2.5.15 Mouth of the Colorado River

The Colorado River was rerouted to Matagorda Bay by the SWG in 1992 to supply fresh water to the Bay. The rerouted river is one of the primary sources of fresh water flow and sediment into the Matagorda Bay system. Aerials indicate that a delta began forming almost immediately in Matagorda Bay after the diversion occurred (Figures 13 to 15). The delta is likely a significant source of muddy material into the system. The amount of sediment contributed to the system is unknown but significant.

2.6 Matagorda Nautical Depth

2.6.1 Background

Fluid mud flow up the MSC was observed from survey data. Hydrographic surveying on waterways containing fluid mud, a.k.a. fluff, compared to more consolidated bottom materials like sand can pose difficulties in determining where the channel bottom actually lies. The acoustic reflection of conventional hydrographic surveying equipment used to measure water depth may not necessarily identify a depth within the fluid mud column that characterizes a nautical bottom. The term nautical bottom is defined by the

Figure 13. Pre re-route in 1990.

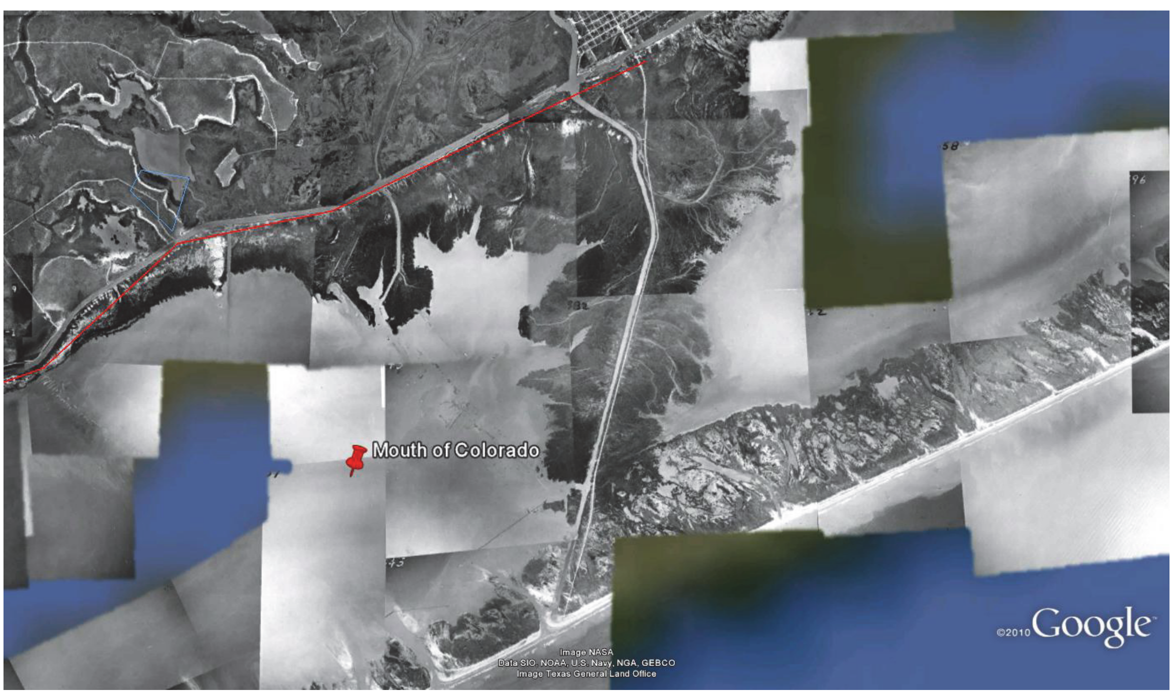


Figure 14. Post re-route in 1995 – formation of delta evident in Matagorda Bay.

Figure 15. Re-routed Mouth of the Colorado River in 2011.

Permanent International Association of Navigation Congresses (PIANC 1997) as "the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and maneuverability." With nautical bottom defined as such, the term nautical depth (PIANC 1997) is defined as "the instantaneous and local vertical distance between the nautical bottom and undisturbed free water surface."

The USACE presently has no standardized method to measure the fluid mud to determine nautical depth. The Engineer Manual 1110-2-1003 Hydrographic Surveying (USACE 2003) states "when the upper sediment layer is not well consolidated, the three major depth measurement methods used in the Corps (sounding pole, lead line, and acoustic echo sounding) will generally not correlate with one another, or perhaps not even give consistent readings from one time to the next when the same type of instrument or technique is used." This ambiguity in determining depth has hindered the USACE optimization of maintenance dredging in navigation channels with significant amounts of fluid mud.

An operational definition of nautical bottom in areas of fluid mud based on density or other rheological parameters has reduced maintenance dredging costs in Europe (De Meyer and Malherbe 1987; Herbich et al. 1989; Teeter 1991) and allowed the use of innovative dredging techniques such as sediment conditioning where the fluid mud is pumped into a modified hopper, conditioned (oxygenated and mixed to reduce viscosity and yield strength), then returned to the bottom (Wurpts 2005; PIANC 2008).

2.6.2 Physical Characteristics of Fluid Mud

As defined by McAnally et al. (2007) "fluid mud is a high concentration aqueous suspension of fine grained sediment in which settling is substantially hindered by the proximity of sediment grains and flocs, but which has not formed an interconnected matrix of bonds strong enough to eliminate the potential for mobility, leading to a persistent suspension." Therefore, the fluid mud can be characterized as suspensions with density gradations that are slightly greater than that of the overlying water in its upper layers. To set a frame of reference of density values, work conducted by Krone (1963) was modified to illustrate the relation of bulk density and solids concentration relative to concepts such as turbidity, fluid mud (high and low density), and typical bottom sediments in Table 14.

Table 14. Ranges of bulk densities and solids concentrations (modified after Krone 1963).

Average Bulk Density (g/cm^3) to Solids Concentration (g/l)

Qualitative Descriptor	Solids Concentration (g/l)	Bulk Density (g/cm^3)
TURBIDITY	0 - 5	1.000 - 1.003
Low Density	5 - 225	1.003 - 1.140
FLUID MUD		
High Density	225 - 500	1.140 - 1.311
"TYPICAL" BOTTOM SEDIMENT	> 500	> 1.311

Assumes Solids - 2.65 g/cm^3
Water - 1.000 g/cm^3

While density and viscosity are related, that relationship can be complicated by other factors (Teeter 1992). The factors include (PIANC 1997) the following:

- stress history
- sand content
- particle diameter
- clay mineralogy
- rate of deformation (shear rate)
- percentage of organic material
- water chemistry (especially pH, salinity, etc.)

Because of the variability in these factors from site to site, fluid mud rheological properties can vary significantly in different locations. Herbich et al. (1989) conducted a survey of US ports and USACE Districts to evaluate the number of harbors and channels experiencing fluid mud conditions and determined that "a high percentage of responses clearly indicated that many US ports experience fluid mud problems and presently no uniform procedure to accurately define the channel depth is practiced."

2.7 Dredging Project Challenges with Fluid Mud

The presence of fluid mud in the navigation channel can present challenges to conventional hydrographic surveying methods and equipment in accurately and precisely determining where the channel bottom is. As indicated by Kirby et al. (1980), the static suspension time-dependant properties control their respective detection by echo sounding and affect the following critical dredging project management aspects:

- measurement of navigable depths
- measurement of dredging required
- increases in depth achieved by dredging
- timing of dredging

This ambiguity in determining depth has hindered the USACE optimization of maintenance dredging in fluid mud areas. An operational definition of the nautical channel bottom in areas of fluid mud based on density or other rheological parameters could reduce maintenance dredging costs (De Mayer and Malherbe 1986; Herbich et al. 1989, 1991; Teeter 1992). Herbich et al. (1989) report that the *navigable* or *nautical* depth concept is practiced unofficially in many US ports as the pilots guide ships through channels that contain fluid mud layers.

2.7.1 Hydrographic Surveying Challenges

Hydrographic surveying in areas with fluid mud often results in ambiguous depth measurements due to effects on mechanical (lead line) and acoustic measurement techniques. The USACE recognized these effects as early as 1954 and attempted to determine navigable depth by correlating depths measured by lead lining and echosounding.

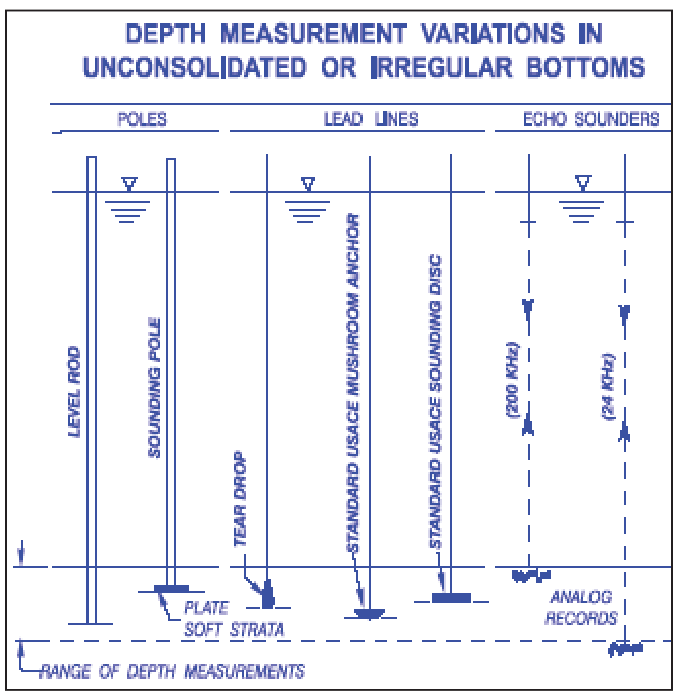
Laboratory and field tests were conducted with variously sized and shaped lead lines in fluid mud and compared to depths recorded by echosounding. The effort focused on attempting to (1) formulate recommendations for better sounding lead shape and procedures, (2) confirm the large range of depth values that can be measured at same station, (3) show range of variables that affect soundings, and (4) indicate the *highly subjective* nature of depth values determined from lead line soundings.

2.7.2 Conventional Acoustic (Echosounding) Depth Measurement

Acoustic echo sounding is the method most commonly used to measure depths in USACE navigation projects. Measurement of water depth was primarily done by lead line until development and implementation of single beam echo sounders in the 1930s, that ultimately became the dominant hydrographic surveying technology used today. However, it is difficult to determine the depth with fluid mud. Depth measurement variations for acoustic echo sounding in fluid mud result from surface reflectivity, density, signal/noise levels, receiver sensitivity, and transducer frequency (USACE 2003).

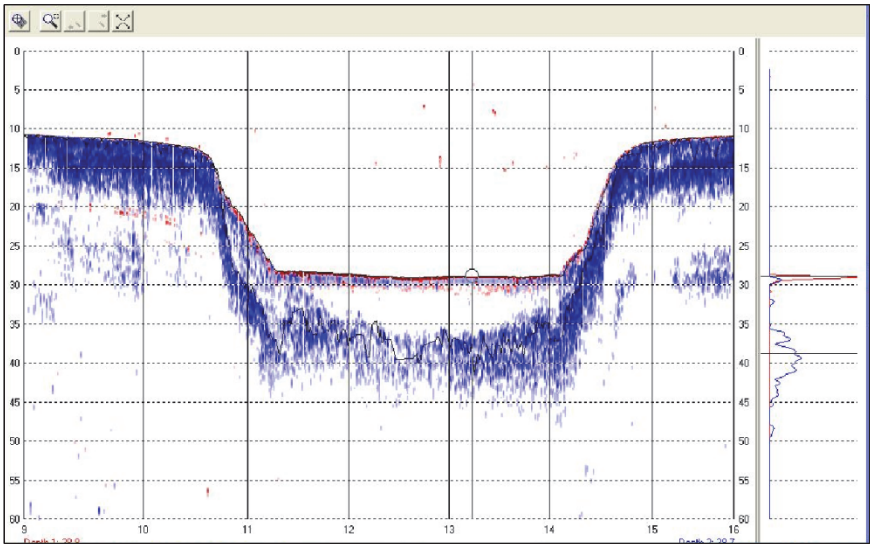
Hydrographic surveys are usually conducted with either a high or low frequency transducer (such as 24 and 200 kHz) or a combination of both frequencies (a duo-frequency system). The depth in fluid mud that an acoustic pulse reflects from is a function of the *sharpness* of fluid mud density gradient (or rate of change in density) not a specific density value itself (USACE 1954). Attenuation of acoustic energy is directly proportional to its frequency. The high frequency energy will normally reflect from the upper layer of the reflective material, even a very low density one, while the lower frequency depth sounders will penetrate to a lower depth than the higher frequency at the same transmitting power level and receiver sensitivity as shown in Figure 16.

Figure 16. Depth measurement variations over hard and soft bottoms (USACE 2003).



High-frequency echo sounders (200+ kHz) can reflect off the water/muddy water interface, and (given transmit and sensitivity settings are comparable) the lower frequency echo sounders can reflect off a density gradient (or density gradients) deeper in the fluid mud layer. This phenomenon is illustrated in Figure 17 that shows acoustic returns from a dual frequency echo sounder used by the Mobile District (41 and 200 kHz). The high frequency return is being reflected from the water/muddy water interface, and the low frequency return is reflected from a density gradient deeper in the fluid mud layer.

Figure 17. Duo frequency echo sounder returns (black - 41 kHz, red – 200 kHz) in Gulfport Ship Channel.



2.8 Sediment Budget

The sediment budget (Figure 18) investigated in this report focuses on the inner bay system and does not extend beyond the MSC Entrance Jetties. Therefore, shoreline response and longshore sediment transport along the Matagorda Peninsula were not included within this study.

Because of lack of quantified information, many assumptions had to be made which should be researched further to verify and refine the numbers in this sediment budget. The following is a list of the assumptions made to create the sediment budget:

1. Fluid mud flow up the MSC was observed from survey and field data. The actual quantity that fluctuates up and down the navigation channel is unknown. In the present study, numerical modeling was used to provide an indication of the patterns of fluid mud flow but did not quantify the amount of fluid mud that flowed in the channel.
2. Fluid mud appears in the Channel to Palacios. The primary reason for assuming the infilling of fluid mud is the amount of material that accumulates at the upper portion of the channel. It was assumed that 20 percent of fluid mud flow moves from cell to cell.

3. Volumes of fine sediment contributing to the system from the Lavaca River and Garcitas Creek are substantial according to historic documents (including the original design documentation for the MSC). Sediment from Lavaca River is approximately 700,000 cy/yr with approximately 500,000 cy/yr contributing to upper MSC. Because sediment from Garcitas Creek is not quantified, it was assumed to be 250,000 cy/yr with approximately 150,000 cy/yr contributing to the Channel to Port Lavaca.
4. For the MSC, it was known that recirculation from open water placement areas adjacent to the channel was contributing to sedimentation in the channel but the percentage of material recirculating was unknown. In the areas where more recirculation was evident, 20 percent of material placed yearly was assumed to recirculate to the channel. In the areas where less recirculation was evident, it was assumed that 10 percent of the material was recirculated.
5. The amount of sediment infilling the MSC and Palacios Channel from adjacent bays is not quantified. The amount of sediment infilling the channel from the bays was estimated by trial and error and solving the channel cells to determine the amount of fill needed to balance the cell.
6. The sediment budget investigation in this effort involves many uncertainties and unknowns that need to be researched to better estimate sediment movement. It is unclear what the quantity of sediment infilling is in the MSC in terms of fluid mud versus sedimentation from the bay versus recirculation from the placement areas. This sediment budget was intended to evaluate the alternatives to reduce the sediment shoaling in the upper reaches of the MSC.

Figure 18. Matagorda Bay sediment budget movement.

3 Coastal Modeling

A development version of the USACE Coastal Modeling System (CMS) numerical models (Demirbilek and Rosati 2011) was applied in Matagorda Bay. The model results were used to qualitatively illustrate the mixed-size sediment transport driven by waves and currents. This chapter describes the model setup, calibration, and limited results for the existing conditions. Model results were evaluated in detail to help visualize sediment transport sources, sinks, and pathways. Based on these qualitative results, alternatives were developed within the coastal process and engineering activity framework described in Chapter 2.

The CMS was developed under the Coastal Inlets Research Program at ERDC and has been validated and verified for waves, currents, sediment transport, and morphologic change for coastal inlet systems (Demirbilek and Rosati 2011; Sanchez et al. 2011a, 2011b). It can calculate sediment transport and morphology change under combined current and wave condition by coupling a hydrodynamic model, CMS-Flow, and a wave transformation model CMS-Wave through a coupling module operated in the Surface-water Modeling System (Zundel 2006).

3.1 Model description

CMS-Flow is capable of solving the two-dimensional (2D) flow mass conservation and hydrodynamics based on the depth-integrated continuity and momentum equations (Sanchez et al. 2011a, 2011b; Buttolph et al. 2006). The model is forced by changes in water levels (e.g., from tide) along the seaward boundary, flow discharge at the river boundary, wind input field, and wave stresses on the water surface. Physical processes pertinent to the present study calculated by the flow model are the time-dependent current field, water surface elevation, sediment transport, and morphology change.

CMS-Wave is a 2D full-plane, steady-state wave spectral transformation model that solves the wave energy balance equation to calculate wave field properties (Lin et al. 2008). It contains theoretically derived formulations for combined wave diffraction, refraction, reflection, and wave-current interaction. The model is robust and practical for wave simulations at coastal inlets with navigation channels, jetties, and breakwaters. In coastal inlet applications, it is more efficient to run CMS-Wave on a half-plane mode such that primary waves can propagate only from the seaward boundary toward shore.

In the coastal region, where surface waves can play a major role in littoral processes, the influence of waves to flow and sediment transport is calculated through coupling CMS-Flow and CMS-Wave. The CMS-Flow model used in the present study is a development version that includes the cohesive sediment transport for the calculation of mixed sediment transport and pathways. This CMS-Flow developmental model is not available in the public release version.

3.2 Model domain

A CMS rectangular grid with variable cell-spacing was developed for sediment transport modeling of Matagorda Bay. The model domain covers the entire bay with navigation channels connecting the Intercoastal Waterway and the Gulf of Mexico. The CMS grid extends 43 miles (70 km) alongshore and 45 miles (72 km) cross-shore approximately parallel to the ship channel with the southern offshore boundary reaching to the 69-ft (21 m) isobath. Figure 19 shows the model domain which has 153 × 324 cells with variable cell spacing of 82 ft (25 m) at the bay entrance and 5,250 ft (1,600 m) at the corner of offshore boundary. In general, CMS-Flow and CMS-Wave are not required to run on the same grid. However, in many applications, it is convenient to maintain just one model grid. In the present modeling of Matagorda Bay, both CMS-Flow and CMS-Wave use the same rectangular grid.

3.3 Simulation period and model forcing

The model simulations were conducted for a half-year period from September 2006 to February 2007 that represents a typical fall to winter condition. The channel surveys conducted in September 2006 and February 2007 showed a rapid accumulation of fluid mud in the upper ship channel, on average 3- to 6-ft (1.0 to 2.0 m) buildup.

The time series of water levels specified along the offshore boundary was interpolated from two NOAA coastal Stations: 8771510 at Galveston Pleasure Pier (29° 17.1’ N; 94° 47.3 W) and 8775870 at Bob Hall Pier, Corpus Christi (27° 34.8’ N; 97° 13’ W). Figure 20 shows the hourly water level measurements from September 2006 to February 2007 at two NOAA stations, 8775870 and 8771510. The water level data show stronger variation at the Galveston Pleasure Pier than at Bob Hall Pier as the open coast water levels at Galveston Pleasure Pier are influenced by stronger winds or stronger metrological tides in the fall and winter seasons. Figure 21 shows the wind data (magnitude and direction) collected from September 2006 to February 2007 at two NDBC coastal buoys 42019 offshore Galveston (27° 54.8' N; 95° 21.1' W) and 42020 offshore Corpus Christi (26° 58' N; 96° 41.7' W). These wind data show similar wind magnitude at offshore Galveston and Corpus Christi in the fall and winter seasons.

Figure 19. CMS Bathymetric grid of Matagorda Bay.

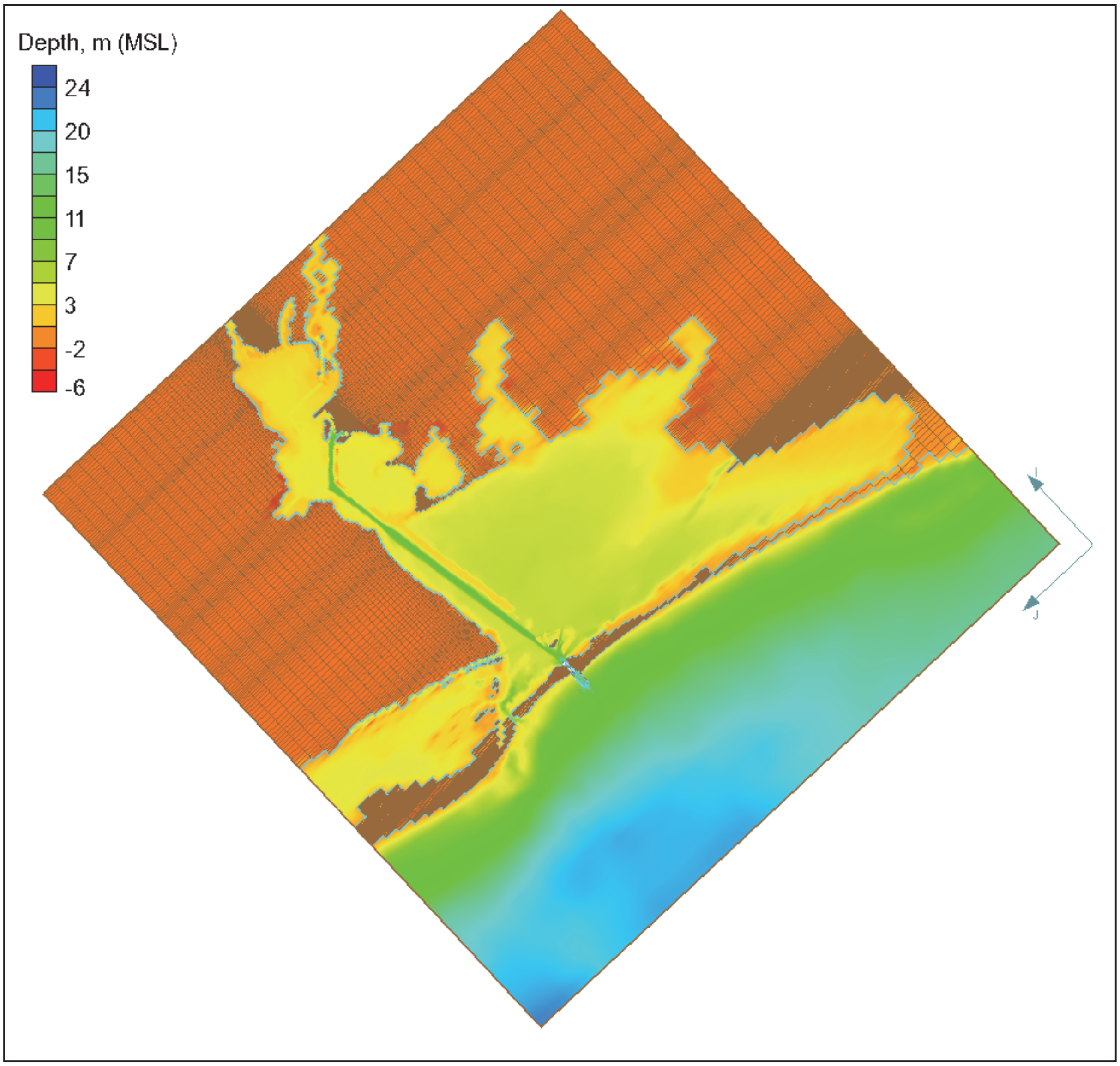


Figure 20. Time series of water levels at NOAA Stations 8771510 (Galveston Pleasure Pier) and 8775870 (Bob Hall Pier) for September 2006 to February 2007.

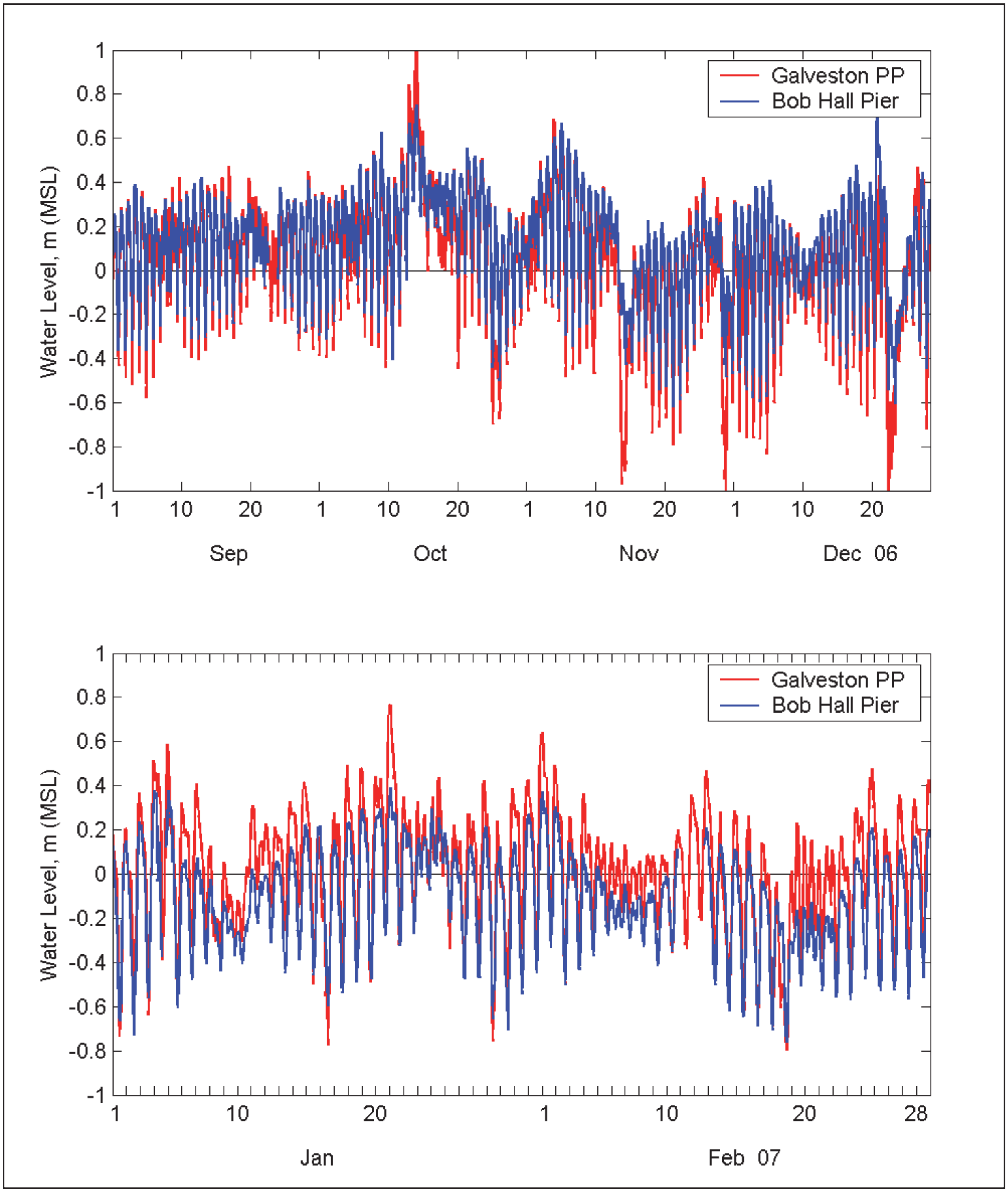
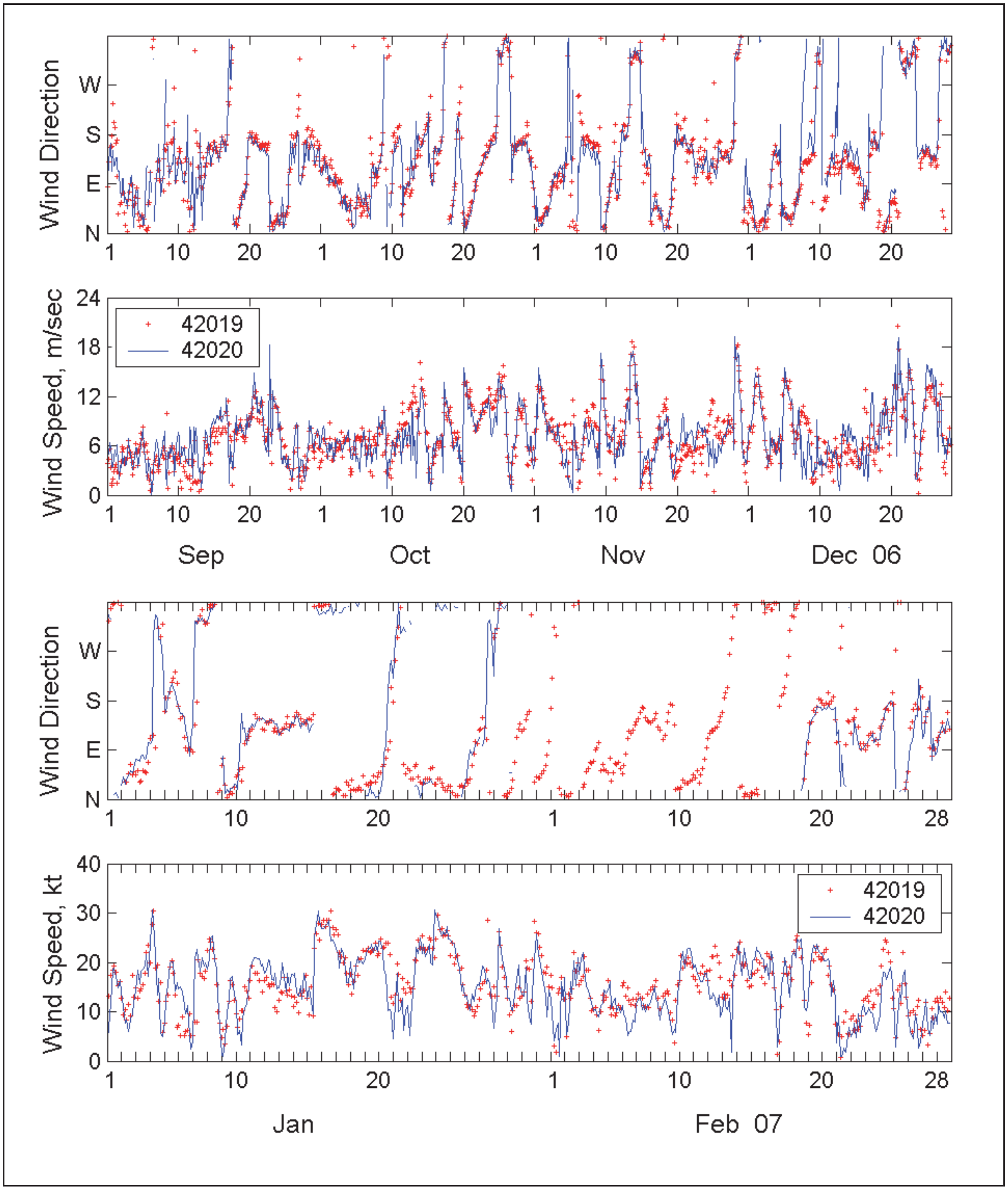


Figure 21. Time series of wind data at NDBC Buoys 42019 (Freeport) and 42020 (Corpus Christi) for September 2006 to February 2007.



Local wind data were available from NOAA Station 87737011 at Port O'Connor (28° 26.8' N; 96° 23.8' W) in the southwest corner of the bay. Figure 22 shows the wind information collected from September 2006 to February 2007 at Station 87737011 and NDBC Buoy 42019. The wind direction is similar at NOAA Station 87737011 and NDBC Buoy 42019. The wind magnitude at NOAA Station 87737011 is overall smaller than at NDBC 42019 as the wind at Station 87737011 is more influenced by land and bay effects than the Buoy 42019 wind in the open coast.

River daily discharge data for Lavaca River were available from USGS Station 8164000 at Edna (28° 55' N; 96° 46' W) approximately 14 mile (24 km) north of Lavaca Bay. The Station 8164000 flow rate data were applied as river boundary conditions for Lavaca River and Garcitas Creek discharge into the upper Lavaca Bay. The river flow data for Colorado River were available from USGS Station 08162500 (28° 58' N; 96° 01' W) near Bay City. Figure 23 shows the river flow data collected at USGS Stations 81625000 and 8164000 from September 2006 to February 2007. Because Colorado River has a much larger watershed area than Lavaca River, the flow discharge at Colorado River is usually much greater than Lavaca River.

Figures 24 and 25 show the time series of wave data collected at Buoy 42019 offshore Galveston from September to December 2006 and January to February 2007, respectively. The directional wave data collected at Buoy 42019 are used for the incident wave conditions along the CMS-Wave offshore boundary.

3.4 Matagorda Bay Sediment Characteristics

In the modeling area outside Matagorda Bay along the Gulf coast of Matagorda Peninsula and barrier islands, the sediment content is primarily fine sand with a median grain size range from 0.15 mm to 0.22 mm. At the MSC Gulf entrance, the narrow inlet constraint has caused the channel to self-scour, and the bed is characterized by gravels and small rocks as a result of strong current in the channel. The sediment at Pass Cavallo is overall coarser than the average sediment on the neighboring beaches because of stronger current through the inlet.

Sediment in Matagorda Bay is mixed, having more sand near the MSC Gulf entrance, Pass Cavallo, and south of GIWW. More silt and clay are found in the northern and eastern bay as fine sediment was supplied from Palacio Bay, Carancahua Bay, and Colorado River. The sediment in

Figure 22. Time series of wind data at NDBC Buoy 42019 (Freeport) and NOAA Station 87737011 (Port O'Connor) for September 2006 to February 2007.

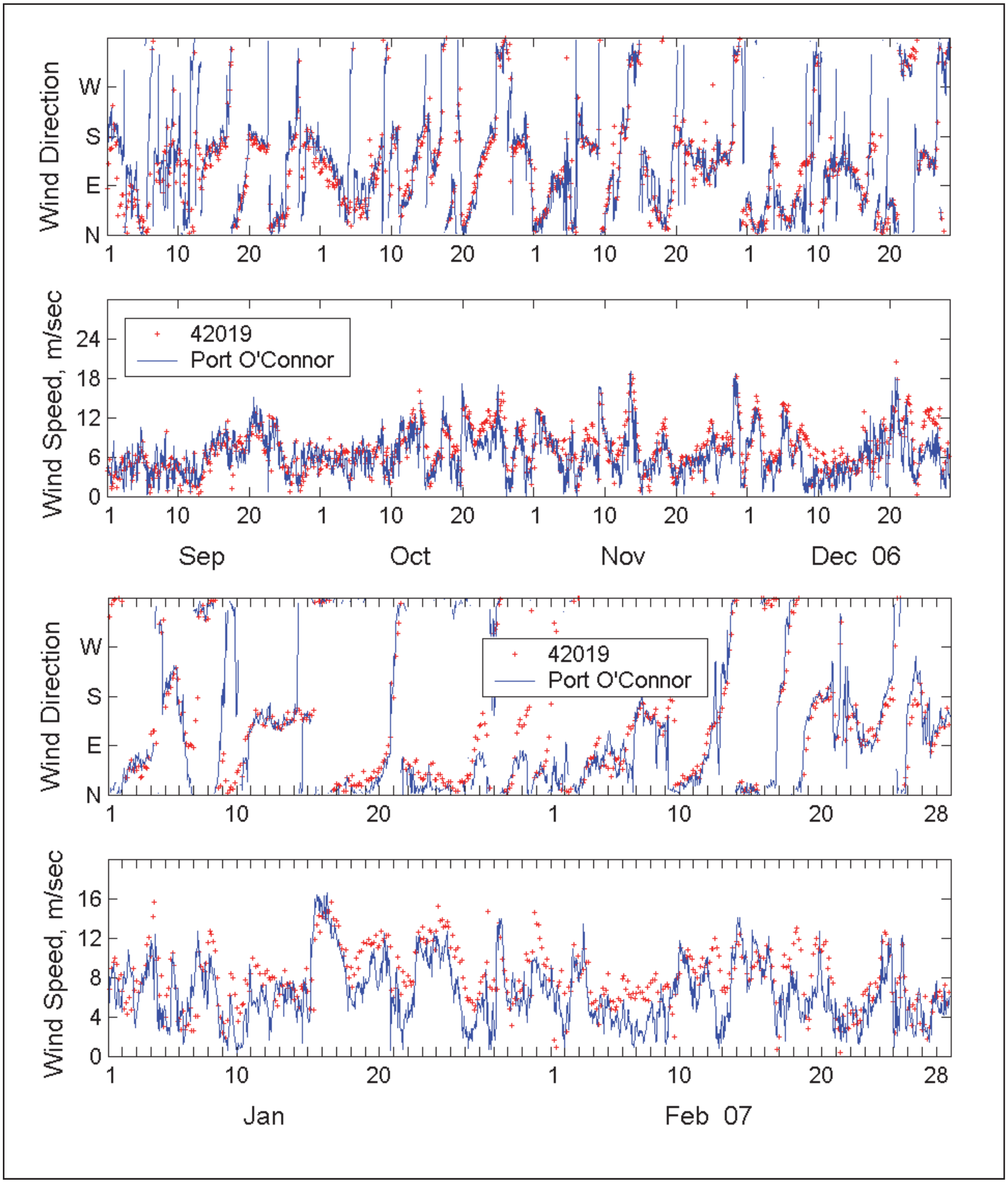


Figure 23. Time series of Lavaca River flow rate data collected at USGS Station 8164000 (Edna, Texas) for September 2006 to February 2007.

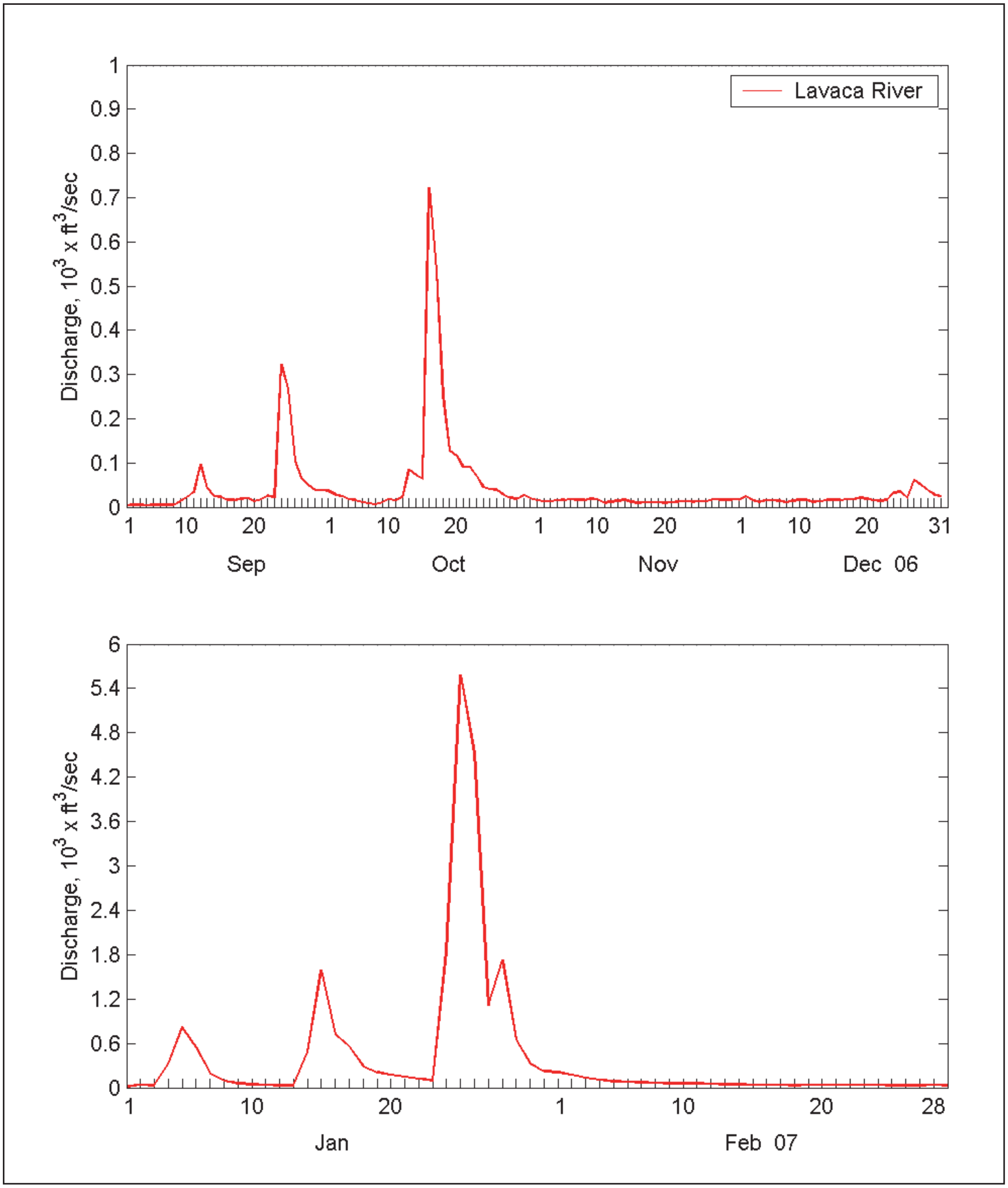
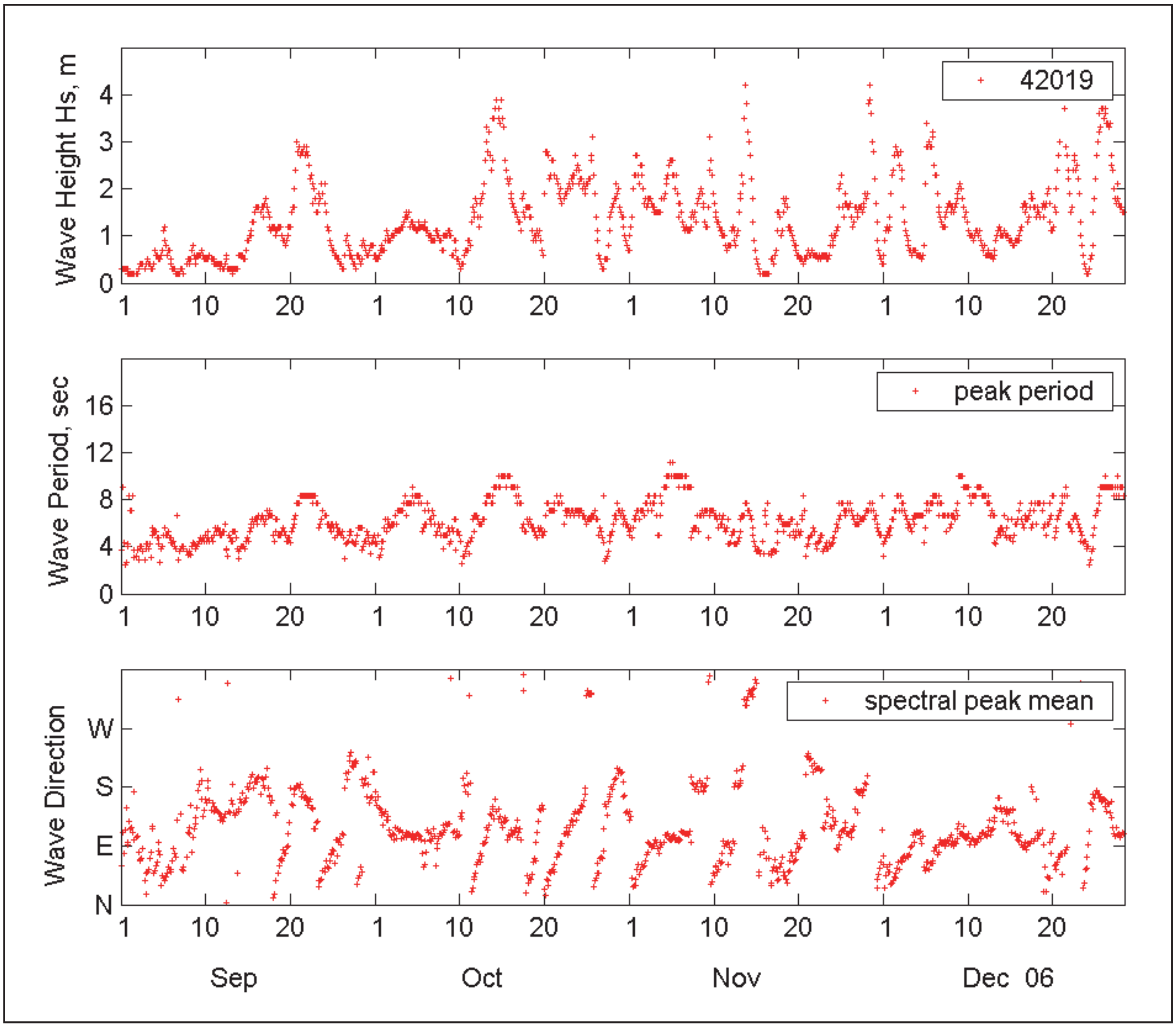
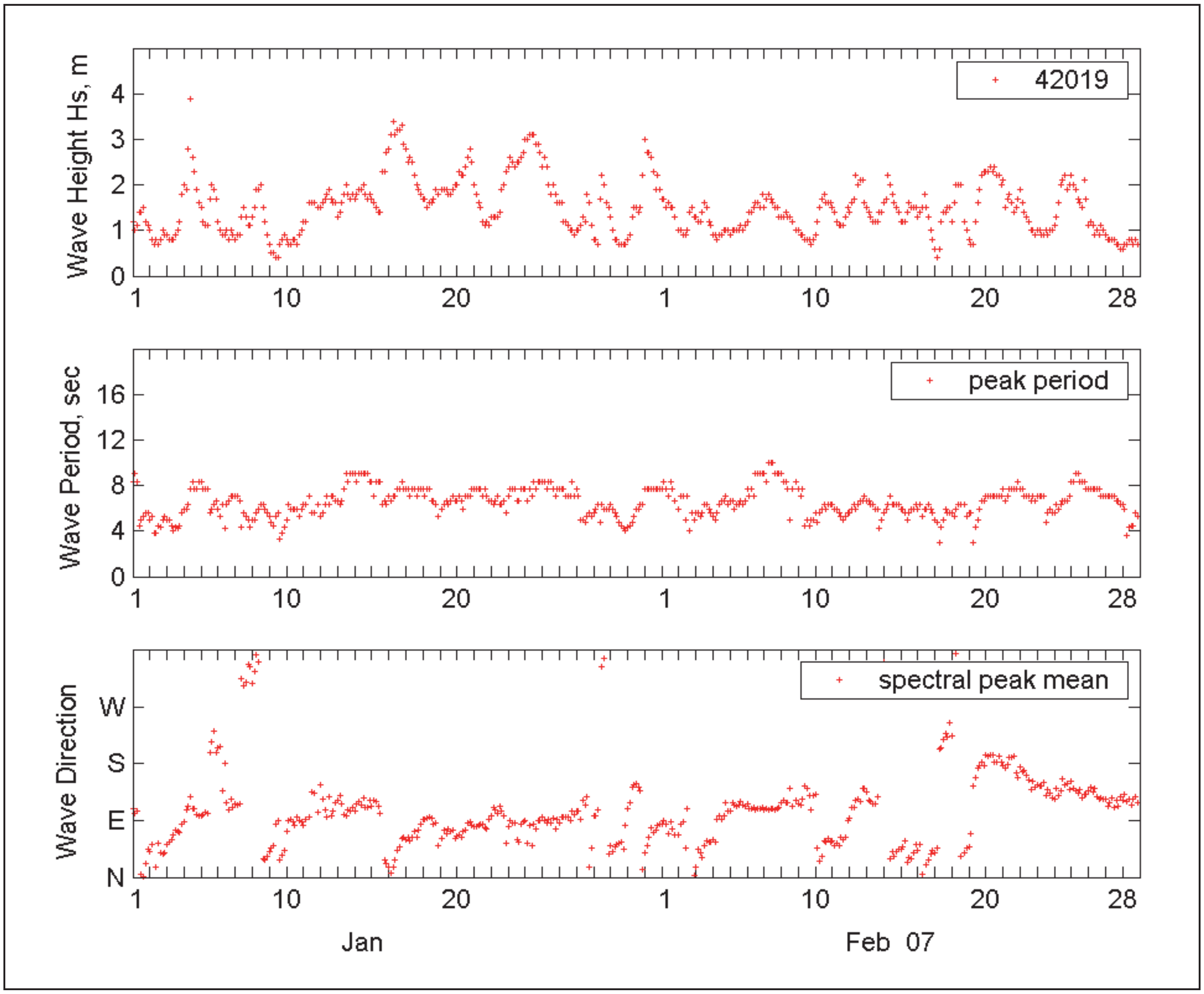


Figure 24. Time series of significant wave height, peak wave period, and spectral peak mean direction from Buoy 42019, September to December 2006.



Lavaca Bay is primarily cohesive material that comes from Lavaca River and Garcitas Creek. Because Lavaca Bay is geologically isolated in the northwestern corner of Matagorda Bay, the fine sediment inside Lavaca Bay is basically trapped and rarely is transported to Matagorda Bay. During fall and winter months, fluid mud is often observed in the upper MSC as induced by strong wind and wave motion in the Lavaca Bay. The rapid accumulation of fluid mud in the MSC has required more frequent dredging cycles in recent years. Figure 26 shows the different median grain size used in the present sediment modeling in Matagorda Bay.

Figure 25. Time series of significant wave height, peak wave period, and spectral peak mean direction from Buoy 42019, January to February 2007.



3.5 Modeling Results

The model simulations were conducted for a half-year period from September 2006 to February 2007. Figure 27 shows the comparison of calculated and measured water levels at Port O'Connor, NOAA Station 87737011, for September 2006 to February 2007.

Figures 28 and 29 show typical strong current fields calculated by coupling CMS-Flow and CMS-Wave for flood and ebb conditions, respectively.

The development version of the CMS used includes the option to calculate sediment transport for cohesive (silt and clay) and non-cohesive (quartz sand) sediments individually or for combined cohesive and non-cohesive sediments. The detail of method and equations for sand transport in CMS is provided in the report by Buttolph et al. (2006).