Hydraulic Study of Multiple Inlet System: East Matagorda Bay, Texas

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Abstract: The hydrodynamic feasibility of a proposed third inlet to East Matagorda Bay, Texas, was examined by application of a two-dimensional, depth-averaged hydrodynamic model. Wind-driven flows in this remote, shallow bay frequently dominate the weak astronomical tide. The bay presently has two connections to the Gulf of Mexico, one through a short flood-relief channel and the other through a long and circuitous navigation channel. The study had to consider whether installation of a third inlet would cause the relief channel to close or increase the already strong current velocity in the navigation channel that is a concern for boating safety. The model was calibrated with measurements of wind, water level, and current taken in this study. It is concluded that the new inlet will be ebb-dominated because of the wind-induced current, and that the relief channel will not close in the presence of the new inlet. In addition, the peak current at a critical maneuvering area in the navigation channel that presently poses a hazard to vessel traffic will be reduced by as much as 25% as a result of opening the new inlet.

INTRODUCTION

Creation of inlets is an active area of consideration in Texas both for improving water quality and for promoting recreational and commercial boating in coastal waters. The County of Matagorda, Texas, has proposed installing a water-exchange inlet or "cut" that would connect East Matagorda Bay at its southwestern end to the Colorado River Navigation Channel (Fig. 1). The navigation channel was once part of the Colorado River. In 1992 the river was routed west to empty into (west) Matagorda Bay through a diversion channel, with the navigation channel now connecting to the Gulf Intracoastal Waterway (GIWW). The intersection of the proposed SW Cut and the navigation channel would be located approximately 3.2 km upstream of the Gulf of Mexico.

If the SW Cut were implemented, a 3.3-km long channel would be dug from East Matagorda Bay to the navigation channel, and a box culvert bridge would be erected on the road which runs parallel to the navigation channel. Prior to moving forward to final design and construction, the present study was conducted to determine the physical consequences of installing the cut. The general aim of this study was to identify and quantify any factor that might be of such serious consequence to the project as to preclude construction of the bridge and associated dredging for the SW Cut. Potential concerns extend from the eastern end of the bay, where there is an artificially opened flood-relief pass called Mitchell's Cut, to the intersection of the navigation channel and the GIWW on the western end of the bay, where strong currents pose a hazard to barge traffic.

The most comprehensive study of the hydraulics of multiple inlets has been made by Van de Kreeke (1990a), who developed an analytic model by simplification of the one-dimensional momentum equation. The model was restricted to forcing by a single tidal frequency, with the bottom frictional stress linearized and the wind omitted. The hydrodynamic prediction was then applied to satisfy simultaneous empirical closure curves developed with the Escoffier (1940, 1977) inlet-stability analysis that indicates whether an inlet will remain open or tend to close. Van de Kreeke (1990b) tested the model at the dual-inlet system of Big Marco Pass and Capri Pass, Florida, where a significant tidal prism exists in the Big Marco River. The theory predicted that Capri Pass, which opened naturally nearby and to the north in 1967, would become the dominant pass, and the previously sole inlet, Big Marco Pass, would close. Moore (1993) reported that Big Marco Pass is indeed closing under dominance of Capri Pass, but that another channel, still south of Capri Pass, is forming. Van de Kreeke (1985) had previously analyzed the (west) Matagorda Bay system with a conceptual dual-inlet model. This bay presently has two inlets, the historically single, large, and stable inlet Pass Cavallo, located in the southwest corner of the bay, and the Matagorda Ship Channel, which was opened in 1963 some 5 km to the north. The hydraulically more efficient deep-draft Matagorda Ship Channel has become dominant, and Pass Cavallo is gradually closing (Ward 1982). Although having to arbitrarily reduce the area of the bay in the calculations to obtain a realistic current velocity, Van de Kreeke (1985) found that Pass Cavallo would close and the Matagorda Ship Channel would scour.

Although an analytic theory as described above is available, it is not applicable to a system as complex as East Matagorda Bay. The bay has three potential openings, numerous connections between the GIWW and bay through openings between dredged material islands, and frequent dominance of wind forcing over the tide in driving the water flow. To investigate the hydraulics of this bay and channel system, extended measurements of the water elevation, current, and wind were made to understand the acting processes and to calibrate a two-dimensional hydrodynamic numerical model. This paper describes the analysis performed for evaluating potential impacts of the proposed cut in the multiple-inlet bay system. Observations of the wind-dominated water level and current in the bay are also discussed.

BACKGROUND

East Matagorda Bay is a pristine, approximately rectangular estuary about 6 km wide on average and extending about 37 km from Caney Creek on the east to the Colorado River Navigation Channel on the west (Fig. 1). The long axis of this remote estuary is oriented approximately 27° counterclockwise to east-west, an orientation that causes the frequent winds along the coast to dominate the hydrodynamics of the estuary, as discussed below.

Originally, Matagorda Bay was a continuous water body extending from Caney Creek to Pass Cavallo on its south-

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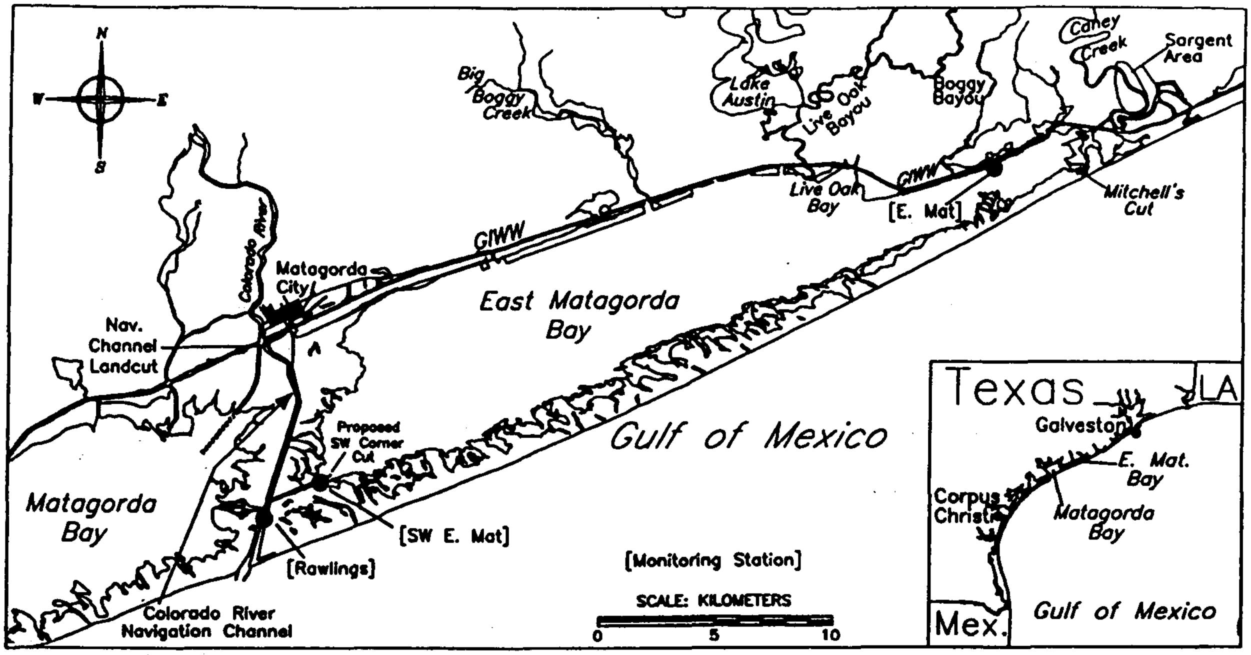

FIG. 1. Vicinity Map for Study Site

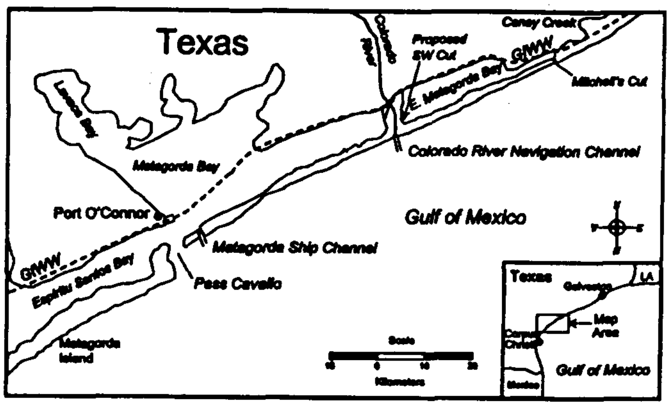

FIG. 2. Detail Map for East Matagorda Bay

western end (Fig. 2). East Matagorda Bay became isolated from the western and larger part of Matagorda Bay and from Pass Cavallo by a prograding delta that crossed the bay from the mainland and joined to Matagorda Peninsula (Bouma and Bryant 1969; Morton et al. 1976). The delta formed rapidly starting in 1929, when a log raft and massive sediments that had been entrapped for centuries on the Colorado River were freed by local interests concerned with flooding of low-lying inland areas. The delta reached Matagorda Peninsula in 1935 and formed a new bay called East Matagorda Bay. In 1992 the Colorado River was rerouted to discharge into Matagorda Bay rather than into the Gulf of Mexico, as an environmental enhancement for oyster cultivation. The crosscurrent at the intersection of the river and the GIWW often disrupts barge traffic along the GIWW. A pair of locks on the GIWW at the intersection mitigates the crosscurrent. These locks, which are normally closed except to allow passage of vessels along the GIWW, were assumed to be closed for the modeling study described below.

The GIWW is presently routed along the northern perimeter of East Matagorda Bay, sheltered from wind waves on the bay by islands composed of dredged material. Typical bay water depth ranges between 0.6 and 1.2 m. The GIWW is maintained to a depth of 3.6 m, with advance and overdredging potentially adding another 0.6 m of depth, and the waterway has a design bottom width of 38.5 m and top width of 91.4 m.

In their natural state, Texas bays and lagoons typically possess major freshwater inflows at their northern ends and a pass on their southern ends (Price 1952). East Matagorda Bay presently does not have an opening in its southwest corner because of the formation of the Colorado River delta. Mitchell's Cut (Fig. 1), a flood-relief channel to the Gulf of Mexico that was dredged open in May, 1989, crosses the GIWW and connects to East Matagorda Bay through a dense wetland. Carothers and Innis (1960) discuss the perceived need for opening of several passes in the Texas barrier islands for improvement of coastal fisheries. The SW Cut is one such pass, and a permit was issued by the U.S. Army Corps of Engineers (USACE) to allow construction of a channel 30 m wide at the bottom and 1.5 m deep with respect to mean water level.

The opening of SW Cut calls into consideration issues such as stability of the cut, stability of Mitchell's Cut, and alterations to the currents in the navigation channel and GIWW. Only limited monitoring and modeling information is available on the physical processes of East Matagorda Bay. An assessment of local physical processes at Brown Cedar Cut (presently closed) was made by Mason and Sorensen (1971). Brown and Root Inc. (1979a,b) conducted elementary hydrodynamic and salinity numerical modeling studies for East Matagorda Bay, supplemented by soils investigations and local hydrographic and topographic surveys. The aim of the Brown and Root studies was to determine the hydraulic feasibility of opening a cut to the Gulf of Mexico for establishing a salinity gradient across the bay and for developing recreational opportunities. The SW Cut was one of four alternatives studied. The USACE, Galveston District (1987), conducted an initial reconnaissance to determine the feasibility of providing flood control improvements to the East Matagorda Bay area. Five alternatives were studied, including the SW Cut. Both the Brown and Root Inc. (1979a,b) and the USACE (1987) studies concluded that the SW Cut alternative was probably infeasible without maintenance dredging because of anticipated sluggish flows in the long, shallow channel.

In a preliminary assessment of the proposed SW Cut made using the Manning equation, Martin (unpublished memorandum, 1993) estimated the tidal current velocity ". . . to determine if the (SW) Cut is likely to accumulate silt and sand or if it will be scoured by tidal flows." In contrast to the Brown and Root (1979a,b) studies, Martin obtained what he believed to be maximum possible velocities in the channel of about 60–70 cm/s, which he recognized were more than sufficient to move silt and sand. Owing to the recognized limitation of not having results from a complete hydrodynamic model of the circulation, Martin could not definitively conclude whether the channel of the SW Cut would either silt in or maintain itself.

Because of ambiguity in previous studies and lack of data, field measurements were made and an analysis performed to make a more reliable determination of whether the SW Cut would remain open, and to focus on issues that would make the cut unacceptable.

FIELD MEASUREMENTS

Field data collection was implemented to quantify the water motion in East Matagorda Bay and to provide data for calibration of the hydrodynamic model. The monitoring included a hydrographic survey over a two-day period and extended monitoring of water level and current velocity for approximately three months at two locations and of wind at one location.

Because East Matagorda Bay is not navigable (except for the GIWW) so that published bathymetric data are old, a hydrographic survey by dual-frequency echosounder and hand-held pole was conducted. The survey was controlled horizontally by differential GPS and covered approximately 220 km of transect lines.

Wind was expected to play a major role in controlling the water level and circulation in the bay; therefore, sustained monitoring of wind, together with water level and current, was conducted from October, 1995, through January 26, 1996. The monitoring was initiated in autumn so that both prevalent southeasterly winds and intermittent winter northeasterly winds would be documented. The resultant record contains almost complete time series of water elevation and current at the two longitudinal ends of the bay, and of wind at the eastern end. One instrument platform (called EMAT) was located at the eastern end on a platform operated by the state of Texas (see Fig. 1). The other platform (called SWEMAT) was specially constructed for this study at the southwestern end of the bay.

The two stations recorded the 3-min average water level at 6-min intervals. The water-level measurements were made with an acoustic system as used by the National Ocean Service (NOS). The wind at EMAT was measured with an RM Young Model 5103 anemometer of the type used by the National Weather Service. Although the anemometer typically reports wind at hourly intervals—during the middle, approximately 55 days of the monitoring period—6-min records were downloaded from the gauge to allow closer correlation of wind with the water-level and current measurements.

Water-level measurements are also available from a tide gauge called Rawlings, in the navigation channel located close to the intersection of the proposed SW Cut (Fig. 1), and at an NOS gauge located on the Galveston Pleasure Pier, 140 km to the north. In preliminary analysis, water elevation along the central Gulf coast of Texas was determined to rise with little phase difference, so that application of the long-term Galveston gauge data was appropriate for forcing the model. Therefore, despite remoteness of the site, substantial water-level and current measurements were made in and around East Matagorda Bay for an extended time in support of this study.

An Acoustic Doppler Velocimeter (ADV) was mounted at mid depth at EMAT and SWEMAT and measured three components of the current velocity (Kraus et al. 1994). On some occasions in the winter, the water level in East Matagorda Bay reached extreme lows accompanying the seasonal drop in Gulf of Mexico waters, such that the probes became intermittently exposed to wave action and the air. During weekly or biweekly visits to the site, the ADV probes were twice lowered to compensate for the low water in the bay.

Wind

Wind roses developed from the EMAT gauge measurements are depicted in Fig. 3 for (a) the year 1995, and (b) the observation period (Oct. 10, 1995, to Jan. 26, 1996). Wind direction is defined as the direction from which it blows. The annual wind rose shows that winds are incident predominantly from the southeast and east-southeast (120–150°) and that strong winds (>9 m/s) also blow from the east-northeast and northeast (45–75°) and from the north and north-northwest. Wind rarely blows from the west at the study site. For the shallow-water bays of Texas, the writers have found that winds with speeds greater than about 9 m/s generate a current that can dominate the tidally forced circulation (Kraus and Militello 1996; Brown and Kraus 1997). Because of the approximate east-west orientation of East Matagorda Bay, wind with an easterly component will drive water from the eastern side to the western side. Fig. 3(b) shows a dominance of wind out of the north-northwest to east-northeast for the observation period. The data collection also captured strong wind events from the southeast.

The wind speed and direction for the time period simulated

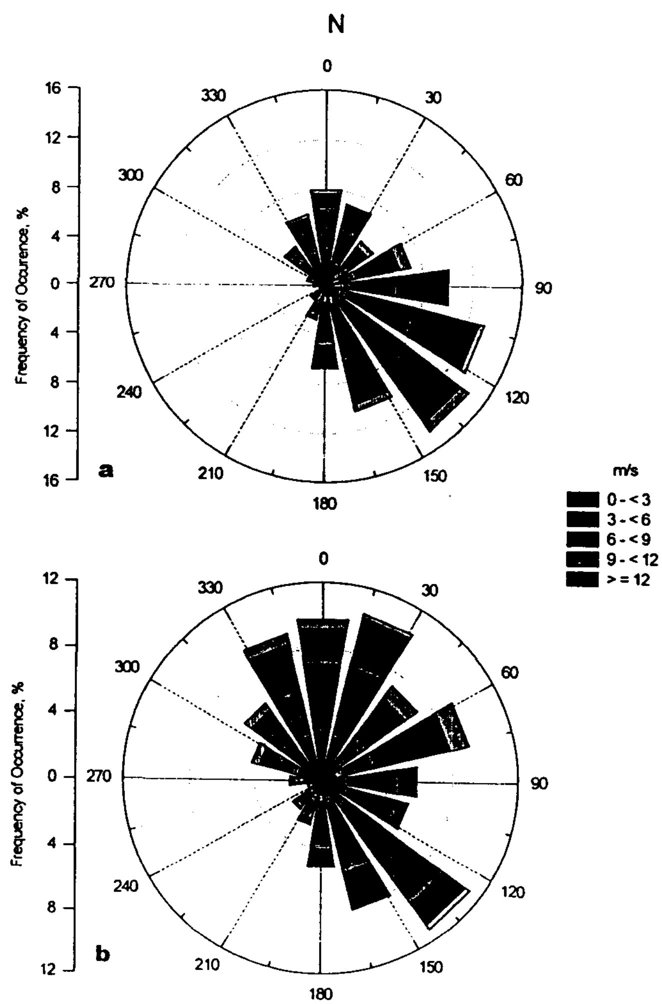

FIG. 3. Wind Rose for (a) 1995, and (b) Monitoring Period (10/10/95–01/26/96)

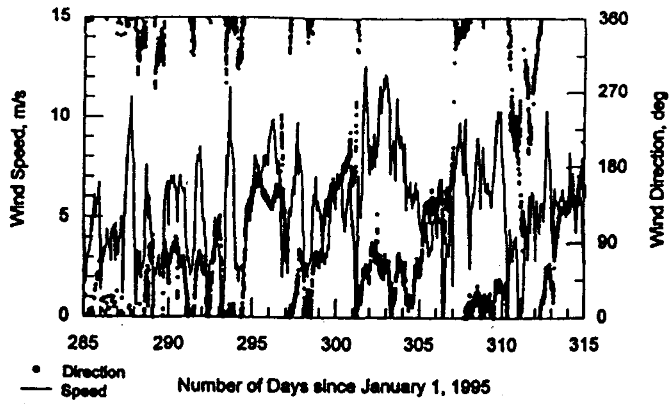

FIG. 4. Wind Speed and Direction during Modeling Period

with the hydrodynamic model are shown in Fig. 4. The direction north is either 0 or 360°, and wind from the east has direction 90°. The weather fronts that periodically move across the bay are apparent as abrupt shifts from 0 to 360°, interspersed with periods of east-southeast to southeast wind (150°). Wind speed shows sharp peaks associated with the passing northern fronts. Spectral analysis of the 108-day observation record revealed maximum wind energy to have a 5.2-day period, corresponding to the movement of the fronts.

During the selected 30-day modeling period [Oct. 12, 1995, (JD285) to Nov. 11, 1995, (JD314), where "JD" stands for Julian Day], several fronts moved through the area, with wind speeds exceeding 10 m/s. Some fronts brought sharp impulses of wind, such as on JDs 287 and 294. A sustained interval of strong wind speed occurred during JDs 301 to 304, with direction fairly steady from about 45° or northeast.

Water Level

Water level at the EMAT gauge for the observation period is plotted in Fig. 5, starting on JD275 (Sept. 7, 1995) and ending on Day 425 (Feb. 8, 1996). In this and other figures, water level is referenced to mean lower low water (MLLW) at the EMAT tide station. The overall trend of the water level is to decrease until approximately Day 400, after which the water level trend becomes constant. The small daily fluctuations in the water level correspond to the astronomical tidal forcing from the Gulf of Mexico, which has a range of 0.6 m at Galveston. In contrast, the tidal range for EMAT is only 10 cm. The trend of decreasing water level during the time period shown is part of the annual cycle of water level change in the Gulf (Lyles et al. 1988), attributed to seasonal variations in atmospheric pressure, whereas the larger spikes correlate with sustained strong wind.

Fig. 6 plots the water level at EMAT and SWEMAT measured during the modeling period, with the mean value at each location removed. A striking behavior in the two water level records appears as numerous simultaneous pairs of inverted spikes for which the water level at EMAT is set down and the water level at SWEMAT is set up. For example, on JD301 the difference in water level between the eastern and western ends of East Matagorda Bay was almost 0.6 m. As seen from Fig. 4, this substantial tilt in water level was produced by an impulsive northeast front with wind speed of about 12 m/s. The frontal wind impulse had been preceded by several days of moderate wind from the southeast, after which the wind turned sharply and blew from the northeast. A 0.6-m tilt in the water level over some 32 km between measurement stations is remarkable considering that this bay, surrounded by marshes and wetlands, is only 1.3 m deep in its deeper regions.

In addition, an approximately 4-day-long (JD307–JD310) persistent 0.3-m tilt in the water surface is observed in Fig. 6

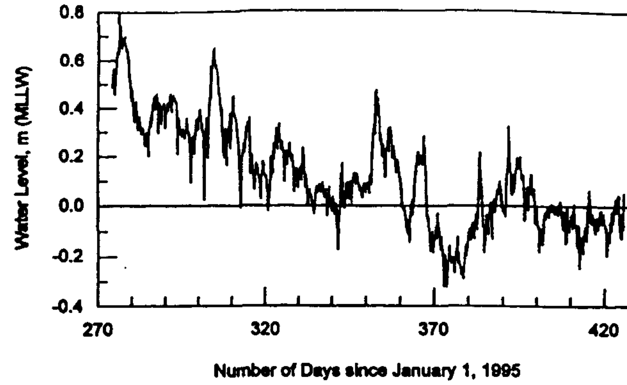

FIG. 5. Water Level at EMAT during Observation Period

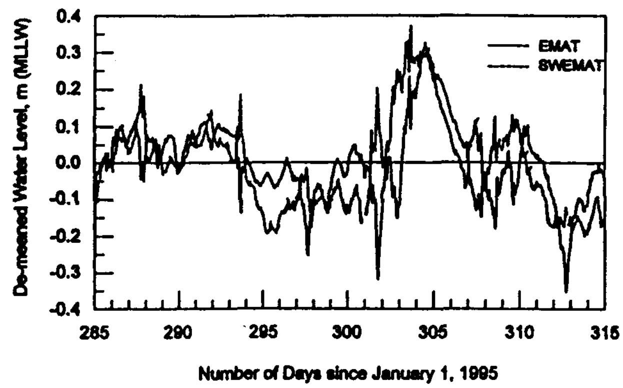

FIG. 6. De-Meaned Water Levels during Modeling Period

for winds that blew steadily from the north-northeast with winds typically in the range of 6–10 m/s. Under persistent moderate south-southeast and southeast winds (Fig. 4), the tilt reversed, and the water set up at EMAT and set down at SWEMAT (e.g., JD295–297, JD299–301, and JD305–307). The data on water-level elevation obtained at EMAT and SWEMAT during the monitoring period of this study provide an exceptionally dynamic record of water movement for testing and calibration of a numerical model with competing wind and tidal forcing.

In order for the water level to tilt 0.6 m along the major axis of the bay, a substantial volume of water must flow from east to west. Thus, it is expected that the pattern and strength of the circulation in the bay during times of moderate to strong wind is dominated by wind-induced flow.

Current

Because of the approximate east-to-west orientation of East Matagorda Bay and the frequent occurrence of wind with an easterly component, there is substantial movement of water along the major (E-W) axis of the bay. The E-W components of the current measured at EMAT and SWEMAT during the 30-day modeling period are shown in Fig. 7, in which positive values indicate flow toward the east. A gap is present at the start of the EMAT record because of equipment malfunction. The E-W component of the current at EMAT has a typical maximum in the range of ±15 cm/s, whereas the current at SWEMAT has a range less than ±5 cm/s. The magnitude of the current at SWEMAT is less than that at EMAT because the SWEMAT station was located in a relatively confined region with wetland marshes on three sides.

Presently, Mitchell's Cut is the main, although indirect, connection of East Matagorda Bay to the Gulf of Mexico. Measurements of water level and current in the bay as described above indicate that the tidal signal is relatively weak compared

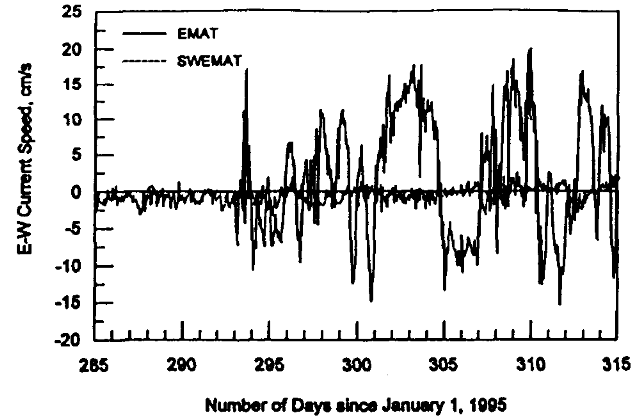

FIG. 7. Measured E-W Current at EMAT and SWEMAT during Modeling Period

with the signal produced by the wind. However, tidal flow in Mitchell's Cut can be strong and, without the cut, the daily tide signal in the Bay would be almost absent. During one short-term synoptic observation, the current at Mitchell's Cut was flooding strongly with a northward directed mean flow of 111 cm/s and standard deviation of about 17 cm/s over the more than 1-hr measurement interval.

NUMERICAL SIMULATION OF HYDRODYNAMICS

The two-dimensional numerical model applied in this study calculates water-surface elevation and two horizontal components of the depth-averaged current at cells defined by a variably spaced, rectilinear computational grid. The persistent and strong wind blowing over the shallow water produces a well-mixed, vertically homogeneous system (Ward and Armstrong 1982), indicating suitability of a depth-averaged model. The model was subjected to numerical integrity tests that covered numerical damping (slosh tests), conservation of mass, stability of individual terms that included the advection terms, and comparison to a one-dimensional analytical solution and a published numerical solution (Spaulding 1984) for two-dimensional wind forcing (Militello 1998).

Calculation Grid and Boundary Conditions

Four grids were generated in this study: existing conditions, SW Cut installed, existing condition with Mitchell's Cut closed, and SW Cut installed with Mitchell's Cut closed. Each rectilinear grid consisted of approximately 8,000 active computational cells with minimum cell-size dimension of 33 m and maximum dimension of 505 m. The most refined cells were located in channels. For example, the SW Cut was represented by a channel one cell wide (33 m), and Mitchell's Cut was typically represented with four to six cells with 50-m width. The largest grid cells were located in the Gulf, and typical cell width in the interior of the bay was 100 m. Grid cell aspect ratio (length divided by width of a cell) was always less than two. Grid cell resolution was dense and partially displayed with color in Kraus and Militello (1996).

The rectilinear grids were oriented with one coordinate axis parallel to the main axis of East Matagorda Bay and the other coordinate axis approximately normal to the trend of the shoreline and depth contours in the Gulf. The offshore portion of the grid consisted of two parts approximately centered on the navigation channel entrance and on Mitchell's Cut. The portion at the navigation channel entrance extended 1.5 km seaward and 7 km alongshore, and the portion of the grid at Mitchell's Cut extended 2.1 km seaward and 8 km alongshore.

Water-surface elevation forcing boundaries were established at grid edges in the Gulf of Mexico. The forcing was specified as 6-min time series of water level measured at the NOS Galveston Flagship Pier tide gauge. Boundary conditions at Caney Creek and the GIWW were nonforcing and specified as a temporally varying constant gradient in water-surface elevation. This nonforcing flux condition in the channels allows water to flow freely through the boundary.

Governing Equations

The model is a finite-difference approximation of the mass continuity and momentum equations given by

$$\frac{\partial \eta}{\partial t} = h\left(-\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right) \tag{1}$$

$$\frac{\partial u}{\partial t} = -g\frac{\partial \eta}{\partial x} - u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} + fv - C_b\frac{u|u|}{(h+\eta)} + C_d\frac{\rho_a}{\rho_w}\frac{W^2\cos(\theta)}{(h+\eta)} \tag{2}$$

$$\frac{\partial v}{\partial t} = -g\frac{\partial \eta}{\partial y} - u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - fu - C_b\frac{v|v|}{(h+\eta)} + C_d\frac{\rho_a}{\rho_w}\frac{W^2\sin(\theta)}{(h+\eta)} \tag{3}$$

where h = still-water depth; η = deviation in water level from h; t = time; u = current speed parallel to x axis; v = current speed parallel to y axis; g = acceleration due to gravity; f = Coriolis parameter; C_b = empirical bottom friction coefficient; C_d = wind stress (drag) coefficient; ρ_a = density of air; ρ_w = density of water; W = wind speed; and θ = wind direction. Contributions from lateral mixing, which can be included in the model (Militello 1998), were found to be small and therefore neglected.

The friction coefficient is calculated by the equation

$$C_b = \frac{g}{C^2} \tag{4}$$

in which C = Chezy coefficient given by $C = (R^{1/6})/n$; R = hydraulic radius; and n = Manning coefficient. For each component of flow in each cell, the hydraulic radius is calculated as the cross-sectional area normal to the flow divided by the wetted perimeter (including the displacement η).

The wind-stress coefficient applied in (2) and (3) is given by (Hsu 1988)

$$C_d = \left(\frac{0.4}{14.56 - 2\ln W_{10}}\right)^2 \tag{5}$$

where W_{10} = wind speed at an elevation of 10 m.

The explicit finite-difference solution scheme is central in space and forward in time, with the exception of the advective terms, discussed below. Variables are discretized on an Arakawa C-grid in which velocity is calculated on cell faces, and water level is calculated at cell centers. The momentum equations are first solved without the advective terms by application of water level and velocity from the previous time step. The solution for water level in the continuity equation incorporates updated values of velocity from the momentum equation calculations (Kowalik and Murty 1993). Contributions from the advective terms are then computed from the updated velocities and velocities from the previous time step and are added to the momentum equations.

Discretization of the variables, illustrated for one dimension for simple derivative terms is

$$h\frac{\partial u}{\partial x} \approx h_{i,j}\frac{(u^{k+1}_{i+1,j} - u^{k+1}_{i,j})}{\Delta x_{i,j}} \tag{6}$$

and

$$\frac{\partial \eta}{\partial x} \sim \frac{2(\eta^k_{i,j} - \eta^k_{i-1,j})}{(\Delta x_{i,j} + \Delta x_{i-1,j})} \quad (7)$$

where i and j = cell indices for the x- and y-coordinates, respectively; k = time step; and Δx = cell dimension. Eqs. (6) and (7) demonstrate how derivatives are defined for a variably spaced rectilinear grid. Variables in the momentum equation, such as bottom friction and wind forcing, are defined on cell faces.

The advective terms for the x-momentum equation (2) are discretized through spatial and temporal averaging as follows:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} \sim \frac{1}{4}(2\alpha^{k+1}_{i,j} + \alpha^{k+1}_{i,j+1} + \alpha^{k+1}_{i,j-1}) \quad (8)$$

where

$$\alpha^{k+1}_{i,j} = 0.5\left[\left(u\frac{\Delta u}{\Delta x}\right)\Bigg|^{k+1}_{i,j} + \left(v\frac{\Delta u}{\Delta y}\right)\Bigg|^{k+1}_{i,j} + \left(u\frac{\Delta u}{\Delta x}\right)\Bigg|^{k}_{i,j} + \left(v\frac{\Delta u}{\Delta y}\right)\Bigg|^{k}_{i,j}\right] \quad (9)$$

The difference equations for terms on the right side of (9) are given by

$$\left(u\frac{\Delta u}{\Delta x}\right)\Bigg|^{k+1}_{i,j} = 2u^{k+1}_{i,j}\frac{(u^{k+1}_{i+1,j} - u^{k+1}_{i-1,j})}{(\Delta x_{i-1,j} + \Delta x_{i,j})} \quad (10)$$

$$\left(v\frac{\Delta u}{\Delta y}\right)\Bigg|^{k+1}_{i,j} = \frac{1}{4}(v^{k+1}_{i,j} + v^{k+1}_{i,j+1} + v^{k+1}_{i-1,j+1} + v^{k+1}_{i-1,j}) \cdot \frac{(u^{k+1}_{i,j+1} - u^{k+1}_{i,j-1})}{[0.5(\Delta y_{i,j+1} + \Delta y_{i,j-1}) + \Delta y_{i,j}]} \quad (11)$$

Approximations involving time step k have the same form as those shown for time step $k + 1$.

The time step Δt for the model is limited by the stability criterion

$$\Delta t \le \frac{\Delta s}{\sqrt{gh}} \quad (12)$$

where Δs = size dimension of a cell, with s representative of either the x or y coordinate. Practical application of this criterion for the model requires the time step to be approximately 0.6 to 0.7 times the theoretical maximum time step given by (12). For the present application, the time step was 3s.

Model Calibration

The bottom friction coefficient was the only parameter adjusted for the calibration, which took typical values, based on the bottom and side bank conditions (Chow 1959). In the majority of cells, the Manning coefficient ranged between 0.022 and 0.028 s/m$^{1/3}$, with higher values assigned in areas of expected greater bottom roughness, such as at oyster beds. Calibration required larger values of the Manning coefficient, up to 0.1 s/m$^{1/3}$, in the vicinity of the mouth of the navigation channel, to account for transition losses at the entrance.

Figs. 8–10 show calculated water levels obtained with the calibrated model and the measured water-level fluctuations at (respectively) Rawlings, EMAT, and SWEMAT. The calculated water-level fluctuations follow closely those of the measurements, and both the shorter period (tidally induced) and longer period (wind-induced) motions are reproduced by the model. The model captures the influence of the wind on the water-level fluctuation and the current (next paragraph), which indicates that the wind stress formulation employed (5) works well in extremely shallow water. The root-mean-square (rms) difference between calculated and measured water levels at

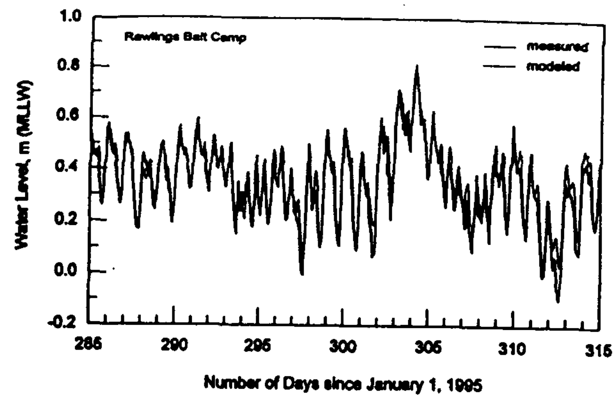

FIG. 8. Comparison of Measured and Simulated Water Level at Rawlings

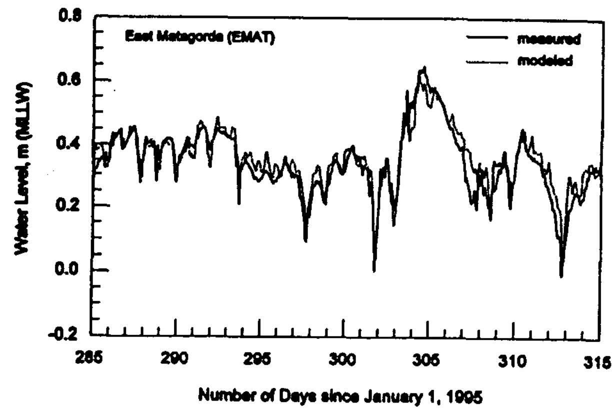

FIG. 9. Comparison of Measured and Simulated Water Level at EMAT

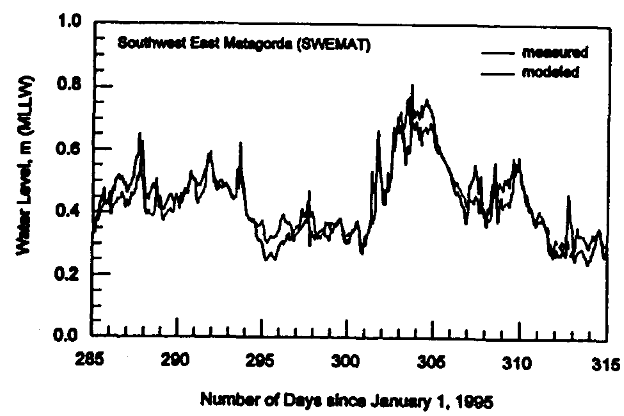

FIG. 10. Comparison of Measured and Simulated Water Level at SWEMAT

Rawlings, EMAT, and SWEMAT were 5.2, 4.8, and 4.2 cm, respectively.

Comparisons of the calculated E-W current speed and the measurements are shown in Figs. 11 and 12 for EMAT and SWEMAT, respectively. The measured currents were low-pass filtered with a cutoff frequency of 12 cycles/day to remove the wind waves. The simulated currents generally track the measured currents and indicate that the model calibrated well. Deviations between the measured and calculated currents are typically 2–3 cm/s at EMAT and 1–2 cm/s for SWEMAT, with the measured current at SWEMAT being very weak (−2 to 5 cm/s). The rms error between calculation and measurements was 4.9 and 1.4 cm/s, respectively, at EMAT and SWEMAT.

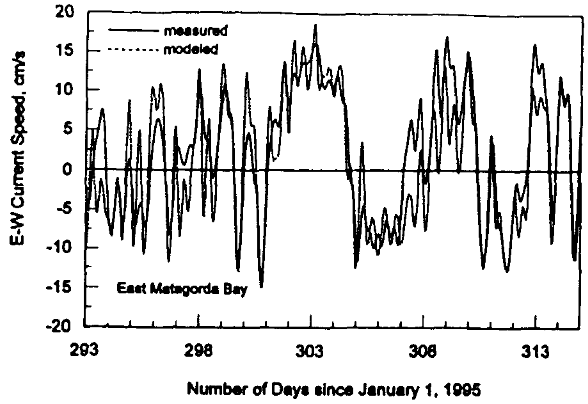

FIG. 11. Comparison of Measured and Simulated E-W Current Speed at EMAT

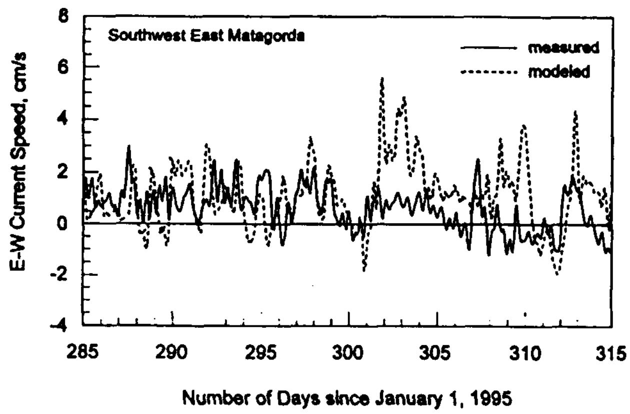

FIG. 12. Comparison of Measured and Simulated E-W Current Speed at SWEMAT

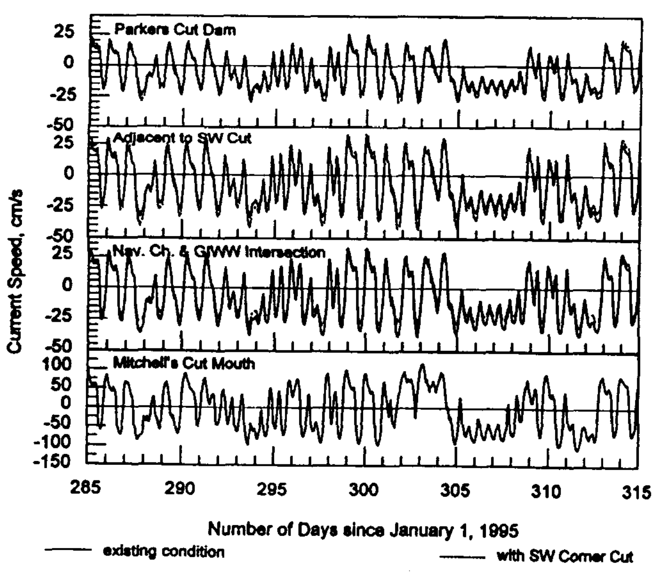

FIG. 13. Calculated Current at Selected Points for Existing Condition and with SW Cut in Place

SIMULATIONS WITH PROPOSED SW CUT

Predictions of water-level fluctuations with and without the SW Cut were examined for several locations in channelized portions of the study site. The navigation channel reach located seaward of the SW Cut was calculated to have a reduced tidal range with the cut installed. The reduction in tidal range diminished in the Gulfward direction as the influence of the Gulf forcing increased. During flood tide, the SW Cut will allow water to flow into the bay, reducing the gradient in the water surface from the point where the SW Cut meets the navigation channel to the mouth of the navigation channel. During ebb tide, the SW Cut will allow water to flow from the bay to the navigation channel and increase the water-surface gradient from the point of connection to the Gulf. The flow of water out of the bay through the SW Cut will be increased by winds with an easterly component and will keep the hydraulic head at the Cut higher than it would be without the wind.

The SW Cut will take a portion of the flow that normally passes through the navigation channel, resulting in reduced water-level fluctuations in the channel upstream of the Cut. Reduction in range occurs in the navigation channel and in the western reach of the GIWW, along the northern perimeter of the bay. The tide range gradually approaches that of the existing condition toward the eastern end of the GIWW and is only slightly altered (decreased) in the vicinity of Caney Creek.

The flow in the system will be modified by the presence of the SW Cut according to location, as shown in Fig. 13. The current speed Gulfward of the cut increases with the SW Cut installed, and the speed decreases upstream (Rawlings). An important benefit of the SW Cut will be a reduction in peak flow speed at the intersection of the GIWW and the navigation channel by as much as 25%, which would improve navigability in the GIWW. The reduction in current speed upstream of the cut results from the SW Cut carrying a portion of the flow that would otherwise travel through the navigation channel. Mitchell's Cut had no perceptible change in current speed with the SW Cut present, and the change in current at the GIWW in the vicinity of Caney Creek also was negligible.

With the SW Cut present, the discharge in the navigation channel at Rawlings (north of the Cut) was reduced by approximately 20–25%. On average, the discharge diverted through the SW Cut was 30% of the total flow rate through the navigation channel south of the Cut for the month-long simulation period. The reduction in flow at Rawlings occurs for both flood and ebb tide.

Flow in SW Cut

For grids containing the SW Cut, entrance and exit losses were accounted for by assigning values of Manning's n of 0.08 and 0.06 $s/m^{1/3}$ at two cells on the ends of the confined portion of the SW Cut. The value of 0.08 $s/m^{1/3}$ was applied at the outermost cells, relative to the confined region of the SW Cut, and the value of 0.06 $s/m^{1/3}$ was applied to the adjacent inner cells. All remaining cells in the confined portion of the SW Cut were assigned values of $n = 0.025$ $s/m^{1/3}$.

Magnitude and direction of the flow through the SW Cut have implications for scour or deposition in the Cut and for exchange of water between East Matagorda Bay and the nav-

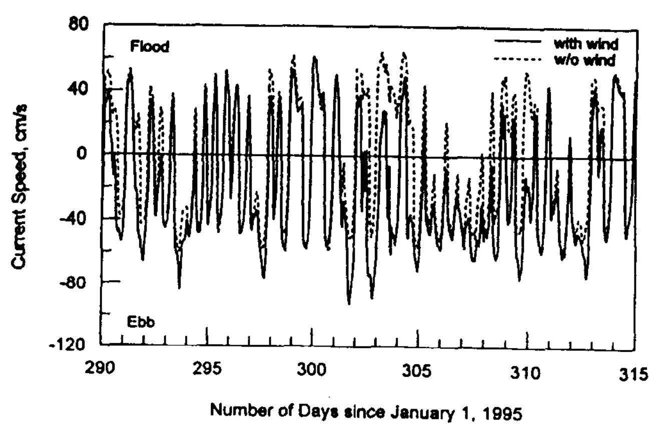

FIG. 14. Calculated Current in SW Cut with and without Wind Forcing

igation channel. Fig. 14 plots the calculated current velocity in the middle of the SW Cut for the modeling period. Positive values denote flooding into the bay from the navigation channel, and it is seen that there is a bias for flow to ebb out of the bay. A net outward flow is expected because of the frequent winds with an easterly component and resultant wind setup on the western end of East Matagorda Bay, with a water-elevation gradient induced between the bay and navigation channel. The mean discharge through the cut will be directed out of the bay for most of the year, and the net (outward) discharge of the flow for the modeling period varied between about 9 and 11.5 m^3/s, depending on the value of the friction coefficient assigned to the Cut. The outflow through the cut is balanced by increased flow into the system through the GIWW, Caney Creek, and Mitchell's Cut.

Role of Mitchell's Cut

Change in current velocity and discharge at Mitchell's Cut with installation of the SW Cut is of concern for longevity of Mitchell's Cut. However, Fig. 13 showed that there would be no significant change in current velocity through Mitchell's Cut with installation of the SW Cut. The net increase in inflow at Mitchell's Cut with the SW Cut installed will only slightly increase, typically when the tide is flooding. Over the modeling period, the average change in discharge at the mouth of Mitchell's Cut was approximately 3 m^3/s (net flooding), which is less than 2% of the typical daily peak discharge of about 200 m^3/s. The increased flow into Mitchell's Cut is a response to water flowing out of East Matagorda Bay through the SW Cut.

Mitchell's Cut is the most direct opening through which water can be exchanged between the Gulf of Mexico and East Matagorda Bay. Simulations were performed without Mitchell's Cut to understand the role that the cut plays in the hydrodynamics of East Matagorda Bay and to examine the consequence of closure of Mitchell's Cut. The water level at both EMAT and SWEMAT decreased over the modeling period. The decrease in water level is expected because the nearly persistent winds cause setup along the western end of the bay and water flows out of the bay via the SW Cut, as described earlier. With Mitchell's Cut closed, water cannot enter the bay fast enough to replace that lost through the SW Cut, and the net result is a decrease in water level. If Mitchell's Cut were to close, the water level in the bay would likely drop to an equilibrium level with a new balance of outflows and inflows.

HYDRAULIC FEASIBILITY AND INLET STABILITY

In classical tidal inlet analysis for stability of the channel cross section (Escoffier 1940, 1977), the tidal prism is a central parameter (Jarrett 1976). The tidal prism is the change in total water volume in an estuary or bay between high and low water. In the present study, tidal prism is not the sole controlling factor governing discharge through the inlet, because wind-induced setup at the southwest corner of the bay produces a quasi-steady ebb current at the location of the proposed cut (Fig. 14). The calculated current in the SW Cut for the modeling period has a bias for ebbing. The peak ebb current speed typically reaches 40 cm/s on flood or ebb, and the stronger ebb currents are in excess of 80 cm/s as a result of wind-driven set up.

A two-dimensional model is useful for calculating the hydrodynamics of this multiple-inlet system with and without wind forcing. A comparison of such calculations is shown in Fig. 14. Although qualitative trends in variation of the current are reproduced, the ebb flow is notably increased with wind forcing. The general (downward) shift toward ebb, present when wind forcing acts, is absent in the current calculated without wind. With wind, the mean discharge through the SW Cut was -11.4 m^3/s, whereas without wind the mean discharge was -0.1 m^3/s.

Current velocities in excess of 60 cm/s will readily erode clay and sand (typical sediments in East Matagorda Bay). Tidal inlets with stable cross sections must possess maximum currents on the order of 1 m/s for an open coast (e.g., Jarrett 1976; see Bruun 1990 for a review) and 30 cm/s for wave-sheltered coasts and limited longshore transport (Riedel and Gourlay 1980), the present situation. Currents of 1 m/s magnitude were measured in this study both at the mouth of Mitchell's Cut and at the mouth of the navigation channel. Currents often exceeding 60 cm/s were also calculated by the hydrodynamic model for the SW Cut with its design depth of 1.5 m. In other simulations, the current speed was found to exceed 1 m/s if the cut scoured to a nominal depth of 3.7 m (which is the approximate depth at its connection with the navigation channel). This study therefore concludes that the cut will be naturally stable (not require maintenance dredging). The study also confirms the general observation of Price (1952) that the southwest corner is a hydraulically optimum location for an inlet on the Texas coast, and therefore stabilizing currents are anticipated.

In summary, the current in the SW Cut will be biased toward ebb under forcing by southeast and northeast winds. At its design dimensions, the current speed will exceed 60 cm/s under typical wind speeds and will flow faster under stronger wind. As opposed to a classical tidal inlet, the SW Cut will act more as a tidal river mouth, with the river flow replaced by a quasi-steady, wind-driven outflow having tidal fluctuations superimposed on it. No flood tidal delta in the bay will form because of the ebb bias in the current. On a continuing basis, fine sand, silt, and clay will be transported out of the SW corner and into the navigation channel. Suspended fine-grained sediment might increase water turbidity, and the additional material would eventually be deposited in shoals off the mouth of the navigation channel. The volume of additional material is expected to be very small compared with the several hundreds of thousands of cubic meters per year dredged at the mouth (Heilman 1995) and should not alter navigability of the channel.

Mitchell's Cut has remained open since it was created in May 1989, and it evidently owes its longevity to the adequate flow from the GIWW and Caney Creek. It is suspected, but was not verified in this study, that infrequent heavy precipitation and subsequent strong discharges from Caney Creek may be a significant factor in maintaining the stability of Mitchell's Cut. Therefore, a drought might tend to promote closure of the Mitchell's Cut. Mitchell's Cut is an ephemeral inlet; because it is not stabilized by structures, it has a finite life. If Mitchell's Cut were to close after opening of the SW Cut, the results of the present study indicate that the closure process would be unrelated to the hydraulics in the SW corner of East Matagorda Bay. However, the water level in the bay would be lowered if Mitchell's Cut closed, which could have a deleterious environmental impact.

SUMMARY AND CONCLUSIONS

The presence of multiple inlets and waterways and the competing driving forces of wind and tide required application of a two-dimensional hydrodynamic model to investigate the feasibility of creating a water-exchange cut in East Matagorda Bay. Field measurements performed for the analysis documented a shallow-water system with flows frequently dominated by wind.

Based on the hydrodynamic analysis, the SW Cut, if opened, will remain open unless artificially closed. The flow in the cut will be ebb dominated because of a bias introduced by the wind, and the current speed will regularly reach 0.6 to 1 m/s if the design dimensions of the Cut are maintained. Because of the expected strong outflows, the Cut will have a tendency to scour at its intersection with the navigation channel. The current speed will increase if the cut scours, so that scour-abatement strategies should be considered in design. Scour in the wetland area adjacent to the channel of the SW Cut is not expected to occur, because current speeds in the Cut are similar in magnitude to those measured at Mitchell's Cut. The wetlands adjacent to channels at Mitchell's Cut have been effectively stable since its opening in 1989.

If the SW Cut is opened, the peak current and discharge will decrease at the intersection of the GIWW and the Colorado River Navigation Channel land cut. A maximum decrease of 25% in peak current is predicted and will improve navigability in the GIWW. If the Cut is opened, there will be a slight increase in both ebb and flood peak flows at the mouth of the navigation channel, which will act in favor of maintaining the channel. The stability of Mitchell's Cut will not be altered with opening of the SW Cut.

If Mitchell's Cut closes (closure being independent of the existence of the SW Cut), then the presence of the SW Cut and absence of replacement water that would otherwise enter through Mitchell's Cut would lead to a lowering of mean water level in East Matagorda Bay. Calculation of the amount of lowering was beyond the scope of this study, but it is believed that it would be appreciable.

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APPENDIX I. REFERENCES

Bouma, A. H., and Bryant, W. R. (1969). "Rapid delta growth in Matagorda Bay, Texas." Lagunas Costeras, Un Sinposio, 171–189.

Brown, C. A., and Kraus, N. C. (1997). "Environmental monitoring of dredging and processes in the Lower Laguna Madre, Texas." Tech. Rep. TAMU-CC-CBI-96-01. Conrad Blucher Institute for Surveying and Science, Texas A&M University–Corpus Christi, Tex.

Brown and Root Inc. (1979a). "Improvements at Brown Cedar Cut, East Matagorda Bay, Texas. Report of preliminary engineering services, phase I: feasibility study, prepared for Messrs. Roy and Harry Cullen, Trustees." Brown and Root Inc., Houston, Tex.

Brown and Root Inc. (1979b). "Improvements at Brown Cedar Cut, East Matagorda Bay, Texas. Final report for phase IIa: Preliminary design and site selection." Brown and Root Inc., Houston, Tex.

Bruun, P. (1990). *Port engineering, volume 2: Harbor transportation, fishing ports, sediment transport, geomorphology, inlets, and dredging*, 4th Ed., Gulf, Houston, Tex.

Carothers, H. P., and Innis, H. C. (1960). "Design of inlets for Texas coastal fisheries." *J. Wtrwy. and Harb. Div.*, ASCE, 86(3), 103–128.

Chow, V. T. (1959). *Open channel hydraulics*. McGraw-HIll, New York.

Escoffier, F. F. (1940). "The stability of tidal inlets." *Shore and Beach*, 8(4), 114–115.

Escoffier, F. F. (1977). "Hydraulics and stability of inlets." *GITI Rep. No. 13*, U.S. Army Wtrwy. Experiment Station, Coastal Engineering Research Ctr., Vicksburg, Miss.

Heilman, D. J. (1995). "The effects of the Colorado River project on longshore sediment transport at Matagorda Peninsula, Texas," MS thesis, Texas A&M University, College Station, Tex.

Hsu, S. A. (1988). *Coastal meteorology*. Academic, San Diego, Calif.

Jarrett, J. T. (1976). "Tidal prism-inlet area relationships." *GITI Rep. No. 3*, U.S. Army Corps of Engineers, Coast. Engrg. Res. Ctr., Vicksburg, Miss.

Kowalik, Z., and Murty, T. S. (1993). *Numerical modeling of ocean dynamics*. World Scientific, River Edge, N.J.

Kraus, N. C., Lohrmann, A., and Cabrera, R. (1994). "New acoustic meter for measuring 3D laboratory flows." *J. Hydr. Engrg.*, 120(3), 406–412.

Kraus, N. C., and Militello, A. (1996). "Hydraulic feasibility of proposed Southwest Corner Cut, East Matagorda Bay, Texas." *Tech. Rep. TAMU-CC-CBI-96-03*, Conrad Blucher Inst. for Surv. and Sci., Texas A&M University–Corpus Christi, Corpus Christi, Tex.

Lyles, S. D., Hickman, L. E., and Debaugh, H. A. Jr. (1988). "Sea level variations for the United States, 1855–1986." U.S. Department of Commerce, National Oceanic and Atmospheric Admin., National Ocean Service, Rockville, Md.

Mason, C., and Sorenson, R. M. (1971). "Properties and stability of Texas barrier beach inlet." *TAMU-SG-71-217, COE Rep. No. 146*, Texas A&M University, College Station, Tex.

Militello, A. (1998). "Hydrodynamics of shallow, wind-dominated lagoons," Doctoral dissertation, Div. of Marine and Environmental Systems, Florida Institute of Technology, Melbourne, Fla.

Moore, B. D. (1993). "Channel reformation at Big Marco Pass, Collier County, Florida." *Proc., 1993 Nat. Conf. on Beach Preservation Technol.*, Florida Shore and Beach Preservation Assoc., Tallahassee, Fla., 161–174.

Morton, R. A., Pieper, M. J., and McGowan, J. H. (1976). "Shoreline changes on Matagorda Peninsula (Brown Cedar Cut to Pass Cavallo), an analysis of historical changes of the Texas Gulf shoreline." *Geological Circular 76-6*, Bureau of Economic Geol., The University of Texas at Austin, Austin, Tex.

Price, W. A. (1952). "Reduction of maintenance by proper orientation of ship channels through tidal inlets." *Proc., 2nd Conf. on Coast. Engrg.*, ASCE, Reston, Va., 243–255.

Riedel, H. P., and Gourlay, M. R. (1980). "Inlets discharging into sheltered waters." *Proc., 17th Coast. Engrg. Conf.*, ASCE, Reston, Va., 2550–2564.

Spaulding, M. L. (1984). "A vertically averaged circulation model using boundary fitted coordinates." *J. Phys. Oceanography*, 14, 973–982.

U.S. Army Corps of Engineers. (1987). "Section 205 initial reconnaissance report on flood control improvements East Matagorda Bay." U.S. Army Engineer District, Galveston, Tex.

Van de Kreeke, J. (1985). "Stability of tidal inlets—Pass Cavallo, Texas." *Estuarine, Coast. and Shelf Sci.*, 21, 33–43.

Van de Kreeke, J. (1990a). "Can multiple tidal inlets be stable?" *Estuarine, Coast. and Shelf Sci.*, 30, 261–273.

Van de Kreeke, J. (1990b). "Stability analysis of a two-inlet system." *Coast. Engrg.*, 14, 481–497.

Ward, G. H. Jr. (1982). "Pass Cavallo, Texas: Case study of tidal prism capture." *J. Wtrwy., Port, Coast., and Oc. Div.*, 108(4), 513–525.

Ward, G. H., and Armstrong, N. E. (1982). "Matagorda Bay: A management plan." *FWS/OBS-82-73*, Div. of Biological Services, U.S. Fish and Wildlife Service, Washington, D.C.

APPENDIX II. NOTATION

The following symbols are used in this paper:

C = Chezy coefficient;
C_b = bottom friction coefficient;
C_d = wind drag coefficient;
f = Coriolis parameter;
g = acceleration due to gravity;
h = still-water depth to specified datum;
n = Manning coefficient;
R = hydraulic radius;
t = time step;
u = horizontal current speed parallel to x axis;
v = horizontal current speed parallel to y axis;
W = wind speed;
W_{10} = wind speed at 10-m elevation;
x = horizontal Cartesian space coordinate;
y = horizontal Cartesian space coordinate;
Δs = grid cell length;
Δt = time step;
Δu = change in u component of current velocity;
Δx = grid cell length along x axis;
Δy = grid cell length along y axis;
η = deviation in water level from h;
ρ_a = density of air;
ρ_w = density of water; and
θ = wind direction.

Subscripts

i, j = cell indices; and
k = time step.