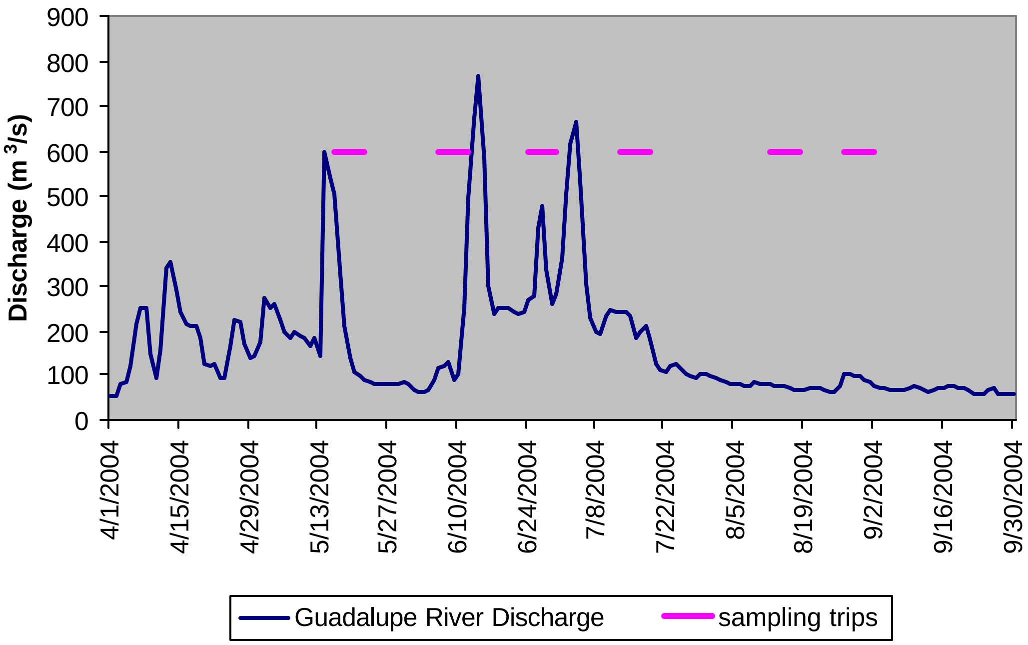

Fig. 6. Guadalupe River discharge during study period. Each value was measured as a combination of Coleto Creek near Victoria (station #8177500), the San Antonio River near Goliad (station #8188500), and the Guadalupe River near Victoria (station #8176500).

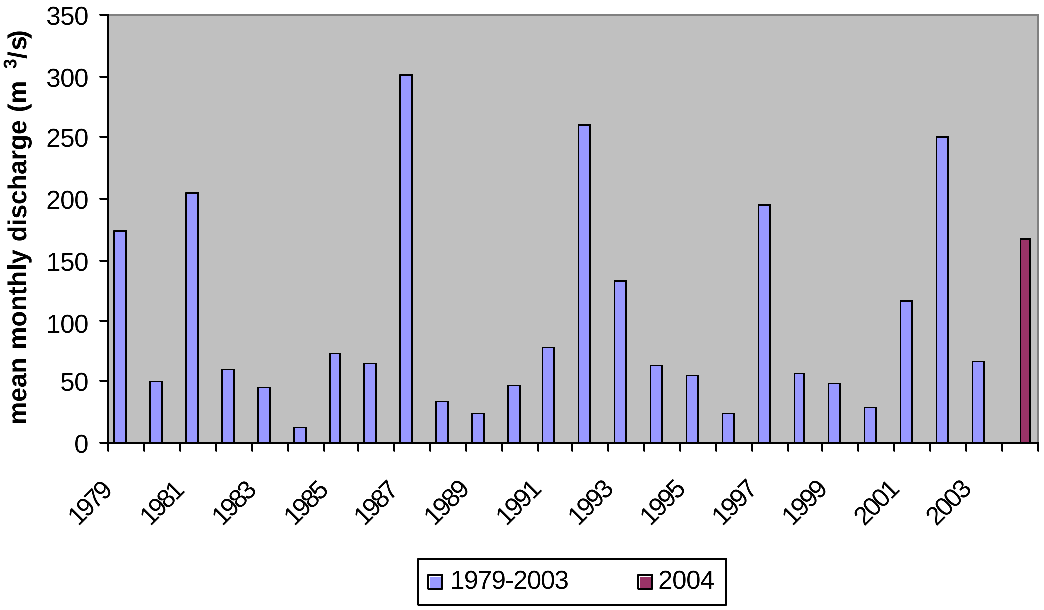

Fig. 7. 25 years of mean Guadalupe River discharge.
Mean instantaneous discharge of the Guadalupe River for the spring and summer months of April to September. Each value was measured as a combination of Coleto Creek near Victoria (station #8177500), the San Antonio River near Goliad (station #8188500), and the Guadalupe River near Victoria (station #8176500). Discharge into San Antonio Bay during the summer of 2004 was higher than normal. Notice that mean discharge during the summer of 2004 was above 160 m^3/s. This was the case only 6 other summers from 1979 to 2003.

Concentrations of TSS were variable throughout the study and among sites (Fig. 8). Considering the last three weeks of study (where there was data collected at all sites), Pump Canal tended to be the lowest in mean TSS concentration and Boat Ramp was highest for two of the three although these were not statistically significant (Fig. 8). Overall, TSS was higher at each site during the July 13 to 19 sampling than any other week. The lowest TSS values at each site were measured during the August 12 to 18 sampling. During this week however, mean TSS at the Boat Ramp site was nearly twice that of each other site (Fig. 8). For the other two samplings during which TSS was measured at Boat Ramp, TSS values were relatively much more similar in value among sites (Fig. 8).

TSS flux values calculated during this study were usually negative, corresponding with the magnitude and direction of flow (Appendix A). This meant that the flux was mostly directed towards the marsh because most flow measured was negative. The flux values measured at the Boat Ramp site were the most variable during each week data were collected there. Flux values ranged over the entire study from -106,000 to +23,000 g TSS/4 hr at SB Creek, from -117,000 to +75,000 g TSS/4 hr at Pump Canal, and from -128,000 to +54,000 g TSS/4 hr at Boat Ramp (Appendix A).

There was a positive relationship between salinity and TSS (Fig. 9). Salinity values were generally low throughout the study as a result of high riverine inflows and direct precipitation (Table 1). Salinity values ranged from 4 to 17 ppt at SB Creek, from 1 (measured during the first week of study) to 16 ppt at Pump Canal, and from 2 to 15

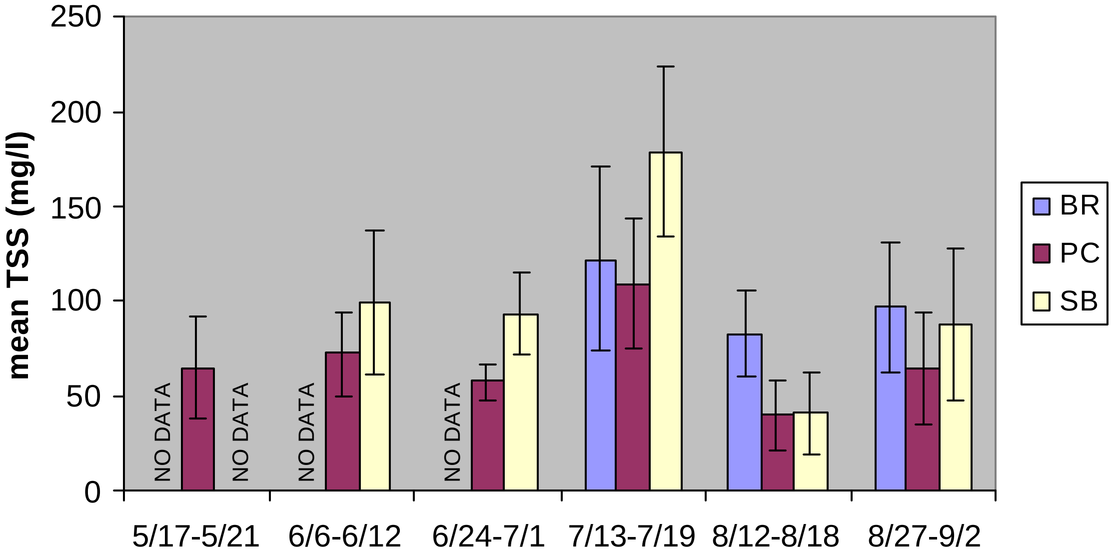

Fig. 8. Mean TSS concentrations for each study area by week. Bars represent +/- one standard deviation. PC tended to be lowest in TSS concentration. SB was always higher than PC and was even higher than Boat Ramp once after Boat Ramp became a part of the study. TSS was highest in concentration at all sites during the study period of July 13 to 19.

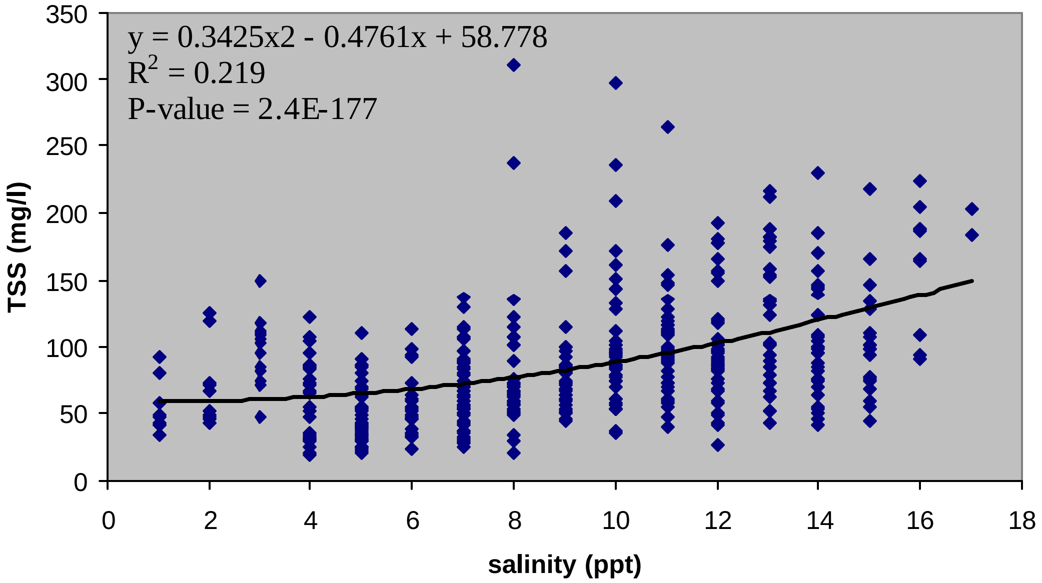

Fig. 9. TSS versus salinity. TSS and salinity are positively related to one another as shown in this scatter plot and fitted line. These data represent all TSS and corresponding salinity values measured throughout the study.

ppt at Boat Ramp. TSS values ranged from 20 to 312 mg/l at SB Creek, from 19 to 238 mg/l at Pump Canal, and from 38 to 296 mg/l at Boat Ramp.

3.3. Bedload Sediment

A loose pattern of bedload movement across the channel transect existed at Pump Canal. Less sediment was typically trapped on the depositional bank of the stream that contained seagrass, while more bedload was trapped on the opposite side of the channel where flow was generally unobstructed. Flow rates were confirmed to be greater along the unobstructed bank while conducting the hand-held flow measurements described earlier. Twenty of 27 total bedload samplings had the highest amount of sediment trapped in the unobstructed half of the channel. The dry weight of bedload measured in a trap ranged from about 1 g up to 135 g. Of the 27 samplings, a mean of 19.7 g was measured for the side of the channel containing seagrass and 31.4 g for the unobstructed side. Not including the five-minute time spans, the ranges of bedload dry weights for the two main deployment time spans were very similar. For bedload samples collected over a span of 15 to 25.5 hrs, the range was 3.55 g (with an outlier of 0.9 g) to 135 g. For amounts collected over a span of 6 to 8 hrs, the range was 6 g to 62 g. The data set representing the 15 to 25.5 hr trap deployment time contains 95 values and the data set representing the 6 to 8 hr trap deployment time contains 33 values. Only 6 of the 95 samples were above 60 g.

The highest levels of bedload trapped occurred during the July 13 to 19 sampling period. For all dry weights measured in a sampling period, the mean bedload weight for

July 13 to 19 was 37 g. It was 29 g for June 24 to July 1, 13 g for August 12 to 18, and 14 g for August 27 to September 3.

The data normalized to one hour did not show these trends as readily (Table 3). Overall, the mean amount of sediment accumulated was still slightly higher on the unobstructed side of the channel, but the standard deviations were nearly equal to the means (Table 3). The sum of all dry masses normalized to the hour for each creek position did show slightly higher amounts on the unobstructed side of the channel (Table 3).

Sediment thickness above the manmade channel floor also varied with regularity, both along the transect and over time. Sediment thickness was always greatest on the side of the channel where flow was obstructed by grass beds and least on the unobstructed side. Generally speaking, more bedload was trapped where sediment thickness was least and flow was unobstructed, and less bedload was trapped where sediment thickness was greatest and flow was impeded by grass beds. The obstructed bank could be from 5 to 25 cm in sediment thickness above the original channel floor, and the unobstructed bank could be from 0 to 10 cm (Appendix B).

Barge outflow increased the movement of bedload sediments. In each of the seven cases where barge outflow could be sampled and compared with natural outflow, bedload trapped was greater by at least 1.5 g. The greatest difference measured was nearly 7 g (Fig. 10). If the amount measured can be extrapolated across the channel, then anywhere from 90 to over 400 g (dry weight) of sediment moved outward along the bottom in a five-minute period during a single event of barge outflow.

Table 3. Dry weight of bedload.
Dry weight in grams of the bedload collected from traps normalized to one hour. For creek position, "O" means the value was collected on the side of the creek obstructed by seagrass and "U" means the value was collected on the unobstructed side.

Sample Date/Time	Creek Position and Sediment Dry Weight (g) normalized to one hour			
	O	O	U	U
12pm6/25-10:45am6-26	2.9	5.9	5.0	n/a
12:15pm6/26-7:15pm6/26	4.0	1.5	1.5	1.2
7:15pm6/26-10:15am6/27	3.0	n/a	2.7	0.7
10:15am6/27-4:15pm6/27	2.0	2.2	9.3	1.1
4:30pm6/27-10:45am6/28	1.5	0.5	n/a	1.6
10:45am6/28-6:15pm6/28	2.4	1.2	3.9	1.3
6:15pm6/28-1:00pm6-29	0.9	0.6	2.5	n/a
1:00pm6/29-10:15am6/30	0.5	0.6	0.9	1.4
10:15am6/30-9:30am7/1	0.9	0.7	1.5	n/a
11am7/14-6pm7/14	n/a	8.9	2.5	4.1
6pm7/14-11:45am7/15	2.3	1.3	5.1	3.3
11:45am7/15-12:45pm7/16	1.0	1.2	2.6	2.3
12:45pm7/17-10:45am7/17	0.8	0.6	1.6	2.0
10:45pm7/17-12:30pm7/18	2.9	1.6	1.9	2.5
4:45pm7/17-12:30pm7/18	1.4	1.7	n/a	2.5
12:30pm7/18-12:30pm7/19	n/a	1.9	4.1	5.6
11:30am8/13 to 10:30am8/14	0.3	0.8	0.7	0.4
10:30am8/14 to 9:30am8/15	0.4	1.1	1.0	n/a
9:30am8/15 to 4:30pm8/15	1.5	1.0	n/a	3.7
4:30pm8/15 to 2:00pm8/16	0.3	n/a	0.4	0.5
2:00pm8/16 to 10:00am8/17	0.3	0.4	1.0	0.4
10:00am8/17 to 10:30am8/18	0.5	0.2	0.3	0.9
11:00am8/28 to 7:15pm8/28	0.8	0.7	5.6	1.5
7:15pm8/28 to 10:30am8/29	0.3	0.1	0.4	0.8
10:30am8/29 to 9:15am8/30	0.2	0.5	1.7	0.9
9:15am8/30 to 10:15am8/31	0.6	0.3	0.9	1.1
10:15am8/31 to 11:30am9/1	0.4	1.0	0.7	n/a
11:30am9/1 to 11:15am9/2	0.1	0.3	0.2	0.4
Sum	**32.2**	**36.7**	**58.0**	**40.2**
Mean	**1.2**	**1.4**	**2.3**	**1.7**
Standard Deviation	**1.1**	**1.9**	**2.2**	**1.4**

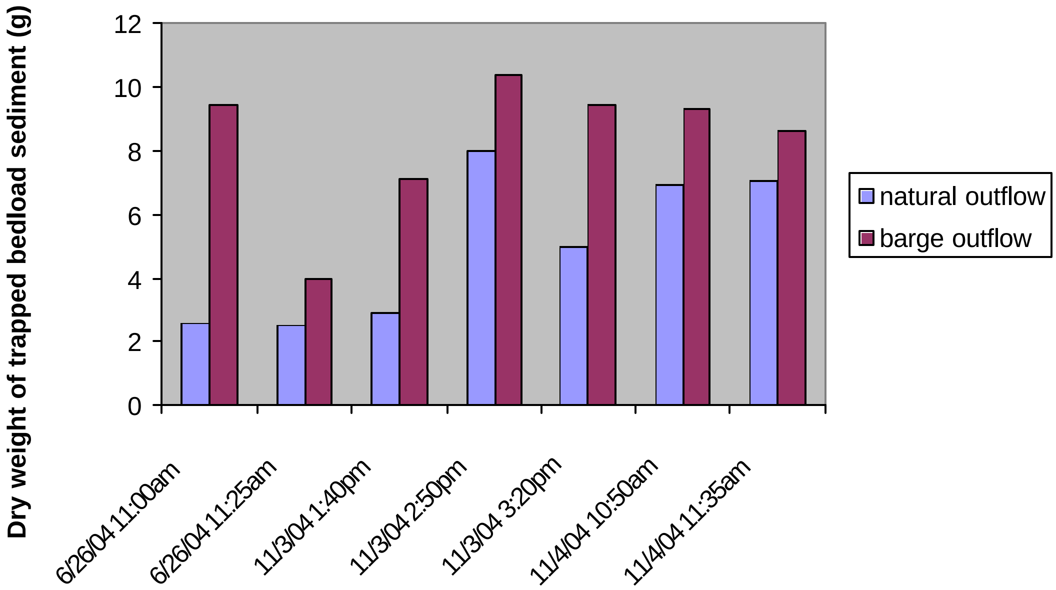

Fig. 10. Natural outflow versus barge-induced outflow. Each blue and red bar represents a five-minute period of time. In all seven barge passings sampled, barge outflow increased the movement of bedload sediments. This does not account for sediment that may have passed all the way through the trap before the doors were shut.

4. DISCUSSION

4.1. Flow

One of the most prominent characteristics visible in water level and velocity data is the influence of a passing barge. A typical response was a rapid outflow of water which lowered water level by several centimeters followed by an inflow that refilled the creek to its previous water level. This occurred in a space of time fewer than ten minutes. These data are consistent with the work of Stockstill and Berger (2001). Through modeling, they found that barge-induced currents within Sundown Bay itself are strongly directed toward the GIWW, which accounts for the observed drawdown of water level. Throughout the portion of Sundown Bay modeled (which does not include creeks), drawdown varied between 5 and 10 cm (Stockstill and Berger, 2001). Their model does not recognize or simulate the secondary currents in the opposite direction once the barge is passed, which are responsible for reflooding the tidal creeks, as was shown in the data of this six-week study.

Boat Ramp and Pump Canal each showed effects of passing barges. At Pump Canal the impact was lessened during low water levels because the creek mouth is separated from the GIWW by a shallow embayment. Barge impact was not muted at the Boat Ramp because the creek mouth empties almost directly into the GIWW (Fig. 1). SB Creek did not show any effect during the study.

The imbalance between positive and negative flow that existed during the six weeks of study was not anticipated. There is no known reason for negative flow to exceed positive flow in almost every case. The first possibility is the equipment took faulty measurements. The flow meter calculates flow according to the velocity and water level it measures and the channel dimensions entered into the software. The highly variable velocity measurements were partly a result of wind activity. It is possible that prevailing wind direction during the sampling period skewed the data toward inflow. As waves rolled up the creek from onshore winds, velocity readings may have reflected wave direction rather than flow direction. However, northerly winds persisted during the last two weeks of study, which should have forced water out of the creeks and into the bays (Table 1). Negative flow continued to be dominant at each site during these last two weeks of sampling.

A second possibility is that there is some connection between the marshes and the bay in another location, allowing flow to enter from the bay in one area and exit from the marshes in another. This circulation pattern has not been observed. If this flow pattern exists, the Guadalupe River could be the force behind it because of the substantial discharge it contributed to the system during the months of study (Fig. 7). The mean discharge from the Guadalupe River between the months of April to September, 2004 has only been exceeded 6 times in the last 25 years (Fig. 7). The San Antonio Bay and surrounding bay system has few inlets between it and the Gulf of Mexico. The major inlets are Aransas Pass on the southern extent of San Jose Island and at Pass Cavallo on the northern extent of Matagorda Island. They are 70 and 40 km from the river mouth respectively. One minor inlet called Cedar Bayou exists in between and is intermittently open. A hydraulic gradient of high to low must exist between the river mouth (a constant source of inflow) and the inlets to the Gulf of

Mexico, inducing a river-influenced flow pattern. Although they were modeling smaller systems, Healey, et al. (1981) conclude that water slope may play a role in the generation of velocity pulses. Further study during periods of lesser discharge from the Guadalupe River or continuous study over the course of a year may show correlation between river discharge rates and the balance of inflow and outflow in the tidal creeks along the Blackjack Peninsula. Bryce, et al. (2003) suggest that hydrodynamic and sedimentary sampling durations of up to a month may not be representative of long term trends. Each of the six sampling periods lasting no longer than a week may only coincidentally record greater inflow. There may be periods where greater outflow is recorded.

4.2. Suspended Sediment

Variability occurred in the TSS concentrations within a site, among sites, and among trips because of the influences of several factors such as tide, wind, water level, and water source. Unfortunately no major storm events took place during the study. Exposure to the GIWW (i.e. effects barge-induced draw down currents, potential for wave-induced re-suspension of TSS, etc.) does not appear to be a strong factor because there were times when SB Creek, the least exposed site, was the highest in TSS concentration values. During the last three weeks of study, SB Creek was always higher in TSS than Pump Canal which is more exposed to the GIWW in that it lacks an island barrier.

TSS influx can be correlated with tide because it rises and falls regularly throughout a sampling period with the water level fluctuations resulting from tidal oscillations (Appendix A). Flux is directly related to the flow of water as suspended materials like sediment are carried with the current. For example, the flux values measured at Boat Ramp had such a high range because of the large amount of water moving through the creek in comparison with the other two sites. Flow values measured at Boat Ramp exceeded those measured at Pump Canal and SB Creek by more than double.

Wind was likely one of the most influential variables, but its importance in controlling TSS exchange and creek hydrodynamics was difficult to discern. There are however some instances where wind can be separated from other variables, such as when wind was coming from the north and northeast during a sampling period rather than from the south and southeast as was the case for most sampling periods (Table 1). During periods of north-easterly winds (the final two sampling periods), the orientation of the creek at Boat Ramp was aligned with the wind direction (Fig. 1), and TSS values were higher than at other sites (Fig. 8). During the fifth week of study, mean TSS values at Boat Ramp were double those at Pump Canal and SB Creek (Fig. 8) whose orientations are nearly perpendicular to a northeast wind direction (Fig. 1).

The lowest TSS values at all sites were recorded during the sampling period of August 12 to 18. This week coincides with northerly winds and clear weather. Less TSS was being resuspended and blown landward as would be the case with southerly, onshore winds. No precipitation during the sampling period or in the weeks prior to it meant no major upland runoff was contributing to TSS. Salinity values were also at the lowest since the first week of study (the positive salinity correlation discussed later).

The reason for the high TSS values measured during the week of July 13 to 19 (Fig. 8) is not fully understood although it is likely a result of some interplay between water level and wind. Water level dropped throughout the duration of this sampling period to the lowest water level measured over the course of the study (Fig. 11). More sediment could have been re-suspended within the bay during lower water levels because wave base would have been in closer contact with the bottom. Because of negative flow, higher levels of suspended sediments in the bays would lead to higher TSS values in the creeks. However, during this sampling period Boat Ramp was a net inflow exception, and positive flow (and therefore a net efflux of sediment) was dominant throughout the sampling period while the other two sites continued the trend of negative flow and net influx of sediment (Fig. 12). Positive flow dominated because water was draining from the lake in response to decreasing water level. TSS values remained high because wave base within the lake became increasingly in contact with the bottom.

It was noted over the course of the study that a thin layer of sediment had usually settled onto the top of the bedload sediment traps prior to collection. This layer of sediment was visibly thicker during the week of July 13 to 19, corresponding with the higher TSS values measured. Amounts of bedload sediment trapped were also higher during this sampling period, suggesting that TSS contributes directly to bedload or that TSS and bedload values are related.

The correlation between salinity and TSS is probably a reflection of water source which carries two possible explanations. First, water originating from the bay is going to

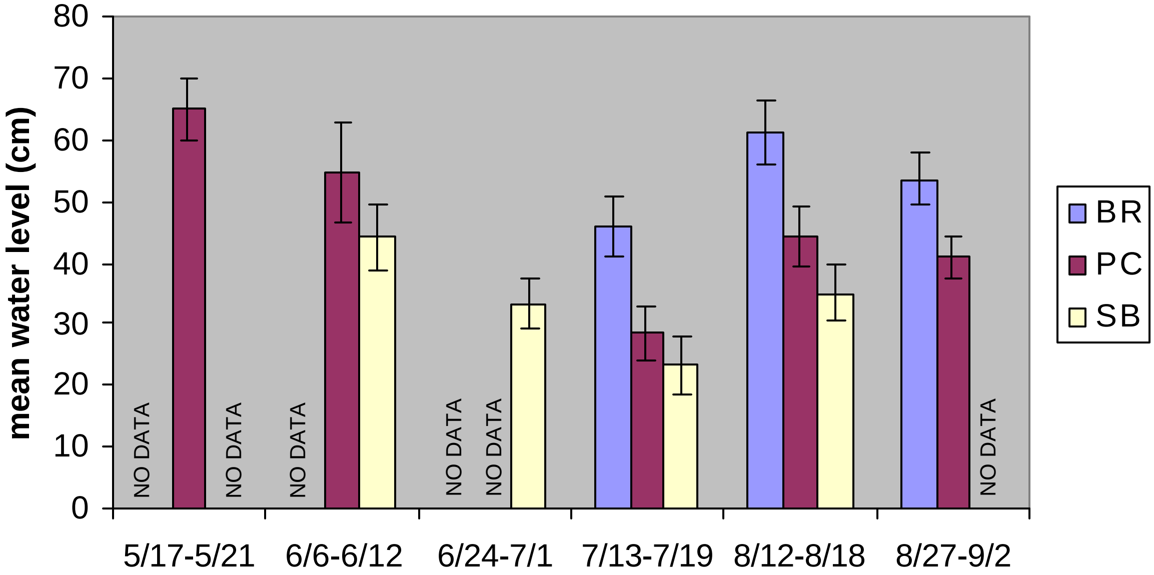

Fig. 11. Mean water level over the six study periods at each site. The lowest water levels to occur during a study period were from July 13 to 19. Ranges represent +/- one standard deviation. The A/V sensors were always placed in the same position when deployed.

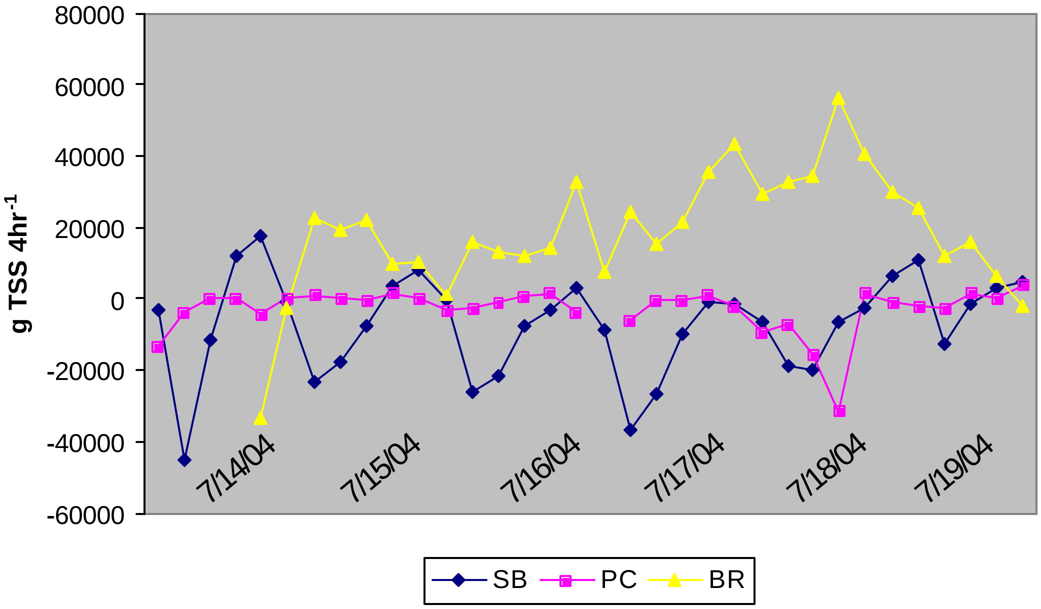

Fig. 12. Flux: July 13 to 19, 2004.
TSS flux values for all three sites from the sampling period during July 13 to 19. Notice that Boat Ramp values are positive nearly the entire time (net efflux) and that Pump Canal and SB Creek remain negative over most of the sampling period (net influx).

carry more sediment than freshwater coming from the upland through the marsh because of the greater potential for resuspension within the bay. When salinity was higher, it is more likely that the dominant source of water was from the bay, which corresponds with TSS influx being higher. When salinity was lower, upland runoff probably made up more of the tidal creek water. Water entering the creeks via the marshes as runoff or groundwater was not contributing as much sediment. However, there was very little precipitation measured after the month of June. It is possible that localized rainstorms still impacted the marshes without being recorded in the rain gauge at ANWR headquarters. Afternoon thunderstorms observed from the field moved in distinct cells and rained heavily across narrow bands of land.

The second possible explanation regarding the correlation between TSS concentration and salinity, though beyond the scope of this research, is a function of differences in chemistry between fresh water and seawater. It is possible that higher ratios of seawater to freshwater will lead to higher amounts of TSS in concentration and that salinity is a relative indicator of the amount of seawater present (Langmuir, 1997). Certain chemical parameters such as pH and any combination of others may exert control over the amount of sediment in suspension (Sassen, 2003). When salinity is low, more freshwater is present, be it from the Guadalupe River or from upland runoff. Freshwater tends to be of a lower pH than seawater for example, and this can promote a range of particle charges which can in turn promote flocculation (Sassen, 2003; Seaman et al., 1997; Langmuir, 1997).

The influence storm events, such as hurricanes, have on suspended sediments in these tidal creeks is not known. No major storm events affected the Texas Gulf coast during this study. Storms are likely an important mechanism for mobilizing sediment and transporting it greater distances into the marshes (Davis et al., 2004, Wren and Leonard, 2005, Rejmanek et al., 1988), especially when they coincide with periods of relatively high water level and incoming tides (Leonard et al., 1995; Stevenson et al., 1988).

4.3. Bedload Sediment

Bedload movement in Pump Canal was likely a function of the presence of the seagrass on one side of the channel. This likely impeded water flow resulting in lower flow velocities for that side of the channel. The slower velocities do not move as much bedload, and the grass can intercept sediment already in motion – serving both to trap bedload and suspended sediment which may settle and become bedload. As a result, less bedload was collected in the sampling traps on the obstructed side of the channel and the sediment thickness on the bottom is greater.

Little difference between shorter and longer collection periods was observed because equilibrium is likely achieved as sediment moves all the way through the box and out the other side. This has been observed by Dr. Daniel Childers in his work with the bedload traps in the Florida Everglades (Childers, D., Personal Communication 2004). After the migrating “front” of bedload sediment has passed through the box, the layer blanketing the trap floor remains relatively uniform independent of time. It is dependent on time at a consistent flow rate until the leading edge of bedload sediments has reached the downstream end of the box, which can also be inferred from this work. In this study, the seven samplings targeting barge-induced flow and the natural flow prior to it are the only ones where the sediment in the trap is closely dependent on time because they occur at such short intervals and over periods of uniform flow.

The formation of deltaic features that exist at the mouths of the tidal creeks is likely a result of outward movement of bedload. These features were noted but never measured in this study. At SB Creek, the delta is not perceptible, but at Pump Canal, it is quite pronounced, as water depth decreases rapidly when exiting the creek mouth. The Boat Ramp site also has a delta, though it is continually reworked by the high energy of the nearby GIWW's deep water and boat/barge traffic. Given that SB Creek's delta was not present and that the site showed no impact from passing barges in the A/V meter data while Pump Canal's delta was pronounced and the site did show impact from a passing barge, there is a plausible case for barges exerting influence over delta formation (i.e. the outward movement of bedload).

Bedload moves with the current. Whether more moves in or more moves out of the system is something that should be quantified in future studies. This can only be done by monitoring bedload movement within tidal cycles. Unidirectional flow was sampled during this study only when individual barge passings were being sampled. It was established that, for the time represented by this study, more suspended sediment entered the tidal creek than left the tidal creek. Once it is known whether this continues and whether more bedload moves in or out, then a sediment budget for these tidal creeks can be established. It could be that bedload is cyclic, and as much moves out with the tide or a barge passing as moves in. But it could also be that most bedload sediments move in, like the net influx of TSS. Another possibility is that sediment movement is relatively balanced, and that sediment enters the tidal creeks suspended and leaves as bedload.

Wind is potentially a factor positively related to bedload if higher TSS values within the tidal creeks contribute directly to higher amounts of bedload. Because bedload moves with current, wind may also be a factor in the event of wind tides, where current is generated in response to wind direction.

Like TSS, storm events may account for some of the greatest amounts of bedload transport. Storm events could serve to relocate bedload sediments that have accumulated in places such as the creek mouth bars or channel floors. Or they could serve to enlarge features like the creek mouth bars and add to existing bedload. Such as in the case of TSS transport, the effect storms have will likely be dependant on other factors such as tide direction during the storm.

5. CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

There were three major conclusions to be made from this study. First, most water and TSS passed through the tidal creeks as influx to the marsh. Second, there was a positive relationship between TSS and salinity. Last, bedload sediments moved with both natural and unnatural currents. This study suggests that barges may move a significant amount of bedload.

TSS concentrations were likely based on a relationship among factors such as proportion of upland runoff versus water from the bays, energy levels and sources of turbulence present in the bays, water level fluctuations, and winds. It could be concluded that most sediment in suspension in the system studied at ANWR originated on the seaward side of the marsh but that the factors controlling TSS concentrations were variable. Any direct link to the Guadalupe River that may have existed regarding TSS concentrations could not be distinguished. However, it is a possibility that discharge from the Guadalupe River could have influenced the inflow of water toward the marsh. Future flow data measured in the tidal creeks at ANWR during years of both low and high Guadalupe River discharge would be able to better identify any influence the Guadalupe discharge may have over flow patterns in the marshes.

Bedload sediments within the tidal creeks studied at ANWR were certainly both mobile through time and responsive to changes in conditions over short periods of time, specifically barge-induced drawdown currents. This study did not monitor bedload sediments at a time scale which could draw further conclusions or see trends in bedload movement as a whole. It did however monitor them at a spatial scale which suggests that there was predictable variability across a channel transect controlled by factors such as vegetation, channel morphology, and current patterns. It could also be concluded that the linear island in front of SB Creek dampened the effect of barges.

5.2. Future work

The scope of impact on the marsh of a net influx of sediment should be addressed in the future through study of processes such as accretion, erosion, and channel deposition. The net influx may be appropriate in maintaining the balance with regional subsidence and sea level rise. Or, it may be too great and is resulting in the infilling of creeks and ponds that are crucial to exchange between the marsh and bay systems. Major storm events, though none occurred during this study, probably play an important role in sediment transport and maintenance in the system and should certainly be targeted in future study so that their influence on both suspended and bedload sediments can be monitored.

There are multiple explanations regarding the positive correlation that exists between TSS and salinity, each of which discussed here suggest that salinity is an indicator of water source. This study can only make an inference about the importance of this relationship. More work should be done that focuses on water chemistry and pH in relation to TSS concentrations. These correlations may prove important to understand with regard to freshwater diversion from the Guadalupe River because removal of a portion of the freshwater input will likely increase the proportion of seawater relative to freshwater along the marshes. This change could alter the chemistry of the water and potentially the behavior of sediment transport as a whole. There are implications that will need to be made concerning ecological and geomorphologic impacts with regard to an increase in seawater potentially leading to higher concentrations of suspended sediments.

Future work with TSS in this system should not only consider the impact of net influx on the marsh through study of such parameters suggested earlier, but should also narrow the study to more directly assess the effect of barges on TSS. The four-hour sampling scheme used in this research was too infrequent for assessing barge influence on TSS.

Another recommendation for future analysis of TSS and bedload samples would be to ash the suspended sediment collected on the filters and the bedload collected in the traps in order to determine the percent organic matter. This would help in making inferences about sediment origin and may be useful in addressing issues such as the higher TSS concentrations that were present during the sampling period of July 13 to 19 which may be attributable to higher amounts of organic matter. It would also be useful to subject the mineral component of the sediment to x-ray diffraction to learn its composition.

A useful element to include in the future would be a series of pieziometers that can reveal groundwater flow trends from the uplands to the bay along the Blackjack Peninsula. This would help in understanding variation in salinity and the relationship that exists between salinity and TSS. It was concluded that salinity is likely an indicator of water source and such hydrologic data, as would be obtained from pieziometers, would be useful in determining whether groundwater is ever a significant source of water in the tidal creeks at ANWR.

The overall impact of barges and the influence they exert on the movement of bedload sediments and flocculated material should be further studied, with attention given to the formation of creek mouth bars or deltas. With the conclusion that the linear island in front of SB Creek dampened the effect of barges, it may be prudent to consider a study that seeks to determine whether barge influence is helpful or detrimental to creek and marsh sustainability.

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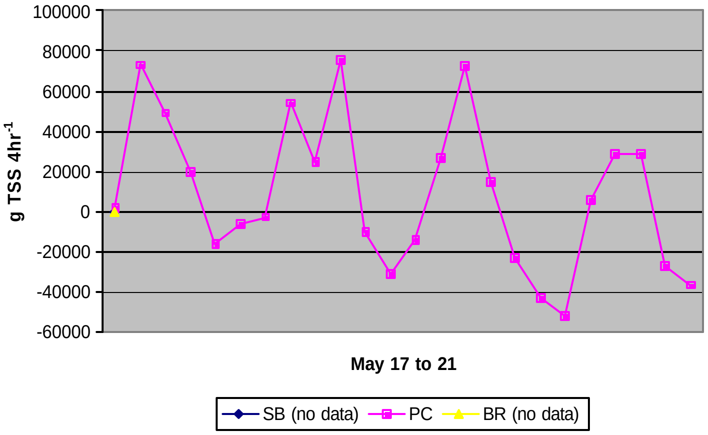
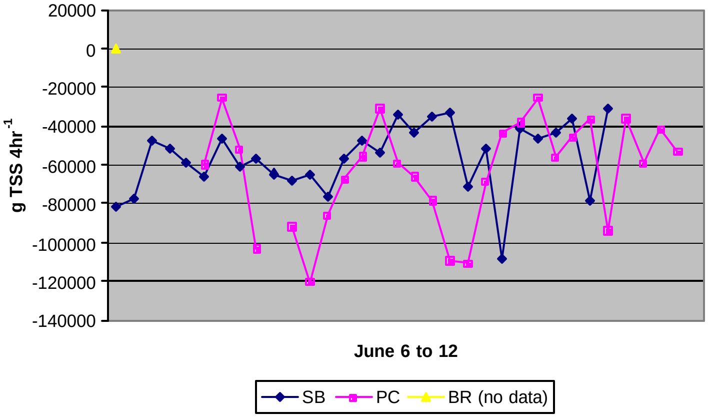
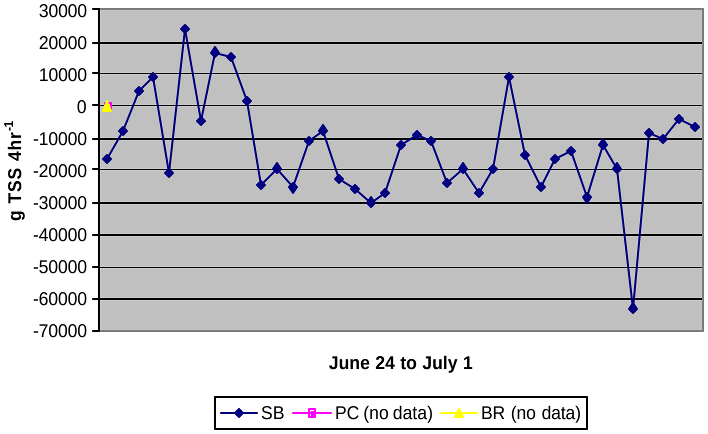
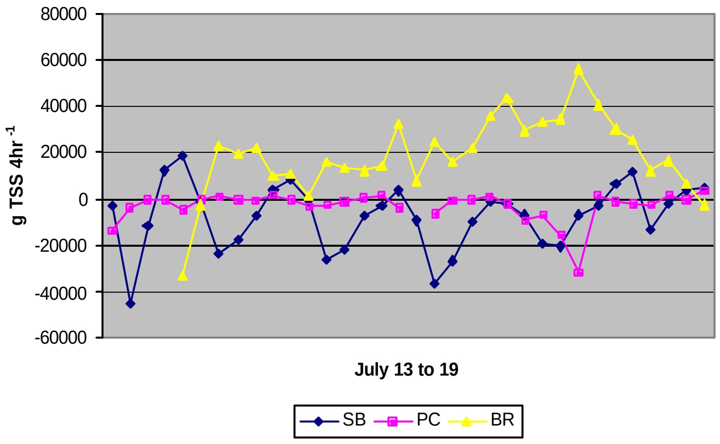
APPENDIX A

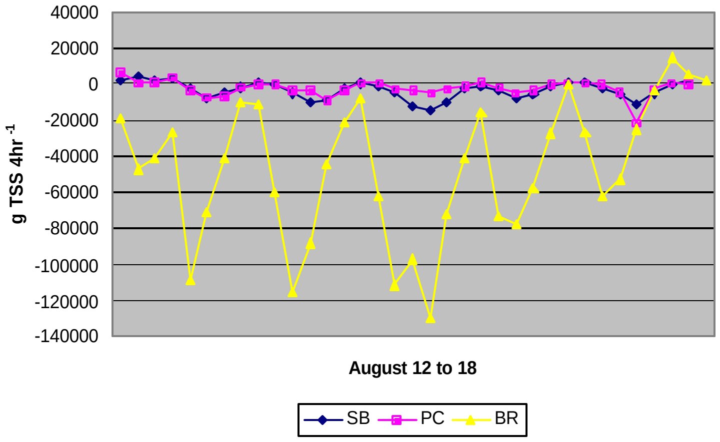
FLUX GRAPHS FOR EACH SAMPLING PERIOD

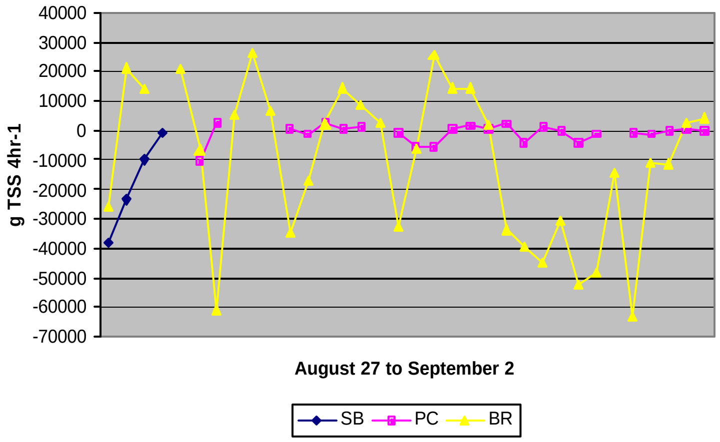







80000
60000
40000
20000
0
-20000
-40000
-60000
g TSS 4hr $^{-1}$
July 13 to 19
SB
PC
BR


40000
20000
0
-20000
-40000
-60000
-80000
-100000
-120000
-140000
g TSS 4hr $^{-1}$
August 12 to 18
SB
PC
BR


40000
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10000
0
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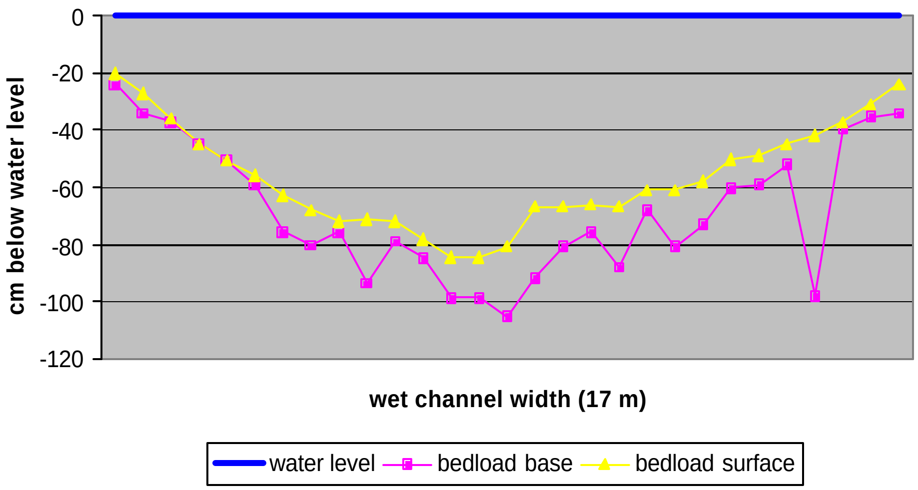
-20000
-30000
-40000
-50000
-60000
-70000
g TSS 4hr-1
August 27 to September 2
SB
PC
BR

APPENDIX B

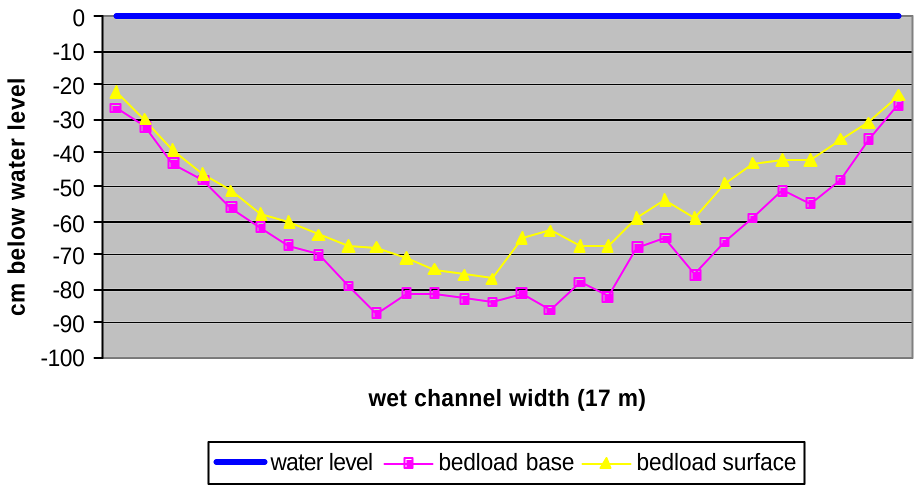
CROSS-SECTIONS OF BEDLOAD THICKNESS AT PUMP CANAL

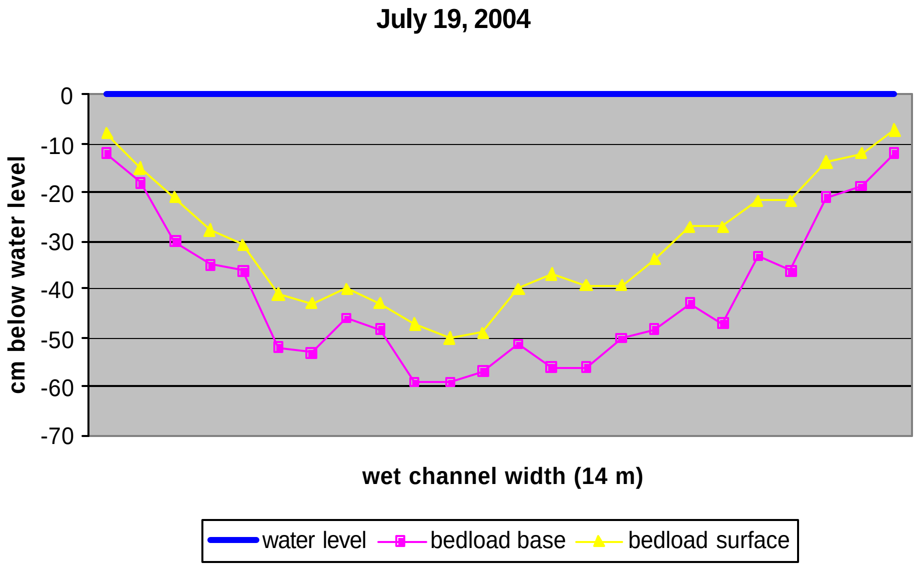
(MEASUREMENTS TAKEN ONCE PER SAMPLING PERIOD)

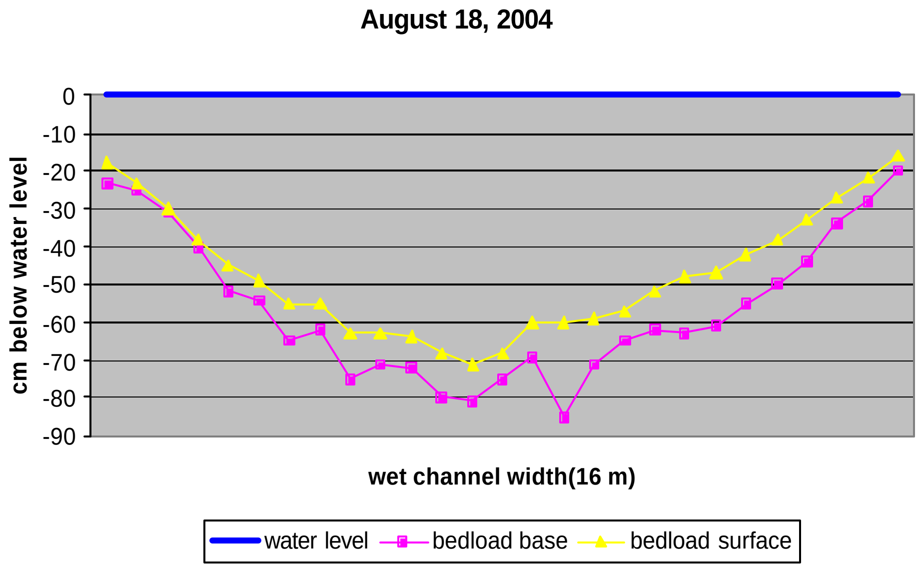
June 9, 2004

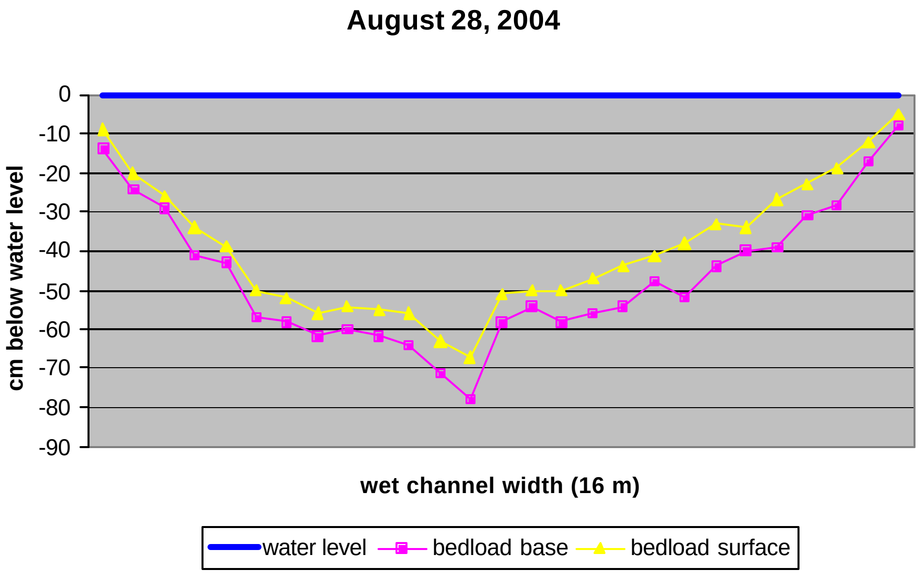


July 1, 2004




July 19, 2004
0
-10
-20
-30
-40
-50
-60
-70
cm below water level
wet channel width (14 m)
water level
bedload base
bedload surface


August 18, 2004
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
cm below water level
wet channel width(16 m)
water level
bedload base
bedload surface


August 28, 2004
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
cm below water level
wet channel width (16 m)
water level
bedload base
bedload surface

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