1 Introduction

At the request of U. S. Army Engineer District, Galveston (CESWG), a study of dredged material dispersal in Laguna Madre, Texas, was performed by the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory located at Waterways Experiment Station (WES). Open-water disposal of dredged material in Laguna Madre has allegedly resulted in a general increase in turbidity and contributed to a decline in seagrass. Laguna Madre contains important seagrass habitats which support diverse ecosystems. Over 85 percent of Texas' seagrass area is located in this system (Dunton 1996).

This study included application of hydrodynamic/sediment modeling and an investigation of sediment properties and transport characteristics. The CESWG has conducted a series of studies in cooperation with a federal-state Interagency Coordination Team (ICT) to evaluate possible effects of dredged material placement and redispersion on water quality and seagrass conditions. Studies involving field data collection (Brown and Kraus 1997; Brown 1997; and Militello et al. 1997), database compilation (Espey Houston and Associates 1997), seagrass growth monitoring and modeling (Cifuentes et al. 1997; Dunton et al. 1998; Burd and Dunton 2000), and sediment budget analysis (Morton et al. 1998; Morton et al. 2001) have been completed. The study reported here developed sediment information and a numerical model to predict the effects of dredged material placement, resuspension, and dispersion on water-column suspended sediment levels. The objective of this model study was to predict long-term (annual) dispersion of placed dredged material and its effect on water-column concentrations and light conditions.

Background

Seagrass and sediment interactions

Seagrasses thrive in shallow (< 2 m), low-turbidity, low nitrogen-nutrient waters. The amount of photosynthetically active radiation (PAR) reaching submersed aquatic vegetation (SAV) is affected by suspended materials, including sediments and particulate organic material, as well as dissolved organic material. Seagrasses trap sediments and damp waves. Seagrass beds generally have much lower levels of water-column turbidity than areas with no vegetation.

The depth range for SAV in coastal waters is often limited by light conditions (Gallegos 1994; Czerny and Dunton 1995; and Gallegos and Kenworthy 1996). The total suspended sediment material (TSM) concentrations limiting growth can be estimated in a simplistic way by assuming that SAV requires 20 percent of incident light to survive long-term and assuming a relationship between TSM and water-column extinction coefficient for PAR. Growth-limiting TSM concentrations presented in Table 1 are based on the TSM-PAR relationship reported by Burd and Dunton (2000) developed for Laguna Madre.

TABLE 1
Limiting TSM for Plant Light

Depth, m	Growth Limiting TSM Concentration, mg/l
1	18
2	7
3	3
4	1

As can be seen from Table 1, even low levels of resuspension and resulting TSM can limit the depth range for seagrass.

Bed shear stress, sediment resuspension (or erosion), light extinction, and SAV influence each other through positive or negative feedbacks (James and Barko 1994). Bed shear stresses are dependent on wind waves (usually) and/or tides, water depth, wind fetch lengths, and, importantly, on the presence of SAV. Momentum transfer from winds to waves depends on wave steepness and is reduced by the presence of SAV that damp waves. Erosion depends on total water-column shear stress and the fraction of this shear stress reaching the bed (100 percent in bare areas) and therefore on the sheltering effects of seagrass. Submersed vegetation reduces local resuspension caused by wind-generated waves (Ward et al. 1984; James and Barko 1994; and Hamilton and Mitchell 1996). Sediment resuspension affects seagrasses mainly through its impact on water clarity and light penetration. Light extinction depends on TSM concentrations, particle size and/or flocculated state of the particles, adsorption, and water chemistry as discussed by van Duin et al. (2001). SAV depends on light and nutrient availability, temperature, and physical stability. The interactions between wind, wave, seagrass, and bed shear stresses, and the influences of wave steepness, seagrass roughness, and resuspension are shown schematically in Figure 1.

Areas with no vegetation are prone to resuspension that can decrease water clarity and may prevent seagrass establishment or may cause further seagrass decline (Onuf 1994). On the other hand, seagrass beds slow water movement, damp waves, and trap and hold sediments (Fonseca 1996). Seagrass reduces shear stress at the sediment bed to lower levels than would occur on a bare bottom. At the same time, seagrass beds greatly increase total resistance to

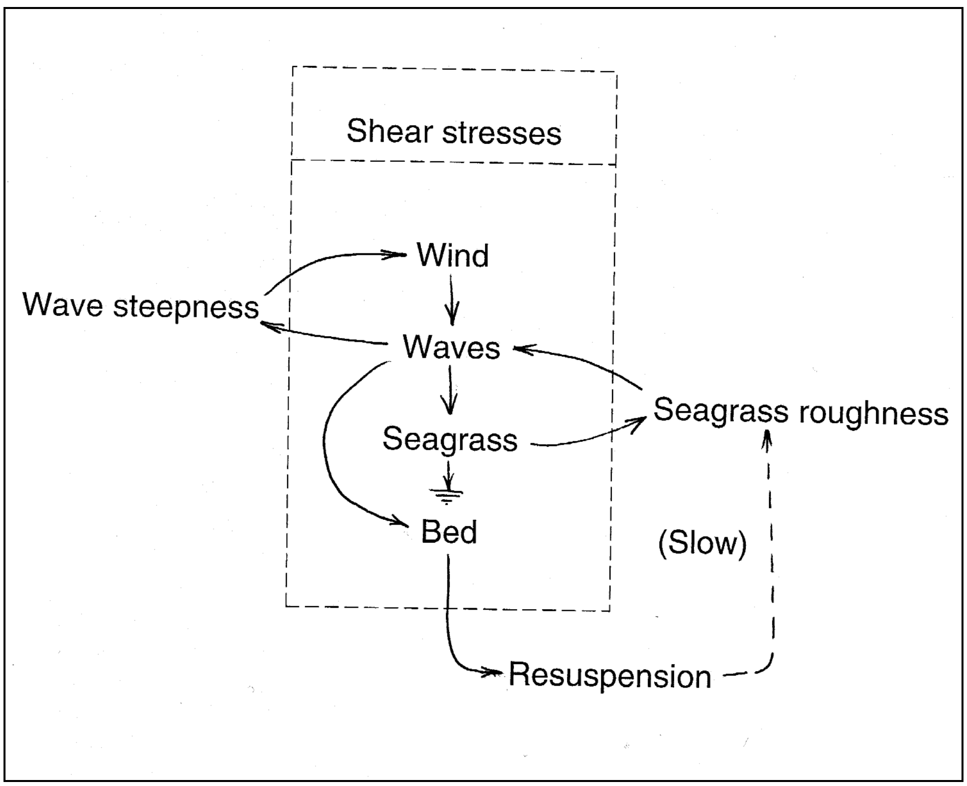

Figure 1. The coupling of shear stresses under the influence of seagrass roughness, wave steepness, and resuspension

flow, increase wave damping, absorb shear stress, and shelter the sediment beds. Previous studies have documented the effects of SAV on total flow friction and on wind-wave damping (see Madsen et al. 2001). Thus, there are feedbacks between the presence of seagrass, water clarity, and the establishment of new seagrass.

Site description

The Laguna Madre is 183 km long and consists of two shallow tidal bays transected and connected by the Gulf Intracoastal Waterway (GIWW). It extends from Corpus Christi Bay to Port Isabel, Texas, near the Mexican border. See Figure 2. The average depth of these bays is about 1 m and the total water surface area is about 1,500 km^2. The GIWW is 4.3 m deep and 38.1 m wide (14-ft-deep by 125-ft-wide). Since its completion in 1949, dredging has typically been performed on short 20- to 38-month cycles to long 5- to 46-yr cycles, depending on the channel reach; the average channel sedimentation rate is about 1.6×10^6 m^3 (2.1×10^6 yds^3) per year (PBS&J 2000).

The system has very low freshwater inputs and is normally slightly hyper-saline. The tide range is about 0.3-m at tidal inlets, and decreases away from the inlets. Tidal currents and circulation are weak. Wind waves and wind stress play important roles in transport and in sediment resuspension (Onuf 1994; Brown and Kraus 1997). The system experiences strong southeast winds most of the year. From October through April, fronts bring strong north winds at intervals of 3 to 7 days. Winds generally have a stronger diurnal component in summer months, while winter winds have strong low-frequency components (Brown and Kraus 1997).

Barrier Islands (Brazos Island and Padre Island) separate Laguna Madre from the coastal ocean. These barrier islands are mostly sand-sized sediments, with little silt and clay. The Rio Grande River previously discharged through southern Lower Laguna Madre and formed fine-grained flood-plain deposits. Remanent Rio Grande deltaic deposits affect sediment texture in the southern part of Lower Laguna Madre. The Arroyo Colorado was previously a Rio Grande channel. From Port Mansfield southward, the western shore of Lower Laguna Madre includes areas of less-than 4,500-year-old deltaic deposits and reworked fluvial sediments (White et al. 1986). Bay bottom along that same shoreline ranges from coarse to fine silts with a few areas of very fine sand.

North of Port Mansfield, western shoreline and lagoon bottom sediments are coarse grain sediments consisting of eolian deposits and a barrier system. The north shore of Baffin Bay consists of older fine-grained deltaic deposits covered with a veneer of sand (White et al. 1989). The bottom sediments along the central axis of Baffin Bay are fine-silts and clays.

The lagoon system receives sediment loads from streams, coastal ocean, biogenic sources, shoreline and dredged-material bank erosion. GIWW construction formed mounds of lagoon sub-bottom sediments along the waterway which have been subject to erosion. In addition, sediment dredging occurs as a matter of routine GIWW maintenance. Much of the maintenance

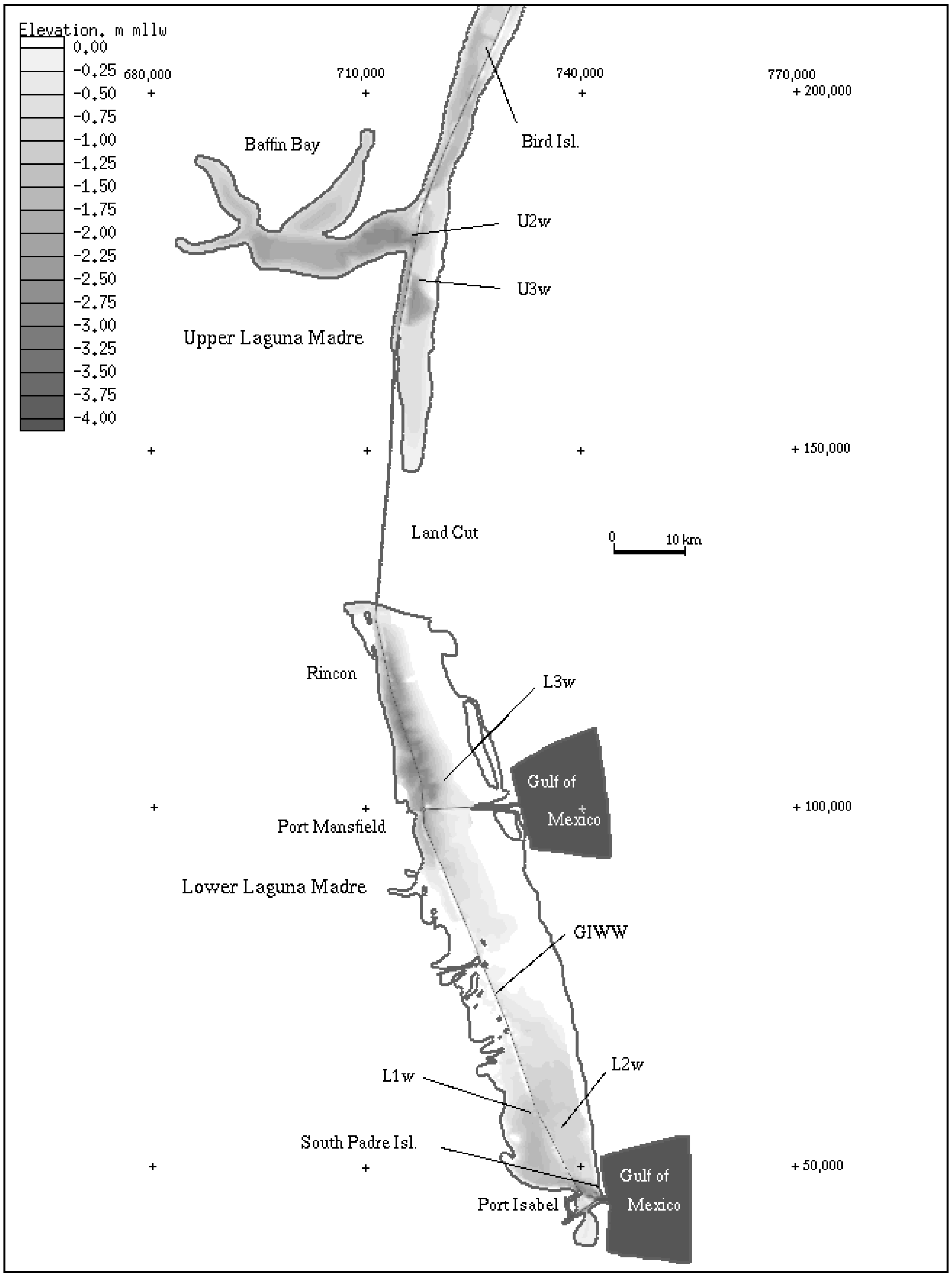

Figure 2. The Laguna Madre study area, wave station locations, and depth contours (coordinates are state plane, NAD27 Texas South, in meters)

material disposed along the GIWW eventually is resuspended and dispersed, although disposed sediments do not represent a new source of sediment to the lagoon but a recycling of material that deposited out of suspension. Channel maintenance materials are mainly fine-grained silts and clays less than 62 µm.

Placement Areas (PA) 233 and 234, located about 12 km north of Port Isabel, receive the highest dredged material volumes in Laguna Madre (PBS&J 2000), and the adjacent channel area has long been identified as one of the major deposition and channel maintenance problems along the Texas GIWW (James et al. 1977). The high deposition and dredging rates have been attributed to the combined effects of cross-channel flow and high TSM concentrations in this area (James et al. 1977, and Brown and Kraus 1997). Historical volumes dredged in each dredging cycle are shown in Figures 3 and 4 for these two PAs. PA 233 has received the greater volume. Both PAs have had peaks in disposal volumes related to hurricanes and other severe storms as noted by Brown and Kraus (1997). On a per dredging cycle basis, however, disposal volumes have been relatively constant and have not significantly increased or decreased (PA 233 p-value = 0.58 and PA 234 p-value = 0.53).

Since Laguna Madre dredging events are not evenly spaced in time, these data are not independent measures of channel deposition; therefore, a data set which more accurately reflects the underlying deposition process and which can be better compared was constructed. This data set is based on annualized disposal. Individual dredging volumes were averaged over the preceding years, when no dredging occurred, to obtain an estimate of the average annual dredging rate as shown in Figures 3 and 4. Smoothed annual dredging lines are also shown in these figures. These lines were produced by local regression which spans about 3.5 years. The annualized disposal data show a pattern of high disposal in the late-1960s and 1970s. Three periods are compared in Table 2.

TABLE 2
Comparison of PA 233 and 234 Dredging Volumes (m^3) for Three Periods

	Years 1952-1965	1966-1980	1981-1994
PA 233 Total	1,615,490	3,079,419	1,897,350
PA 233 Annual	124,269	205,295	135,525
PA 234 Total	976,986	1,972,450	1,197,651
PA 234 Annual	75,202	131,497	85,547
Total for PA 233 and 234	2,593,116	5,051,868	3,095,001
Annual for PA 233 and 234 Combined	199,470	336,791	221,071

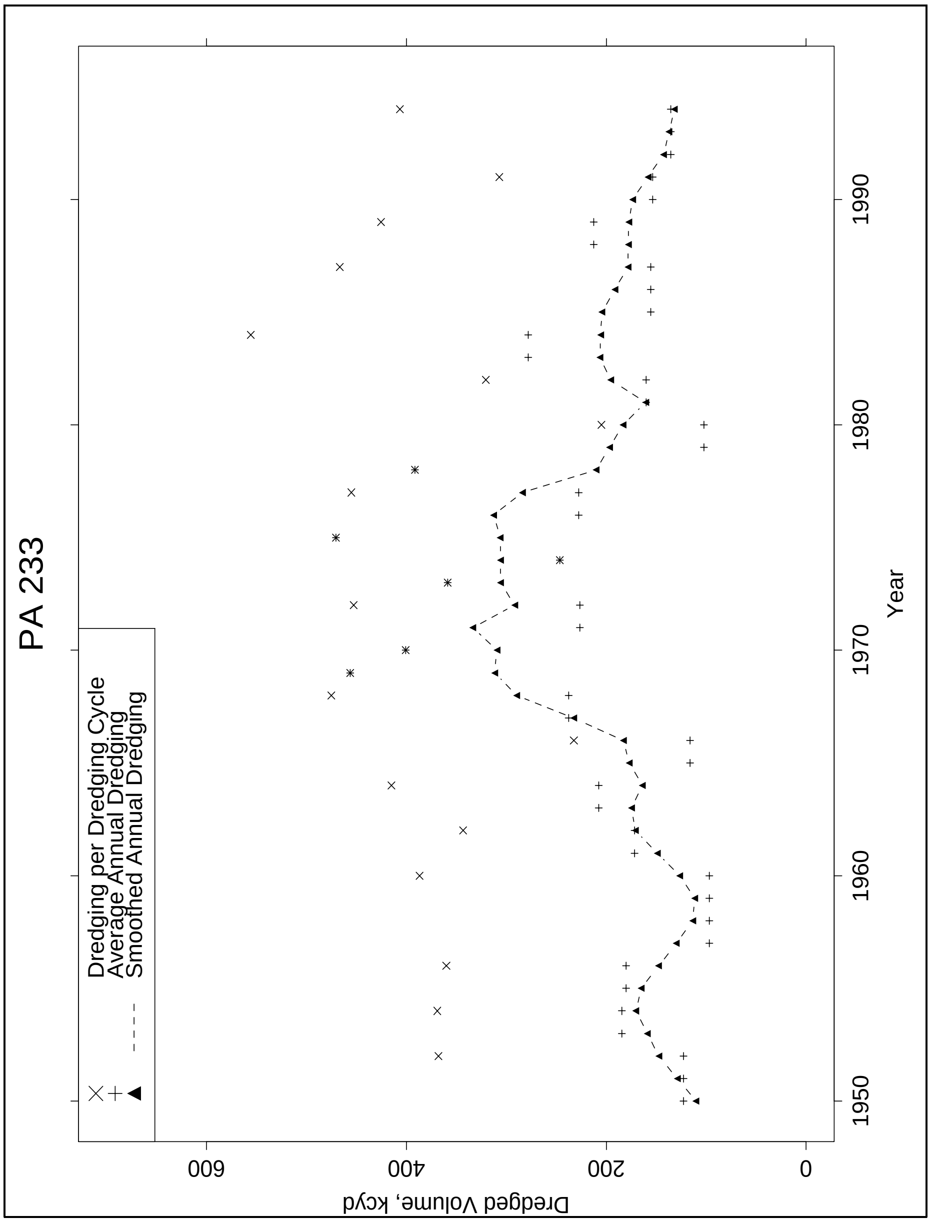

Figure 3. Dredging history for PA 233

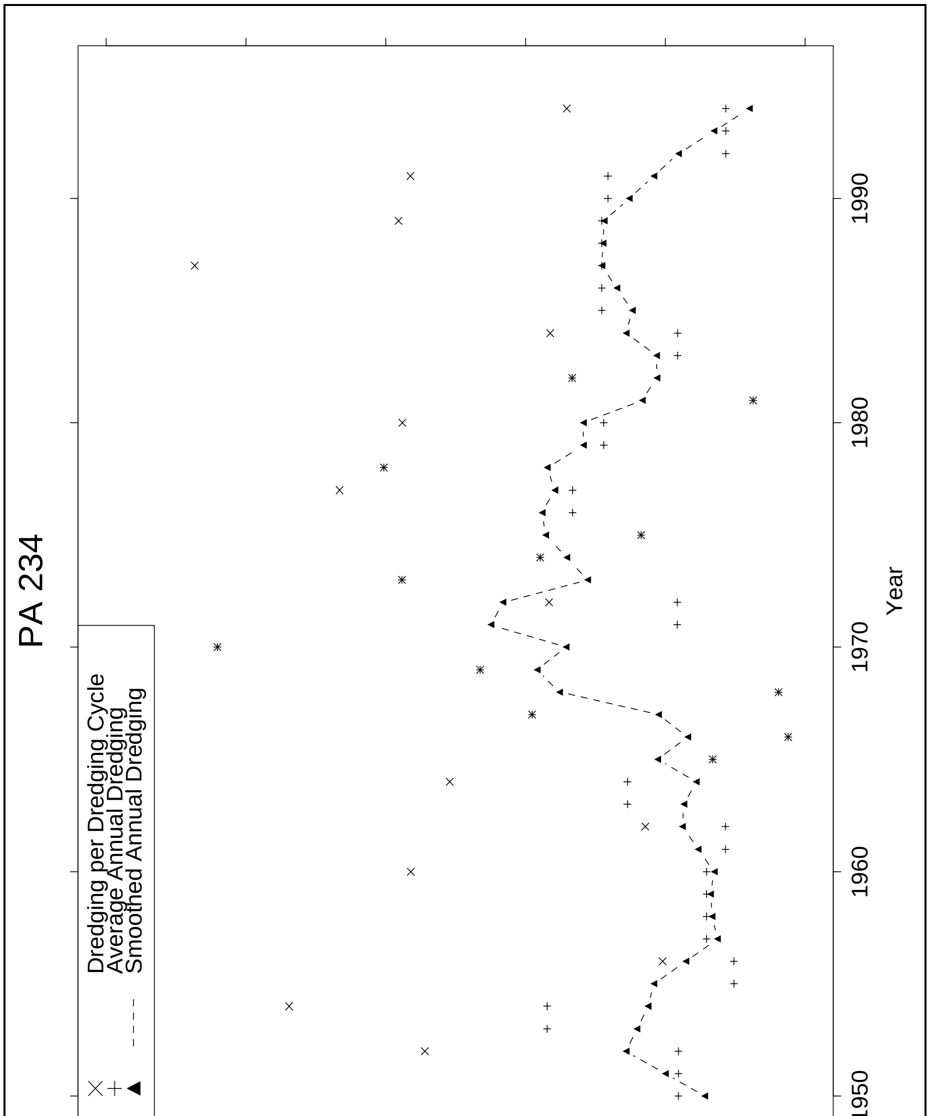

Figure 4. Dredging history for PA 234

For PA 233, PA 234, and the total of PA 233 and 234, years 1952 to 1965 and 1981 to 1994 had statistically lower disposal rates than years 1966 to 1980 (p-value < 0.05) and were not significantly different from each other. Therefore, as pointed out by Onuf (1994), dredging was greater immediately after 1965 than before this date, but it later decreased to pre-1966 levels and has remained at those levels for many years. The lower bound of the 1965 to 1980 period was set to correspond to the seagrass survey. The actual peak period of increased dredging appears to be 1966 to 1978 (4,576,860 m^3 total and 381,477 m^3 annually). It appears that this peak dredging period was an anomaly as it lasted 12 to 15 years of the 45-year record. Better information on TSM levels was available during the last period listed in Table 2. However, it is difficult to reconcile the present TSM and the dredging rates of the 1952 to 1965 and 1981 to 1994 periods with the assumption that the Lower Laguna was vegetated in the earlier period. This information does not seem consistent with the feedback observed in other systems, and observed spatially over much of Laguna Madre, that the presence of seagrass greatly reduces TSM levels and that TSM is responsible for channel deposition.

Environmental concerns

The basis of much environmental concern is that an appreciable area of Lower Laguna Madre became bare sometime between the seagrass survey 1965 and the subsequent survey in 1974 (Quammen and Onuf 1993; and Onuf 1994). A survey in 1988 (Quammen and Onuf 1993) showed no appreciable increase in bare area. The estimated area that converted from vegetated to bare was 140 km^2 for the Lower Laguna Madre, while in the Upper Laguna Madre 130 km^2 converted from bare to vegetated. Losses were mainly in the deep areas of the Lower Laguna Madre. Speculation was that increased turbidity and decreased light penetrations resulting from dredged material disposal and subsequent dispersion were the cause for the seagrass decline (Quammen and Onuf 1993; and Onuf 1994). The date the area became bare in not known exactly. LANDSAT images show that the bare, high turbidity area had appeared by 1972 (James et al. 1977). Unfortunately, studies were not performed during, nor immediately after, the seagrass loss was noted, and the cause or causes of the loss remain unknown.

Two studies have reported long-term impacts of dredged material disposal and underwater light conditions in Laguna Madre. Onuf (1994) monitored underwater light conditions 3 months before and for up to 15 months after dredging and disposal operations in 1988 to 1989. He compared before and after disposal light conditions for seven subdivisions near Port Mansfield intended to represent homogeneous geographic areas. Pooled, multiple regression formulas using wind, proximity to other sediment sources and seagrass beds, and depth were developed for specific areas. Light attenuation deviations between observed and expected values from before and after dredging were estimated for 3-month time blocks and found to be significantly different for the subdivisions north of Port Mansfield where disposal was greatest. Brown and Kraus (1997) reported daily average attenuation coefficients monitored before, during, and one year after October 1994 dredging at the FIX platform near PA 233. Significant differences were found between the groups. Predredge attenuation values were the lowest, and then postdredge, and during-dredging values were the highest.

One weakness often found in this type of environmental study is the lack of control. Light attenuation and TSM levels are sensitive to wind conditions, to antecedent conditions, and to nearby upstream conditions. Environmental conditions are variable and do not repeat on regular cycles. Even when statistically significant differences are found, assigning a cause can be difficult or impossible. One example can be taken from Brown and Kraus (1997). As cited in the last paragraph, postdredging light levels did not recover to predredging levels. Contrary to this finding, postdredging TSM levels did recover, but there were differences in sampling methods. Environmental modeling, on the other hand, strives to isolate the effect of some disposal activity based on with- and without-dredging scenarios.

The dredging data seem to conflict with reported seagrass extents. Channel deposition and dredging are related to TSM and to storm events that produce high sediment transport rates. The previously described feedback between seagrass (and SAV in general) and resuspension would indicate that a significant period of vegetated conditions in Lower Laguna Madre should correspond to low TSM levels and low dredging rates. Yet disposal during the 1952 to 1965 period totaled 3.7×10^6 yd^3 . Since deposition and dredging are related to the suspended load, GIWW dredging should have been lower under vegetated conditions. Also, disposal of the 3.7×10^6 yd^3 magnitude is assumed to be at least locally harmful to seagrass. Two main questions raised by the dredging and seagrass data are how could open-water disposal of this magnitude be accomplished without creating a bare lagoon area and how could TSM levels have been high enough to cause the channel deposition if the entire area was vegetated.

A substantial loss of seagrass was observed in the deep parts of Lower Laguna Madre between 1965 and 1975, which was later attributed to suspended sediment inputs resulting from dredging and in-bay disposal of dredged material (Onuf 1994) or possibly from Hurricane Buelah in 1967 (Brown and Kraus 1997). The extent of seagrass beds has recovered somewhat since 1975. Still, there are concerns about water clarity in Lower Laguna Madre, so studies have been made in recent years and are presently underway.

The key issue from a physical perspective is assessing the contribution dispersed dredged-material has on the natural cycling of sediments in Laguna Madre. The deposition rates in Laguna Madre over the last 50 years have not been estimated, and the source magnitude of sediment inputs are poorly known. A recent sediment-budget study (Morton et al. 1998) concluded that natural sediment inputs were substantially less than the quantities dredged from the GIWW and placed in the bay on an annual basis.

Purpose

It is very difficult to use field data to separate the effects of dredged material resuspension because of variability in environmental conditions. The purpose of this study was to apply a physics-based sediment model, with and without dredged-material disposal, to gauge the water-column TSM effects from disposal area resuspension and thereby to eliminate the variability in other conditions. One purpose of model simulations was to provide suspended-sediment time-series, at certain points within the system, to a Seagrass Productivity Modeling (SPM) team for seagrass growth assessment. Another purpose was to provide spatial distributions of water-column impacts on suspension concentrations, and light availability to seagrasses.

A number of alternatives are being considered for dredging and disposal operations in Laguna Madre, and some disposal alternatives were tested in the field during the 1994 dredging cycle (Brown and Kraus 1997). The model represents a tool which can be used to address a wide range of dredging and disposal questions.

Scope

Two-dimensional, depth-averaged numerical hydrodynamic and sediment transport models were developed and applied to Laguna Madre, Texas, to predict the effects of dredged-material resuspension on suspended-sediment concentrations along the GIWW and in environmentally sensitive seagrass beds. Wind waves are the dominant driving force for sediment resuspension in this shallow lagoon system. Wave measurements were analyzed and used to estimate atmospheric drag coefficients and depth-limited wave properties. Measurements were made of suspended-sediment concentrations, suspended floc-size distributions, and bed material properties. Laboratory erosion experiments were performed on resuspended and settled channel sediments and on bay sediments. Laboratory settling experiments were performed in flocculators and columns. Measurement information from this study, from associated studies, and from previous studies was used to specify initial, boundary, sediment, and seagrass conditions in the model and to validate model performance.

The modeling effort was divided into estuarine circulation, wind wave, and sediment components. In addition, field measurements and laboratory experiments were carried out to develop information on settling, erosion, and depositional properties for the sediment model. In this study, sediment bed erodibility was the key factor under investigation. Erodibility of dredged material depends on the dredging and disposal procedures as well as sediment properties. Erosion parameters were determined by erosion experiments and characterization tests on material from the system. Erosion experiments were performed on undisturbed box cores obtained in the field. Channel sediments were also used in the laboratory to create simulated dredged-material slurries. Slurry samples were allowed to settle and consolidate before erosion testing was begun.

The effect of suspended sediment concentration on floc-settling rate was included in the model. Information on this process was obtained from the field and laboratory settling experiments. Field experiments were carried out to measure floc size on undisturbed suspensions. A limited number of underwater light and turbidity measurements were made in the field. Laboratory settling experiments were performed. Several dozen water samples were collected and organic and calcium carbonate contents determined.

Estuarine circulation modeling

Modeling was performed in two dimensions (2-D), depth-averaged, with the U.S. Army Corps' Surface Modeling System (SMS ©)and the TABS-MDS model. TABS-MDS is an enhanced version of the RMA10-WES and RMA10 models that do not have sediment transport capability. TABS-MDS was given new capabilities for this study. TABS-MDS is capable of 1-, 2-, and 3-D elements, all in the same mesh.

The TABS-MDS model performs implicit finite-element solutions of the depth-averaged Navier-Stokes equations for turbulent flow. Model equations based on conservation of mass and momentum (shallow-water wave equations) include nonlinear advective and friction effects. The latest bathymetry was compiled and used to develop the model mesh. Assignment of model roughnesses was based on the sediment type, bed roughness features, depth, and the species of SAV present. The effect of aquatic vegetation on hydraulic roughness was obtained from literature.

Precipitation and evaporation were included in this study. Because of the very low freshwater inputs and large evaporation, the TABS-MDS model was modified to include a uniform spatial, time-varying water source/sink applied to the model surface.

Wind-wave modeling

Observations have shown that wave action is primary to the resuspension of sediments. The first step in the wave modeling was to assess previously used wave prediction techniques by comparison to new field data. Wave data from three stations in Lower Laguna Madre and three stations in Upper Laguna Madre were collected by Texas A&M University, Corpus Christi - Conrad Blucher Institute (CBI) and analyzed as part of this study.

Waves observed in Laguna Madre did not follow previous wind-wave relationships, possibly because of high wave dissipation due to friction. Bottom friction, white-capping, and seagrass friction are involved in wave dissipation and were especially important in Laguna Madre. A new wind-wave shear stress algorithm was developed for the model system after reviewing previous methods. The algorithm is based on a partitioning of atmospheric shear stress. Expressions for atmospheric drag coefficient and depth-limited wave height and period were also developed.

Sediment transport modeling

Sediment size distributions were discretized into one clay, two silt and one sand fractions for TABS-MDS model simulations. The TABS-MDS sediment model simulates erosion and deposition processes, and includes bed processes such as consolidation and erodibility relationships for grain-size composition and bed density. For a given erosion rate (mass per unit area), the model uses the dry density of the bed layers to compute changes in bed elevation. The model uses a layered bed structure to characterize the density and erodibility horizontally and vertically in the bed.

During model adjustment, sediment parameters were varied in small steps about their estimated values, and the response of the model observed. In this way, the combination of parameters that were physically reasonable and that minimize differences between model and prototype data were determined. Model adjustment simulations lasted long enough to wash out the effects of initial conditions, and to reach equilibrium concentrations with respect to water-mass residence times.

After the model adjustment, the ability of the model to predict suspended-sediment concentrations was quantified by comparing its data to field data. Suspended-sediment concentrations, channel deposition, and PA erosion rates were used in the comparison. The initial model scenarios included annual simulations with and without dredged material disposal. Additional scenarios involving relocation and/or confining PAs with dikes were also tested with the model.

Report Organization

Descriptions of physical processes are presented in the next four chapters. They cover wind waves, suspension characteristics, sediment transport conditions, and near-field sediment dispersion around pipeline discharged dredged-material. Chapter 6 describes the model with emphasis on new model features developed for this study. Hydrodynamic and sediment transport model components and couplings discussed in the last subsection are presented. Model validation and tests are described in Chapters 7 to 9. Conclusions are presented in the last chapter.