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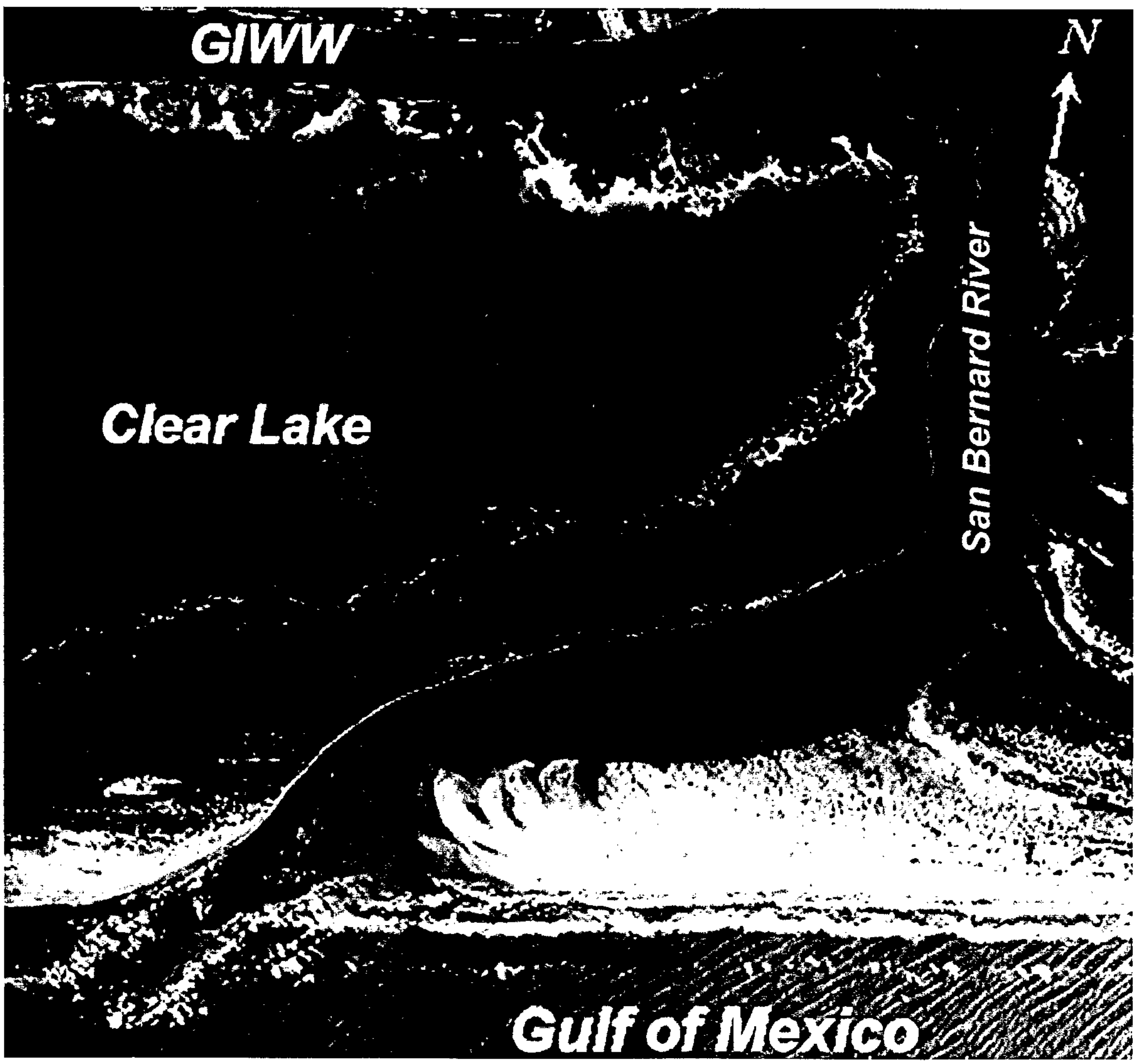
Coastal Processes Study of San Bernard River Mouth, Texas: Stability and Maintenance of Mouth

Nicholas C. Kraus and Lihwa Lin

August 2002



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Coastal Processes Study of San Bernard River Mouth, Texas: Stability and Maintenance of Mouth

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Contents

List of Figures

List of Tables

Preface

This report presents an analysis of coastal processes acting at the San Bernard River mouth, Texas, performed for the U.S. Army Engineer District, Galveston (SWG). Sediment shoaling at the San Bernard River mouth has blocked its discharge to the Gulf of Mexico and diverted the flow into the Gulf Intracoastal Waterway (GIWW), raising concerns for barge traffic along the GIWW. The analysis was made to determine the causes of sediment shoaling at the river mouth and to identify and evaluate alternatives for maintaining the mouth.

This study was performed by Dr. Nicholas C. Kraus, Senior Scientist Group, U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), and Dr. Lihwa Lin, Coastal Evaluation and Design Branch (CEDB), CHL. Mr. Edward A. Reindl was SWG study manager. Geographic Information System analysis of the aerial photography for this study was conducted by Mr. Joshua Caulkins, graduate student summer intern from the City University of New York, supervised by Ms. Shelley Johnston, CEDB. Dr. Liviu Giosan, Woods Hole Oceanographic Institution, provided information on the geomorphic setting of the San Bernard River mouth. Dr. Trimbak Parchure, Tidal and Hydraulics Branch, CHL, provided the water level measurements and bathymetry data from the CHL August 1999 data-collection campaign. Mr. Daniel J. Heilman, Shiner, Moseley and Associates, Inc., Corpus Christi, TX, provided independent review of this report and helpful comments. Ms. J. Holley Messing, CEDB, formatted this report. This study was performed under the administrative supervision of Mr. Thomas W. Richardson, Director, CHL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III was Commander and Executive Director.

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Conversion Factors: Non-SI to SI Units of Measurement

Non-SI units of measurement appearing in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.0283168	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
miles (U.S. statute)	1.609347	kilometers

1 Introduction

Background

This report documents an investigation of the coastal and inlet physical processes acting at the San Bernard River mouth, Texas. The U.S. Army Engineer District, Galveston, requested the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), to conduct this study to assist in formulation and assessment of alternatives for improving navigation along the Gulf Intracoastal Waterway (GIWW) between the Brazos River and the San Bernard River and vicinity.

In recent years, a spit has grown from northeast to southwest across the San Bernard River mouth (Figure 1). The migrating river mouth is narrowing, and sediment shoaling landward of it has reduced the river's discharge to the Gulf of Mexico. Riverflow is diverted into the GIWW, increasing the current velocity in an unpredictable way and possibly increasing sediment shoaling at the intersection of the river and the GIWW, as well as to the east at the west floodgate to the Brazos River. The present study was performed to identify and evaluate alternatives for maintaining the San Bernard River mouth.

Study Site

The San Bernard River is located in north-central Texas and flows through the alluvial valleys of the Colorado River and Brazos River (Figure 2). The central Texas coast spans several zones from humid in the north to dry subhumid in south. Average annual rainfall ranges from 104 to 125 cm, with large variations possible between droughts and precipitation brought by tropical storms (McGowen, Garner, and Wilkinson 1977). The San Bernard River has a much smaller drainage area than either the Colorado River or the Brazos River, with correspondingly much weaker flows and sediment discharge, as discussed in Chapter 3. Therefore, local storms primarily determine its flow.

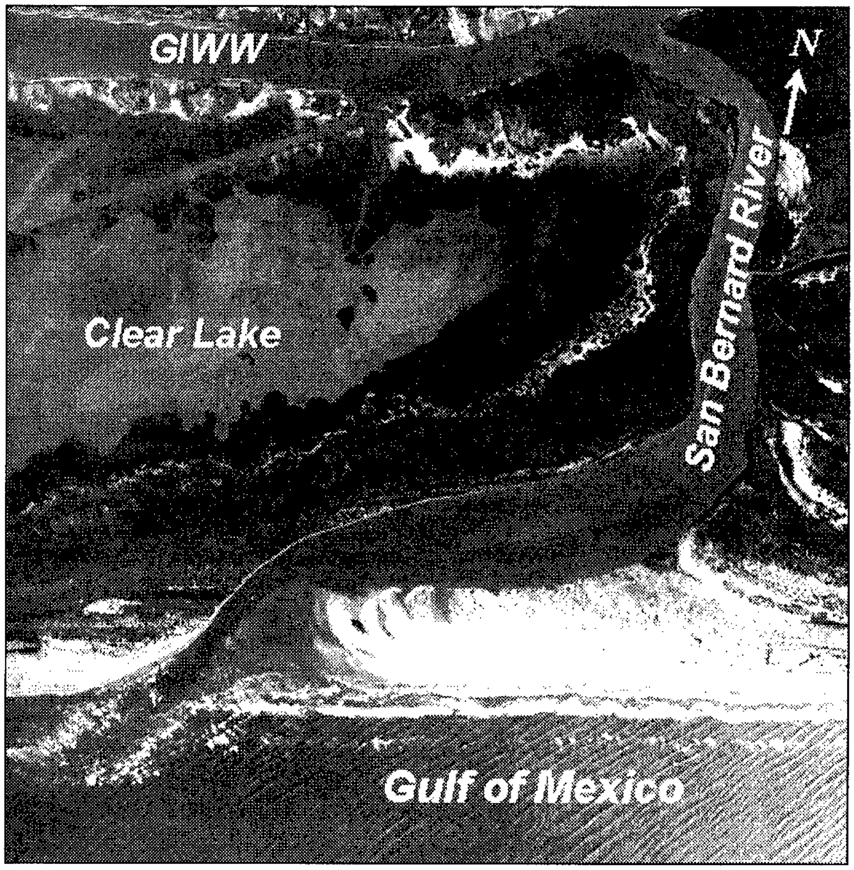

Figure 1. San Bernard River mouth, Texas, September 1995

Along this portion of the Texas coast, longshore sediment transport is directed predominantly to the southwest. Waves are moderate, with a recent hindcast for the years 1990 to 1999 giving an average annual significant wave height[1] of 1.1 m and wave period of 5.6 sec in deep water. Nearshore wave data are available from gauges deployed at the 10-m depth contour 3.2 km offshore of the north jetty at the Colorado River mouth, located approximately 96 km south of the San Bernard River (King and Prickett 1998). For a 17-month period of data collection (1991-1993) that somewhat under-represents the winter months, the mean significant wave height was 0.6 m, and the mean peak period was 5.9 sec.

The Brazos River has been the predominant source of beach sediment, fine to medium quartz sand, for this area of the Texas coast. DeWitt (1985) documents the modern sediments of the new Brazos River delta and discusses longshore transport processes. Because of the relatively small tidal range, the coast is classified as being wave dominated, and wave action has produced the series of beach ridges seen in Figure 3. Various studies of the Brazos River delta as described in Chapter 2 indicate a westward asymmetry of the delta and westward transport of littoral sediments.

[1] The significant wave height as applied here represents the zero spectral moment, calculated as four times the square root of the variance of the record. The peak period is the period associated with the maximum energy band of the spectrum.

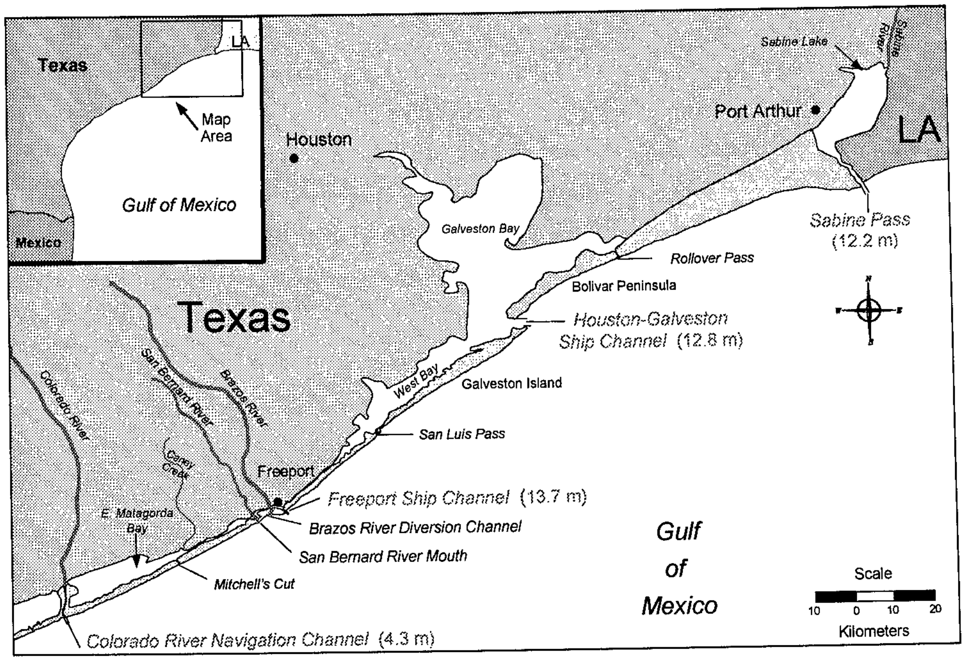

Figure 2. Location map for the San Bernard River, Texas

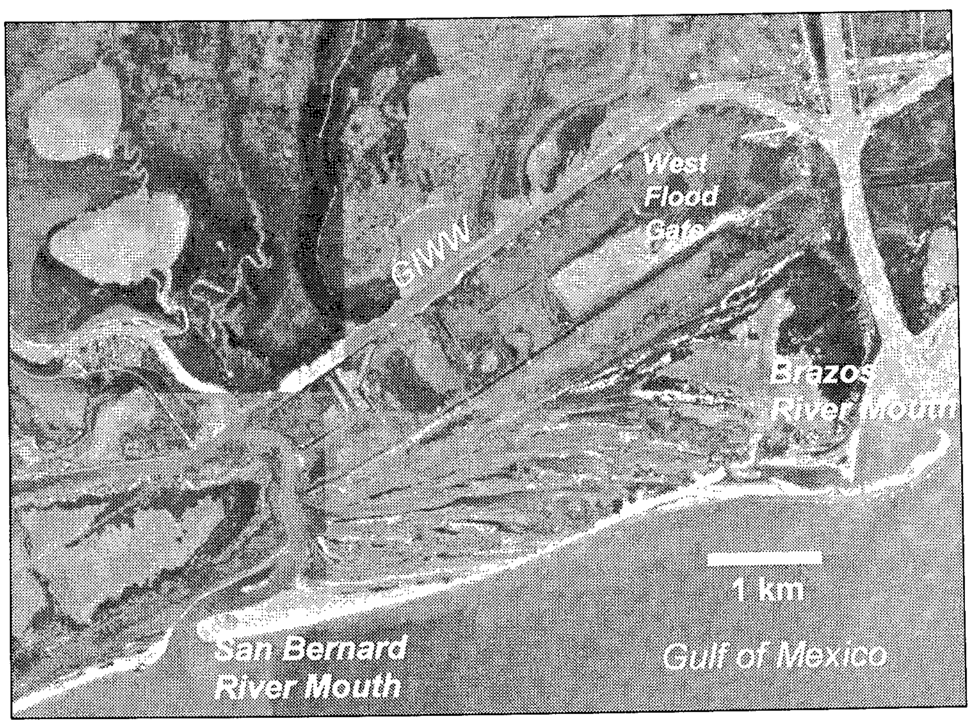

Figure 3. San Bernard River mouth and mouth of the Brazos River Diversion Channel, January 1995

The tide on this portion of the coast is mainly diurnal, having a period of approximately 1 tidal day (24.84 hr). The National Ocean Service (NOS) maintains a long-term tidal station at the Galveston Pleasure Pier, Texas. The diurnal tide range (difference between mean higher high water and mean lower low water) calculated from the record for the 5-year period 1990-1994 was 0.65 m. Strong wind along the Texas coast can often dominate the water level and current in shallow bays, estuaries, and river mouths. River flows can be significant during times of heavy rain such as brought by tropical storms and hurricanes.

The San Bernard River intersects the GIWW almost perpendicularly approximately 1 mile[1] north (upstream) of the river mouth (Figure 1). The Galveston District maintains the GIWW to a depth of 12 ft (with 1 ft each of advance maintenance and overdredging allowed) and top width of 250 ft. The San Bernard River Navigation Channel extends 28 miles upstream from the intersection of the GIWW and is maintained to a depth of 9 ft and width of 100 ft. The San Bernard River channel is seldom dredged, with the last maintenance occurring in 1990 according the to the Galveston District's Dredging History Database. The segment of the San Bernard River from the GIWW to the Gulf of Mexico is not a Federal channel for the purposes of navigation and has not been maintained by the Federal Government (U.S. Army Engineer District, Galveston, 1992).

The San Bernard River reaches the Gulf of Mexico coast 3.5 miles southwest (downdrift) of the present or new Brazos River delta (Figure 3) that began forming after 1929 at the diverted Brazos River mouth. The lower 5 miles of the Brazos River is called the Brazos River Diversion Channel. The diversion channel, which carries all of the river discharge to the Gulf of Mexico, was constructed in 1929 to divert the sediment-laden waters of the Brazos River from the deep-draft port of Freeport (Figure 2). The evolution of the new delta at the Brazos River Diversion Channel exerts great control on the sedimentation at the San Bernard River mouth, as described in Chapter 2.

The San Bernard River has relatively weak flushing action because of the moderate tidal prism (small tidal range and relatively small water surface area in the channels and lagoons) and a small drainage basin. A certain ebb flow is required to maintain the mouth against infiltration of littoral sediments. As a result, the river mouth is no longer positionally stable, and it is migrating to the west. The entrance cross section is unstable (closing) as well. The question as to why the river mouth has lost stability in the past 2 decades is addressed in Chapter 2, and the river and tidal discharges are quantified in Chapter 3.

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[1] Engineering activities such as surveying and dredging that may be associated with this study will be performed in U.S. Customary (non-SI) units. As an aid to those activities and to maintain continuity with previous publications employing non-SI units, those units will be preserved in their context. Oceanographic quantities are expressed in SI units, as are other quantities not expected to be related to engineering activities. A table for converting non-SI to SI units is given on page viii.

Previous Studies

Figure 3 indicates the relatively complex pattern of river and tidal flow expected at the study site. The GIWW intersects the Brazos River, San Bernard River, and Colorado River. Although the west floodgate on the Brazos River is intended to be kept closed to reduce sedimentation into the GIWW, the gate may be open for substantial time intervals because of barge traffic, passage of recreational and commercial boats, and maintenance. Phasing of the tide through the GIWW associated with multiple entrances to the Gulf of Mexico and storage of water in the several shallow lagoons in the area, as well as riverflows and wind-generated currents, indicate care must be taken in modeling of the flow in the area. Sanchez and Parchure (2001) document measurements of the water level and current, as well as other data collection, at the study site made in August 1999. These measurements allowed them to validate a two-dimensional (2-D) (depth-integrated) numerical model of flow established for the area. Other than the work of Sanchez and Parchure (2001), no studies could be found that treat coastal or river processes at the San Bernard River mouth. Wenzel (1975) discusses sand bars on the upper San Bernard and Brazos Rivers.

In contrast, the gemorphology of the new Brazos River delta has been studied (Odem 1953; DeWitt 1985; Fields, Weishar, and Clausner 1988; Abdulah 1995; Hamilton 1995), and coastal and hydraulic studies have been made of the Colorado River mouth and vicinity (King and Prickett 1998; Heilman and Edge 1996; Kraus and Militello 1996, 1999; Kraus, Lin, and Barcak 2002). In particular, Fields, Weishar, and Clausner (1988) studied the feasibility of dredging the Brazos River Diversion Channel to provide continuous navigable depth. Their report contains information of direct bearing for making quantitative estimates of longshore sediment transport rates at the San Bernard River mouth.

Scope of Study and Report

This study was organized in three components as an analysis of the coastal geomorphology and sediment-transport processes, a hydraulic analysis of the river and tidal flow, and a synthesis of results leading to development and evaluation of alternatives. The geomorphic component includes quantification of spit movement at the San Bernard River mouth and the influence of the Brazos River discharge and delta on the San Bernard River mouth. The hydraulic component consisted of establishing and validating a one-dimensional (1-D) numerical model of the water level and currents in the area. A 1-D model was applied because alternatives at the river mouth could be readily implemented and examined within the scope of this study. The model could also be readily transferred to and operated at the Galveston District. A wave hindcast was also performed to interpret the coastal processes. Based on these analyses, alternatives were developed and evaluated for maintaining the San Bernard River mouth.

Chapter 1 is an introduction to the study site and the problem statement. Chapter 2 reviews the geomorphic setting and quantifies changes observed at the spit and river mouth. Chapter 3 presents results of the hydraulic modeling and wave hindcast. Both Chapters 2 and 3 arrive at estimates of the longshore sediment transport rate, of direct consequence to the stability of the San Bernard River mouth and possible maintenance dredging. Chapter 4 synthesizes results of this study in arriving at alternatives and recommendations for maintaining the river mouth.

2 Geomorphology and Coastal Processes

Regional Setting

The San Bernard River is a small stream flowing through the alluvial valleys of the Colorado and Brazos Rivers (Figure 2) on the north-central coast of Texas. The river reaches the Gulf of Mexico coast 5.4 km southwest of the present Brazos River delta. The drainage area of the San Bernard River is approximately 2,000 sq km, and its average annual water discharge is about 15 cu m/sec (http://waterdata.usgs.gov). These values are smaller than for the Brazos River, which has a drainage area of more than 118,000 sq km and average annual discharge of 200 cu m/sec.

The Brazos River is the only significant source of sediment for the central Texas coast. The modern Brazos alluvial plain lies between two low scarps cut by the river in the older Pleistocene deposits. The rate of flow of Brazos River leads all Texas rivers, illustrated by the hydrographs for 1999 plotted in Figure 4. River discharge depends on precipitation received by the particular drainage basin, and flows in the rivers are not necessarily correlated. In general, discharges are greater from January through June as compared to the dry season extending from about July to December. The discharge in the San Bernard River reached 100 cu m/sec only twice in 1999.

In its upper reaches, the Brazos River drains semiarid land that provides most of the sediment load because it has less protective vegetation than the subhumid, extensively vegetated lower reaches of the river. The Brazos is a strongly meandering river, and for this reason a large amount of sediment is stored in point bars. These point bars are eroded during exceptional floods that transport large quantities of sediment downstream (Hamilton 1995). The natural average annual suspended-sediment yield of the Brazos is the highest of all rivers in Texas, estimated at 39 metric tons/sq km of watershed (Curtis, Culberton, and Chase 1973). The Brazos sediment discharge has decreased in the last 3 decades because of damming and less extreme flooding.

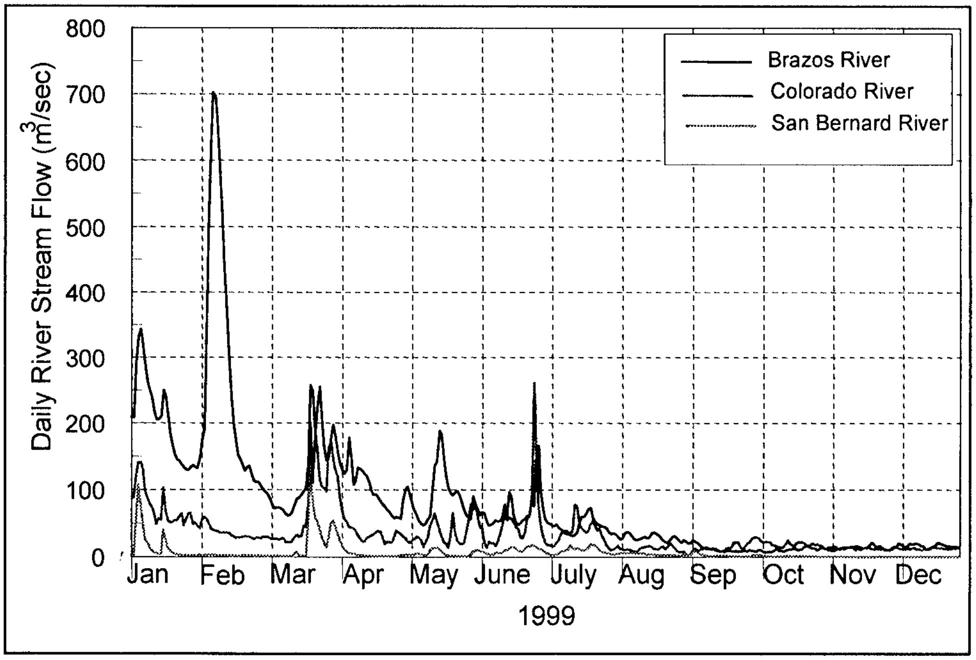

Figure 4. Comparison of discharges for the Brazos, Colorado, and San Bernard Rivers, 1999

In 1929, the Brazos River was diverted by the Galveston District to reduce flooding and shoaling at Freeport (Fox 1931; U.S. Army Engineer District, Galveston 1992; Fields, Weishar, and Clausner 1988). Since that time, the delta at the natural mouth (now the Freeport Harbor entrance) has eroded, and the Brazos River has built a new delta just upcoast of the San Bernard River mouth. The new delta covers approximately 35 sq km, extending past the San Bernard River mouth and seaward to water depths of 15 m (Hamilton 1995). The depositional lobe of the delta is skewed toward the southwest, an indication of net westward longshore sediment transport. There is considerable documentation on the evolution of the new delta (e.g., Odem 1953; DeWitt 1985; Hamilton 1995). Abdulah (1995) describes the regional sedimentologic context of the area.

Basinal Setting

Water level, wind, and waves

The central Texas Gulf coast is a microtidal, wave-dominated coast according to the classification of Hayes (1979). The tide along this section of coast of the Gulf of Mexico is mainly diurnal, and the diurnal tidal range at the Gulf-fronting NOS Pleasure Pier tide gauge on Galveston Island is 0.65 m.

Estimated mean regional sea-level rise for the Gulf of Mexico is 2.3 mm/year, and the mean eustatic rise ranges from 1.2 to 2.4 mm/year (Gornitz and Lebedeff 1987; Germiat and Sharp 1990). The subsidence rate is not precisely known at the San Bernard River mouth, but Seelig and Sorensen (1973) extrapolated subsidence rates for adjacent regions. For the old Brazos delta at

Freeport, they estimated 9 mm/year for the period 1852-1972. The estimated subsidence was even higher at Sargent Beach (15 mm/year) as a result of oil extraction in the region. Morton (1979) estimated an average of 2.5 mm/year for the Colorado-Brazos headland. This rate contrasts with the long-term subsidence rate of 0.1 mm/year reported by Paine (1993) for the Texas continental shelf that is more representative of interfluvial areas of the coast. The elevated rate in the Colorado-Brazos alluvial valley and Holocene delta can be attributed to compaction associated with natural consolidation of the deltaic clayey sediment. In the neighboring Galveston area, for the period between 1908 and 1980, relative sea-level rise was estimated at 6.3 mm/year (Penland, Suter, and McBride 1987; Germiat and Sharp 1990). However, an increase in the subsidence rate to 11.7 mm/year that was attributed to fluid withdrawal was recorded in early 1960's (Penland, Suter, and McBride 1987). The subsidence rate is expected to be decreasing at present because of reduction in oil extraction activity along the coast.

Prevailing winds blow from the south and southeast during the spring and summer months. In the fall, winds are prevalent from the east, whereas in the winter, offshore winds with a strong northerly component are common. The winter winds are associated with cold fronts that travel to the southeast along the Gulf Coast, averaging 47 cold fronts passing across the Texas coast annually (Henry 1979), being most prevalent from October through May. Kraus and Militello (1996, 1999) document the large water setup and setdown that can be induced in shallow coastal estuaries of Texas by the passage of fronts. The strongest winds occur during tropical storms and hurricanes that strike the coast in this region about two times every 3 years (Hayes 1967). Records indicate that the central Texas coast is a relatively frequent landing region for hurricanes (Simpson and Riehl 1981).

A recent wave hindcast for the San Bernard River mouth area is described in Chapter 3. Waves tend to originate out of the southeast. In the offshore in intermediate-depth water, waves have a representative height of about 1 m and period of 5.6 sec. Nearshore wave heights are smaller as the result of dissipation by bottom friction and white capping. During storms, surges in the West Bay behind Galveston Island exceeded 1.2 m approximately every 5 years from 1908 to 1983 (Morton and Paine 1985).

Beach sediment and longshore transport

Beach sands from San Luis Pass and beaches to the south past the San Bernard mouth have an approximately constant median diameter of 0.15 mm (Seelig and Sorensen 1973). DeWitt (1985) and Rodriquez, Hamilton, and Anderson (2000) studied the new Brazos delta depositional environments and found that the grain size mode on Brazos beaches and beach ridges lies between 0.12 and 0.15 mm. Sediments in interridge troughs are predominantly clay intercalated with sand laminae and beds. The coarsest sediments in the delta, with a mode between 0.15 and 0.2 mm and being better sorted than the beach sands, were found on a barrier island that emerged after the 1992 flood (Rodriquez, Hamilton, and Anderson 2000) and are discussed below, suggesting intense reworking by waves. Behind the barrier, finer sediments accumulated with only 10 percent sand. With distance offshore on the subaqueous delta from the distal mouth bar to the prodelta, the sand gradually decreases because the component of the red clays, characteristic of the Brazos River drainage basin, increases (Rodriquez, Hamilton, and Anderson 2000).

The major sediment sources for beach and barrier development on the central Texas coast are the inner shelf, riverine discharge, and updrift beach erosion. However, in recent times, Late Pleistocene and early Holocene sand from the inner shelf must have diminished as a sediment source (Morton 1979). The Brazos River now supplies most of the new sediment to the central Texas coast. Mathewson and Minter (1981) evaluated the response of the river to stream regulation and reservoir sedimentation on the Brazos by examining historical records combined with sediment analyses. Large-scale development of reservoirs began within the Brazos basin in 1929. They found that before dam construction, the river delivered approximately 2.86 million cu m of sand annually, whereas after damming, sand delivery was reduced to approximately 1.16 million cu m annually, about 40 percent of the original discharge. Seelig and Sorenson (1973) estimated that two-thirds of the original sandy supply of the Brazos River to the Gulf of Mexico was reduced by reservoir construction in the 1950's and 1960's.

Longshore sediment transport is the other major source for littoral sediments. Longshore transport does not supply sediment to the coast regionally but can redistribute it, acting to create a local source (erosion) and sink (deposition). Several estimates have been made for the longshore sediment transport rate along the central Texas coast, and they vary greatly. Gross annual transport rate estimates vary between about 92,000 to 800,000 cu m. Studies agree that the net longshore transport is directed to the southwest most of the year (except possibly in July and August, when waves can be stronger out of the south). Estimates of the magnitude of the net rate vary between about 6,000 and 140,000 cu m/year, with most estimates between 33,000 and 52,000 cu m/year. Work done in this study, as described below and in Chapter 3, has refined the magnitude of the longshore transport rate and relative amounts of northeast- and southwest-directed transport.

Fields, Weishar, and Clausner (1988) reviewed early estimates for the new Brazos delta and adjacent region and added their own estimates based on visual recording of waves. For the San Bernard River mouth, they estimated a net annual sediment transport to the southwest of about 30,000 cu m. They hypothesized that increased wave refraction on the Brazos subaqueous delta will generate a lower magnitude of drift at the San Bernard River mouth than at the Brazos River mouth. However, increased progradation and extension of the new Brazos delta to the southwest would progressively increase the potential for longshore sediment transport at San Bernard mouth. The direction of the net longshore sediment transport arrived at by Fields, Weishar, and Clausner (1988) agrees with other indicators, but the magnitude appears to be too low by almost an order of magnitude, as discussed below and in Chapter 3.

Morphodynamics of the Brazos River Mouth

Sedimentation at the San Bernard River mouth depends less on the river's sediment discharge, which is insignificant, than on sediment delivery through longshore transport. In particular, the proximity of the new Brazos River delta appears to exert strong control on the morphodynamics at the San Bernard River mouth, characterized by the development of subaqueous spits and by a downdrift shoreline offset. Therefore, one needs to account for Brazos deltaic evolution and its influence on downdrift sedimentary conditions in analyzing the evolution of the San Bernard River mouth.

The old Brazos subaerial delta was not prominent when the NOS first surveyed the area in 1852, from San Luis Pass through the Matagorda Bay area (Odem 1953; Seelig and Sorensen 1973; Fields, Weishar, and Clausner 1988). However, a subaqueous delta skewed downcoast (to the southwest) was evident, and a small barrier island was emergent on it and the downcoast side. In 1881, construction began to place two jetties at the old Brazos mouth to establish a permanent harbor (Freeport Harbor), and they were completed in 1899 (Seelig and Sorenson 1973; Fields, Weishar, and Clausner 1988). During this period, the sizes of both the subaerial delta and mouth bar increased significantly. A photograph from 1930 shows the morphology of the old Brazos delta to be asymmetric lobate, with a better-developed wing to the southwest (downdrift) relative to the wing to northeast (updrift). Amalgamated ridges were present updrift, and both amalgamated and nonamalgamated ridges were evident downdrift.

In 1929, the Brazos River was artificially rerouted approximately 10.5 km to the southwest to reduce flooding and entrance shoaling in the Freeport Harbor (Fox 1931). Immediately after the completion of the Brazos Diversion Channel, a delta began to form at the new mouth, and the old Brazos delta started to erode. Odem (1953) documents this morphologic development based upon input from staff of the Galveston District, including personnel who had been at the District prior to 1929. The erosion of the old delta, resulting from loss of the sustaining river discharge and tidal prism, provided sediment for building the northeastern flank of the new Brazos delta (Rodriquez, Hamilton, and Anderson 2000).

A series of nautical charts and aerial photographs (Odem 1953, Dewitt 1985, Rodriquez, Hamilton, and Anderson 2000) show the development of the new Brazos delta. In 1940, both the subaerial portion as well as the subaqueous delta at Freeport had all but disappeared. It is evident from the bathymetric evolution that part of the sediment from the eroded old delta has been blocked updrift of the new Brazos mouth in the form of a tidal margin bar.

In 1940, the new subaqueous delta was symmetrical at the 9-m isobath and asymmetrically skewed updrift at the 6-m isobath. In 1984, the new delta became asymmetrically skewed downdrift at the 9-m isobath and remained skewed updrift at the 6-m depth. On the 1940 chart, a prominent subaerial spit is apparent on the eastern side of the mouth subnormally to the general direction of the coast. Since at least 1946 (Hamilton 1995), the eastern side spit had been joined by a barrier developed on the northeastern half of the subaqueous delta, trapping behind it a quasi-triangular lake. This structure of the northern wing of the delta has been preserved by the subsequent growth of new amalgamated beach ridges parallel to the new orientation of the coast.

The above-described morphodynamic evolution emphasizes the groin-like (impoundment) functioning exerted by the Brazos River delta in blocking the southwestward sediment drift. At the same time, the increased size of the downdrift half of the subaqueous delta suggests that the riverine sediment contribution from the new mouth gradually surpassed the sediment removal capacity of wave- and wind-induced longshore transport. However, in absolute terms, sediment discharged by the river decreased after 1929 (Mathewson and Minter 1981; DeWitt 1985) and, as a consequence, the delta changed in part from a river-dominated, protruding feature to a more wave-dominated lobate or crescentic shape. Channel margin bars still form at the Brazos River mouth, as observed by the authors during a site visit by boat in July 2001.

Hamilton (1995) and Rodriquez, Hamilton, and Anderson (2000) noted that downdrift barriers emerged several times on the subaqueous delta, and they related these emergence episodes to major floods that occurred in 1941, 1957, 1965, and 1992. Other floods of shorter duration were apparently not conducive to barrier emergence (Rodriquez, Hamilton, and Anderson 2000). Of interest to the present study is the flood of 1992. This flood began in late December 1991 as a result of substantial precipitation over many of the drainage basins of Texas. Above normal discharges were recorded at the United States Geological Survey (USGS) gauging station at Richmond, Texas, for more than 80 days, with a maximum mean daily discharge of 2,645 cu m/sec occurring on 31 December 1991 and 1 January 1992. Hamilton (1995) determined this to be a 1- in 10-year flood, although anecdotal information from residents as found in this study indicates it was the largest flood in memory. Also, although the elevation of the flood to a certain level may characterize flood frequency of occurrence, duration of a flood is also a decisive factor determining sediment delivery.

After the 1992 flood, sediment was deposited on the subaqueous delta in an axial orientation (Hamilton 1995). During this event, the prodelta experienced up to as much as 0.5 m of vertical accumulation in some locations. Deposition of 8.4 million cu m was estimated. Only 10 percent of the suspended sediment measured at Richmond was sand, but erosion of point bars recorded upstream (Rodriquez, Hamilton, and Anderson 2000) indicated that most of the sand was transported as bedload. After the flood, the new sediment layer was rapidly reworked into a longitudinal body that emerged as an elongated shoal downcoast of the mouth. A professional fishing guide interviewed as part of this study stated that for as long as 3 years after the 1992 flood, recreational fishing boats could pull up on the new shoal and fish from or picnic on top of it. Eventually, the shoal was observed to migrate westward to attach and merge with the shore.

Based on the shoal or barrier emergence after major floods, Rodriquez, Hamilton, and Anderson (2000) hypothesized that this succession of events is the typical mechanism for deltaic development on the downdrift wing. After emergence, shoals or barrier islands elongate and attach to the mainland, generally with the downdrift tip, becoming the new shoreline. This leads to preservation of the preflood shoreline and back-barrier lagoon as a ridge/trough pair within the western delta headland. Fluvial-deltaic and lagoonal mud accumulates continuously in the sheltered environment behind the barrier. These fine-grained deposits could be tidally modified and interbedded with sands washed over the bar during storms. The cycle of barrier formation repeats on a scale of tens of years. Between these episodes, deltaic development is characterized by ridge amalgamation via wave reworking and sand redistribution. During interflood periods, ridge building and shoreline advance is mostly localized at the downcoast distal part of the delta near the mouth of San Bernard River.

Extreme wave conditions occuring during storms and hurricanes do not significantly alter the subaerial morphology of the delta but could sweep away emergent barriers and erode the subaqueous delta (Seelig and Sorensen 1973, Rodriquez, Hamilton, and Anderson 2000). The conceptual evolutive model put forward by Rodriquez, Hamilton, and Anderson (2000) explains the asymmetry in morphology and sedimentary composition of the subaerial delta. The updrift portion of the new lobe includes a higher proportion of amalgamated beach ridges than the downdrift half where nonamalgamated sandy ridges are separated in a succession of elongated lagoons. Also, the downdrift ridges are constructed with reworked sand transported to the mouth bar by the river during floods, whereas on the eastern side of the mouth, the longshore drift (Figure 5) appears to be a greater contributor (Rodriquez, Hamilton, and Anderson 2000).

The increasing influence of the Brazos delta on the evolution of the San Bernard River mouth is clearly shown (Hamilton 1995). By reference to a sequence of aerial photographs, one can distinguish three morphological phases. Before about 1967, the San Bernard River had a funnel-shaped mouth that was slightly more open downdrift. That morphology had been maintained since at least 1930 and was little influenced by the newly constructed Brazos delta. This shape suggests that net sediment drift was relatively low and that the San Bernard discharge was effective in counteracting the drift and consequently in maintaining an unshoaled mouth oriented subnormally to the coast. In 1967, evidence for the accretion of beach ridges related to development of the Brazos delta is evident directly updrift of the San Bernard River mouth.

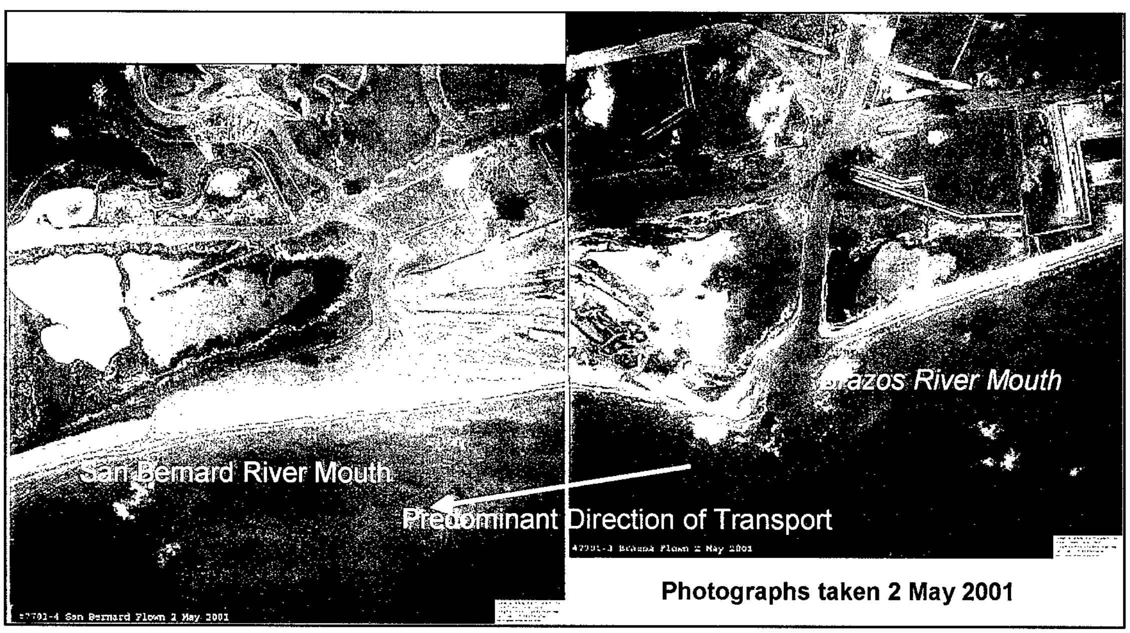

Figure 5. Coastal morphologic structure and longshore sediment transport path from the Brazos River mouth to the San Bernard River mouth

As the new Brazos River delta continued to develop to the southwest, between 1967 and 1983 the shoreline updrift (east) at the San Bernard River mouth prograded significantly, evidenced by several generations of ridges that generated recurves into the San Bernard mouth. However, the mouth maintained its general funnel shape and did not migrate significantly downdrift.

Starting about 1984, the mouth was forced to migrate downdrift by successive addition of recurves on the updrift sides that accumulated to generate a spit. Spit elongation was slow until 1989, but sometimes between 1989 and 1995 it accelerated. It is hypothesized here that this increase in elongation rate was caused by postflood reworking of the new sediment delivered to the subaqueous Brazos delta in 1992 in the form of a channel mouth bar, as well as by erosion of the newly prograded postflood deltaic bulge located directly adjacent to the new Brazos mouth. By consideration of the new Brazos River delta conceptual mophodynamic model, we would expect that elongation of the San Bernard River mouth spit will be somewhat slower during interflood periods, but will commence to significantly increase some time after a flood. This conceptual model is refined in the next two sections.

Morphodynamics of the San Bernard River Mouth

The San Bernard Navigation Channel extends northward for 45 km from the GIWW and is rarely dredged, confirming the relative small riverine load it carries. Since 1943, when new work dredging was conducted with removal of about 1 million cu yd from the channel, the San Bernard Navigation Channel has been dredged 20 times, with a dredging frequency of 2.3 years and a shoaling rate of about 14,000 cu yd/year, according to the Dredging Histories Database of the Galveston District. In contrast, the 1-mile-long stretch extending from the GIWW southward to the Gulf of Mexico is not a Federal project for navigation purposes and has not been dredged.

Modest dredging requirement along the San Bernard Navigation Channel confirms the small sediment loads carried by the San Bernard River, corresponding to its small discharge. As discussed in the previous section, westward migration of the spit and the San Bernard River mouth is primarily in response to sediment delivered to the mouth by longshore transport. The weak discharge of the river is not sufficient to maintain a stable channel cross section and channel position, so that stability of the mouth depends almost solely on tidal flushing.

Sedimentation at the San Bernard River mouth is clearly seen in Figure 6. The lower end of the river is no longer navigable. During a site visit by boat made by the authors in July 2001, even shallow-draft recreational boats could not reach the mouth and pass to the Gulf of Mexico. It is inferred that the flood-tidal current sweeps littoral material into the river channel and tends to deposit it on the northern bank, whereas the ebb-tidal current flows along the east and then the south side of the channel as it turns along the spit. As a result, the mouth is expected to close within the next few years unless a storm elevates water level and/or increased precipitation causes a strong riverflow. In that situation, either the present mouth will reopen or a new channel will be cut through the lower section of the spit so that the ebb-tidal current and riverflow can exit from the shortest route to the Gulf of Mexico.

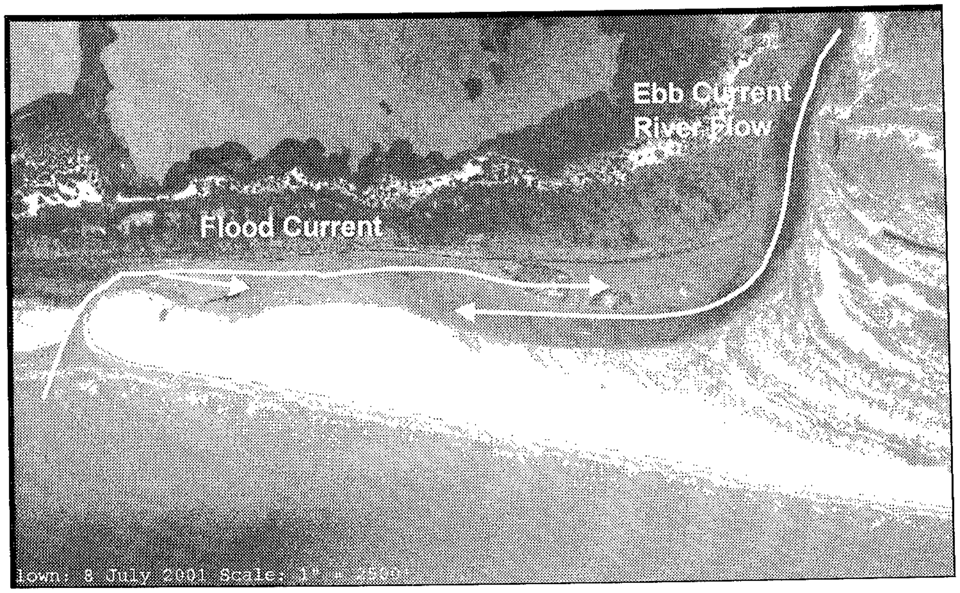

Figure 6. San Bernard River mouth, 8 July 2001, and inferred sediment paths

The process of spit migration and breaching of a river mouth or inlet is well known (Johnson 1919) and has recently been reviewed by FitzGerald, Kraus, and Hands (2001). Figure 7 is a schematic of the river-mouth migration and spit-breaching model. The rate of migration depends on the sediment supply, wave energy, discharge, and composition of the channel banks. If a migrating river mouth becomes entrenched into resistant sediments, further migration will be impeded. Shallow mouths such as at the San Bernard tend to migrate, whereas deeper inlets tend to be more stable, because there is a greater likelihood that their channels have scoured into semi-indurated sediments. As a river mouth migrates, it leaves behind a series of curved beach ridges that define the updrift spit.

River mouth or inlet migration lengthens the channel that connects the sea (Gulf of Mexico here) to the back-barrier bay, lagoon, or marsh and tidal creek system. Elongation of the river mouth channel increases frictional resistance of the flow, quantified for the San Bernard River mouth in Chapter 3. In nature, spits are typically breached in two ways, either from the ocean (Gulf) side by storms with accompanying super-elevation of the ocean water level in the surge, and reduction in spit width and height by erosion, or from the riverside during times of high precipitation and flooding. The new mouth is commonly located along the updrift spit at position where the barrier is relatively narrow and the back-barrier water body is easily accessed. The hydraulically favorable position of the new mouth promotes capture of the flow of the old mouth, leading to its eventual closure. The end product of the spit-breaching process is a relocated river mouth updrift of the old mouth, with the old mouth gradually closing. The new mouth is closer to the main channel of the river, and a large quantity of sediment is transferred from the updrift to the downdrift side of mouth. Such a process can occur cyclically over a period of a decade or more, depending on the longshore transport and river discharge. FitzGerald and FitzGerald (1977) discuss various geomorphic factors that control inlet (or river mouth) stability.

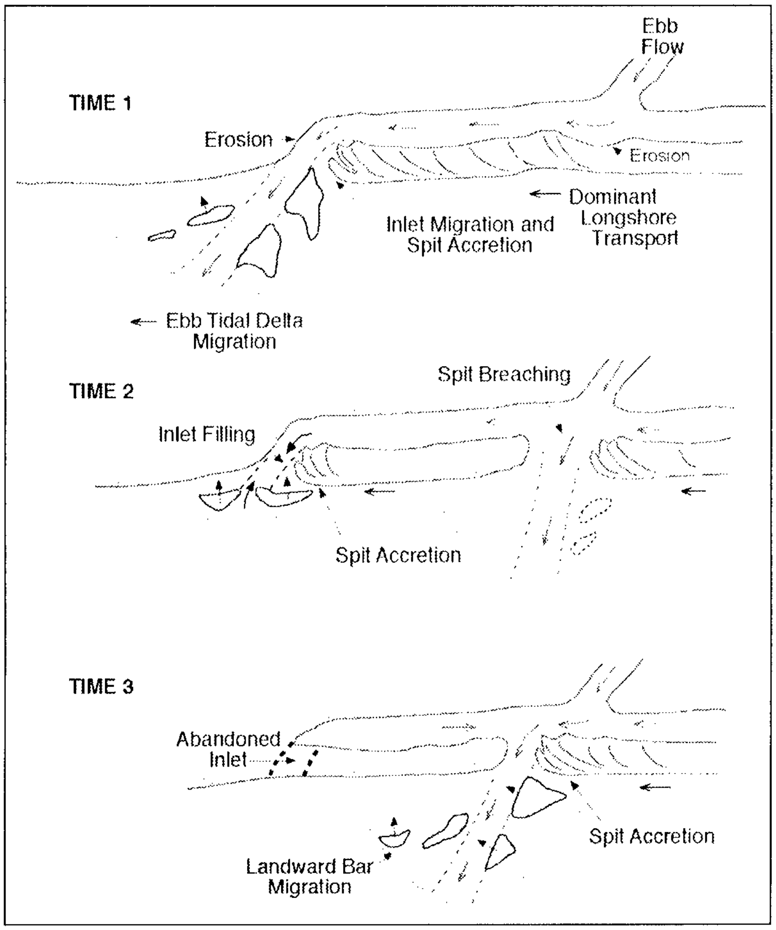

Figure 7. Schematic of river mouth or inlet migration and spit breaching process (from FitzGerald, Kraus, and Hands 2001)

Quantification of spit growth and river mouth translation

As part of this study, previous aerial photography was collected, and the site was also flown to photo-document the recent condition. Many of the assembled photographs have near-vertical orientation and could be analyzed to determine reliable changes in dimensions of the spit. Dates of recent high-quality photography analyzed in this study are listed in Table 1.

The aerial photographs were rectified for the morphologic analysis within ArcView® software employing the extensions of Image Analyst. In addition, the perimeter of the spits was identified by the newly developed BeachTools extension (Hoek, Zarillo, and Snyder 2001), which gave unbiased identification of the shoreline defining the spit, from which spit length, width, and planar area were determined. The geomorphic analysis was done in the following steps:

a. Acquire data (aerial photographs, surveys of the spit, ground control through Global Positioning System (GPS) survey).

b. Manipulate and rectify the images in ArcView® (including error estimate).

c. Delineate area of the spit by means of the BeachTools extension. Measure length and width of spit.

d. Estimate depth of active movement of the spit.

e. Calculate the volume of the spit between consecutive photographs.

A GPS survey of distances along two roads, Route 2918 and the Bernard River Road, that run to the northwest corner of the intersection of the GIWW and San Bernard River was made to provide control for the photograph rectification. Based on the known distances between four to six measured points, depending on coverage of the photograph, an rms error was obtained in the rectification (Table 1). The error depends on the degree of obliqueness, tilt and distortion of the photograph, number of control points (minimum of four is required), scale, and quality of the photograph. On a smaller-scale photograph, a digital pixel occupies more area and, therefore, has lower resolution. Error in the digitization varied between about 1 and 15 m, with the greatest error associated with the smaller-scale 1 April 1989 photograph. However, the time between that photograph and the next is 6 years, so that the potential error/year is small for the total period.

Table 1
Rectification Error of Aerial Photographs, San Bernard River Mouth, Texas

Date of Photograph	Image Rectified To:	Pixel Resolution, ft	Rectification rms Error in pixels (ft and m)*
1 Apr 89	19599-1.jpg	20	2.5 (50 ft / 15.2 m)
1 Sep 95	19599-1.jpg	4.5	0.48 (2.2 ft / 0.7 m)
6 Oct 99	CAD drawing dated 09/99	3	3.1 (9.4 ft / 2.9 m)
17 Jan 00	19599-1.jpg	3	2.5 (7.6 ft / 2.3 m)
7 Jul 00	19599-1.jpg	3	3.0 (9.0 ft / 2.8 m)
5 Jan 01	19599-1.jpg	3	2.3 (6.9 ft / 2.1 m)
2 May 01	19599-1.jpg	6	2.0 (12.1 ft / 3.7 m)
8 Jul 01	7701-4_sb_may01.jpg	4.5	5.7 (25.7 ft / 7.8 m)

* Average Error = ± 16 ft or ± 4.9 m

The photographs allow measurement of the subaerial perimeter to determine the length and width of the spit. The process of spit growth is displayed in Figure 8, and analysis results are plotted in Figure 9. Vegetated beach ridges are located on the eastern side of the spit, implying greater age and elevation (by trapping and accumulation of wind-blown sand) as compared to the sandy portion to the west and indicating relatively recent transport to that location. The baseline for referencing spit elongation was placed on the west side of the northwest-southeast (NW-SE) trending portion of the San Bernard River channel. The various colored lines represent the perimeter of the pit for the given date as determined by the BeachTools analysis.

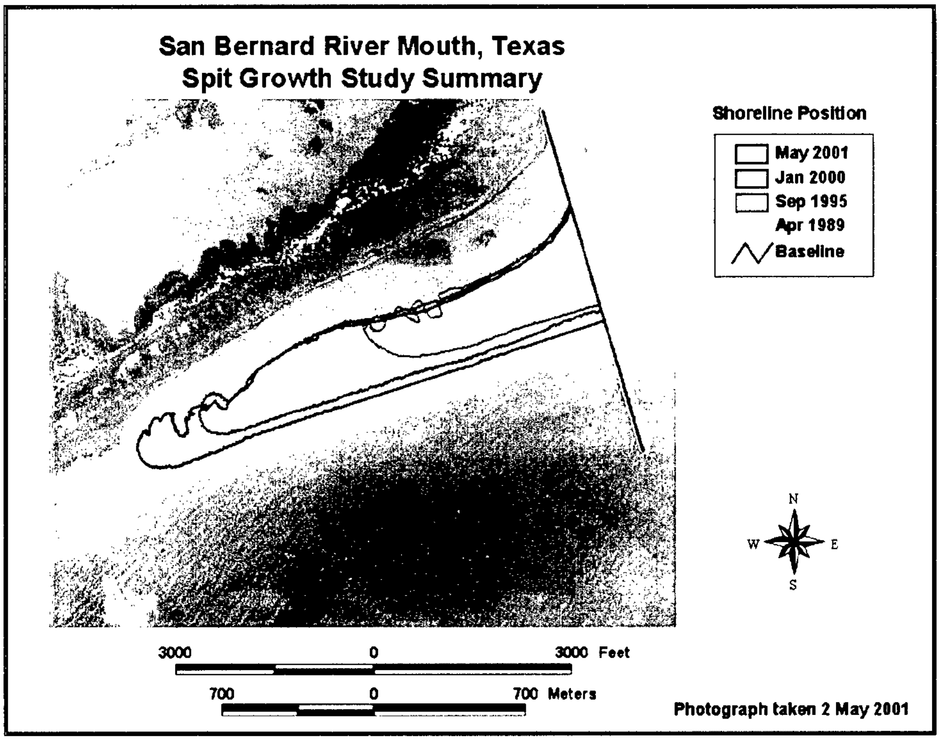

Figure 8. Spit growth at the San Bernard River mouth

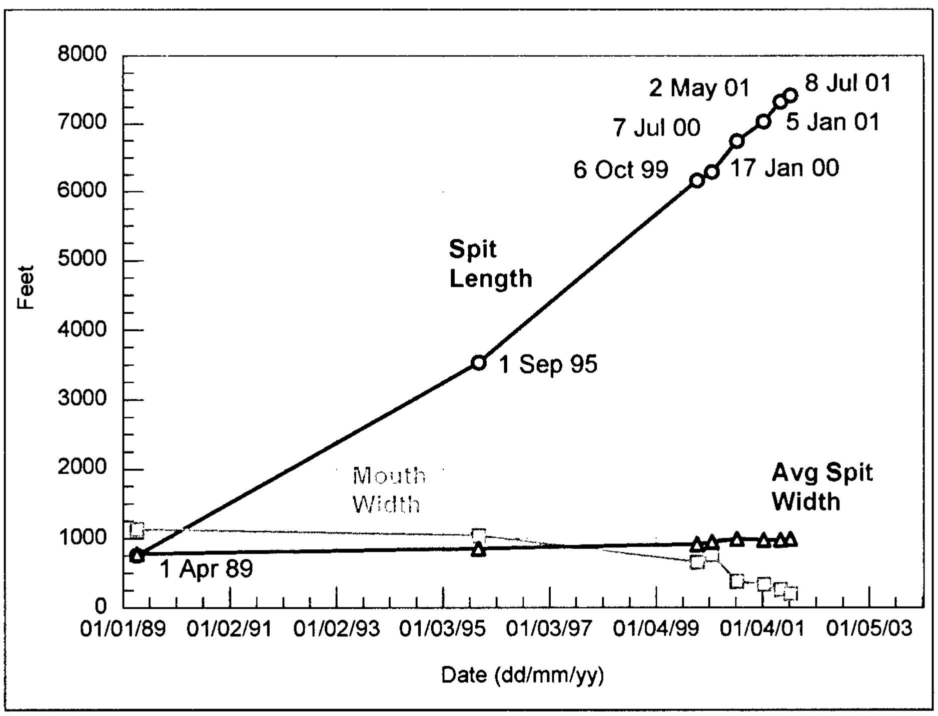

Figure 9. San Bernard River mouth spit length and width, and width of mouth

From this analysis, values of the subaerial spit length and width and width of the channel mouth were determined to the accuracy given in Table 1, Figure 9 indicates that from April 1989 until July 2001, the spit grew almost linearly at an average rate of 1.2 ft/day, with a somewhat larger rate of 1.6 ft/day after September 1995. The average width of the spit measured over its total length at the time of measurement was nearly constant at approximately 1,000 ft. The width of the river mouth decreased from 1,127 ft in April 1989 to 200 ft in July 2001.

Three surveys in and around the river mouth were conducted as part of this study:

a. Channel, 8 August 1999.

b. Nearshore, 3 March 2001.

b. Channel and subaerial spit, 24 July 2001.

The survey transects are shown as the black lines in Figure 10. Transects on the spit were spaced 100 ft apart and started from a location just east of the heavily vegetated beach ridges. Figure 11 is a three-dimensional (3-D) view of the spit based upon the survey measurements that displays the spit relief and channel.

Representative cross sections are plotted in Figure 12 for the yellow lines drawn in Figure 10. The land survey was joined to the offshore survey by a straight line for continuity in viewing. Survey results are plotted to mean low tide (mlt), a navigation datum defined by the Galveston District that is located below mean lower low water (mllw). At least one nearshore bar is expected to be present between the shore and 18-ft-depth mlt, as is typical of the sandy portions of the Texas coast, but the survey did not cover this region. The spit is relatively flat at elevation +5-ft mlt, upon which low dunes and vegetated areas increase the elevation. At about +1-ft elevation, the bank-to-bank width of the spit is about 1,000 ft on the more mature regions of the spit, becoming narrower as the channel is approached. At the time of the July 2000 survey, the minimum width of the mouth, Cross Section 1, was about 200 ft, and the maximum depth there was only 2.5-ft mlt. Cross Sections 2 through 5 show a narrow river channel of approximate 100-ft maximum width because of the large linear flood shoal located on the northern side of the river. There is almost no channel at Cross Section 2, indicating the river mouth is almost choked with sand.

A geometric shape of constant form (Figure 13) reasonably represents the configuration of the spit because it is straight and has almost fixed width. If appropriate values of the limiting depth of the spit in the Gulf of Mexico, limiting depth of the spit in the river channel, elevation of the spit, and spit width and length are given, then a volume can be calculated that represents the net transport at the site. Moore and Cole (1960) appear to be the first to have estimated a net longshore sand transport rate by this method. Kraus (1999) measured spit growth from aerial photographs to estimate the net longshore transport along Corpus Christi Beach (North Beach) in Corpus Christi Bay. Converted to a rate, this transport provides a reliable estimate of dredging maintenance requirements at the river mouth.

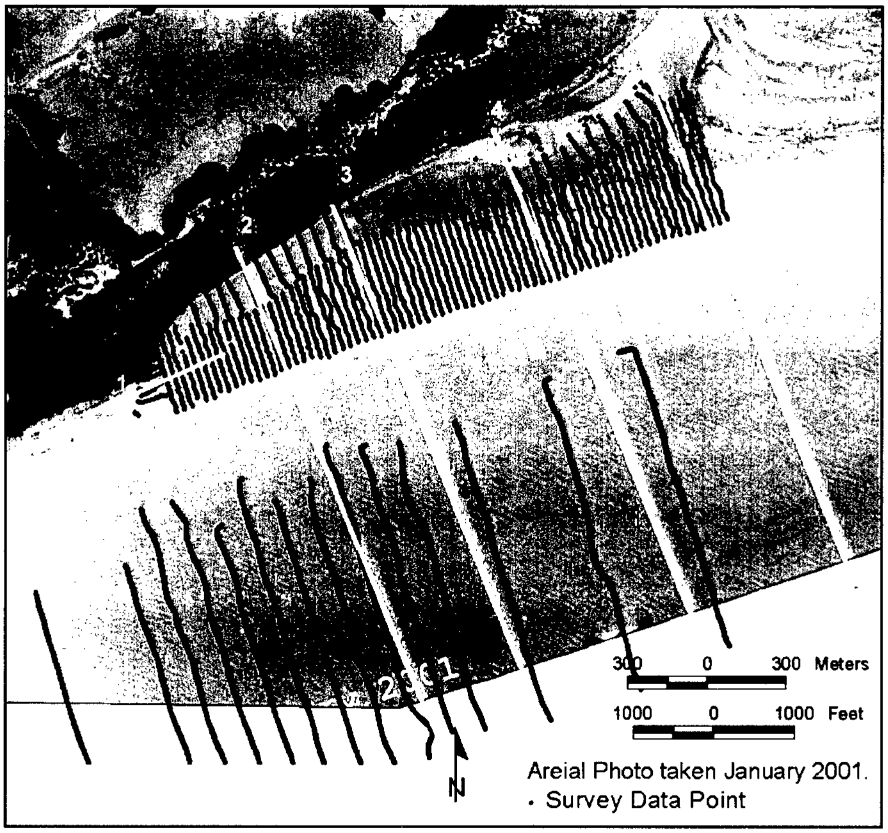

Figure 10. Locations of survey lines and selected transects for display

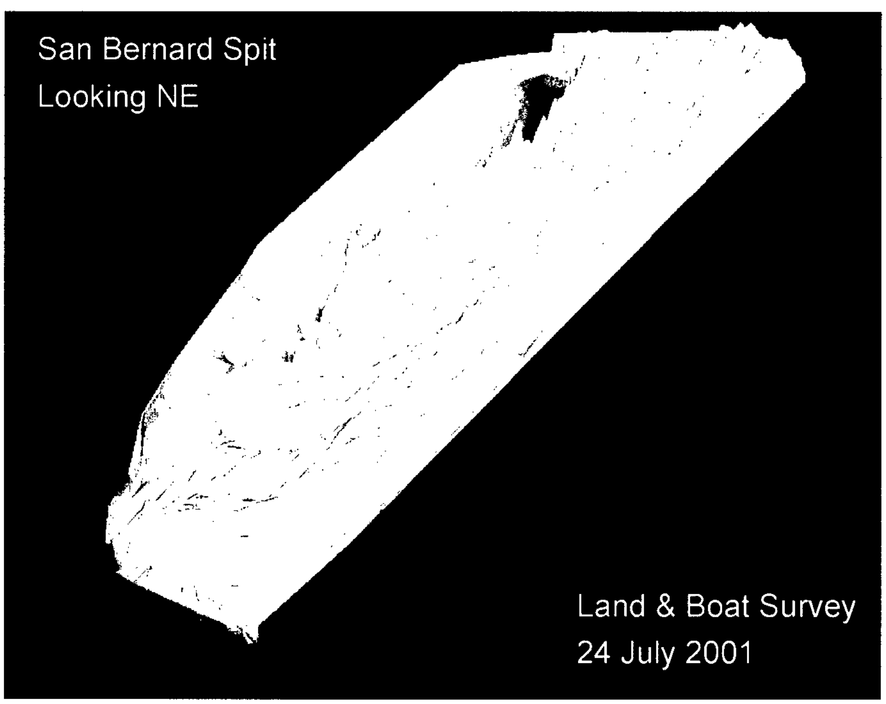

Figure 11. Three-dimensional view of the San Bernard River mouth spit

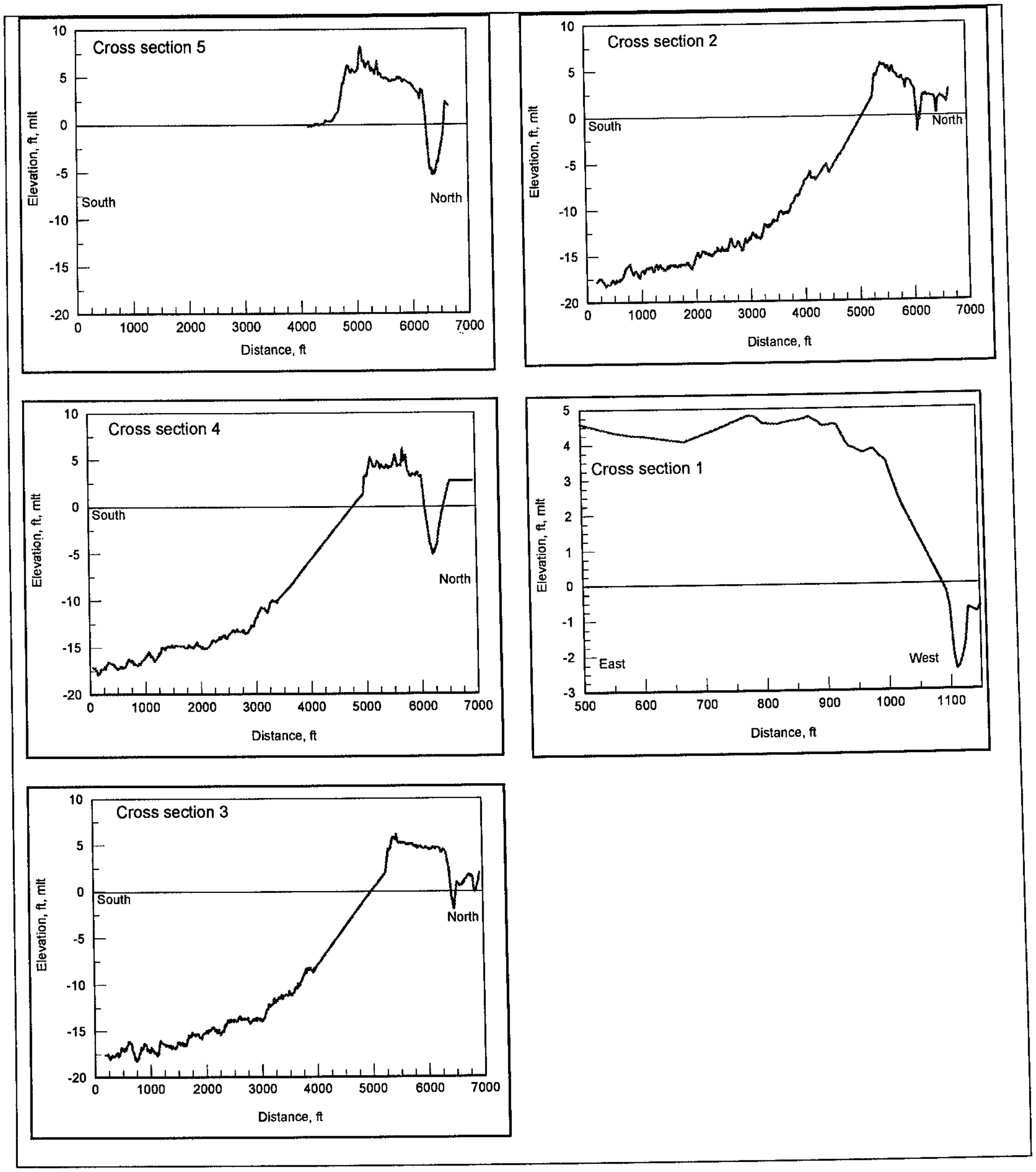

Figure 12. Representative cross sections along the spit and across the San Bernard River mouth

Elevations on the upper or subaerial pyramid were approximated from the land survey, and the slopes of the offshore and channel prisms were similarly estimated from the surveys. The depths of the channel and offshore prism were taken as 4-ft mlt to represent the net volume-rate of spit growth. The river channel reaches a maximum depth of 4-ft mlt, and it was assumed that the depth of the river mouth does not exceed 4-ft mlt under the acting longshore sediment transport conditions. Any sediment moving alongshore at a greater depth would bypass the channel and be unaccounted in the volume rate of change of the spit. The net longshore sediment transport rate inferred from the spit movement is, therefore, an underestimate of the total (which could be determined if the river mouth were very deep).

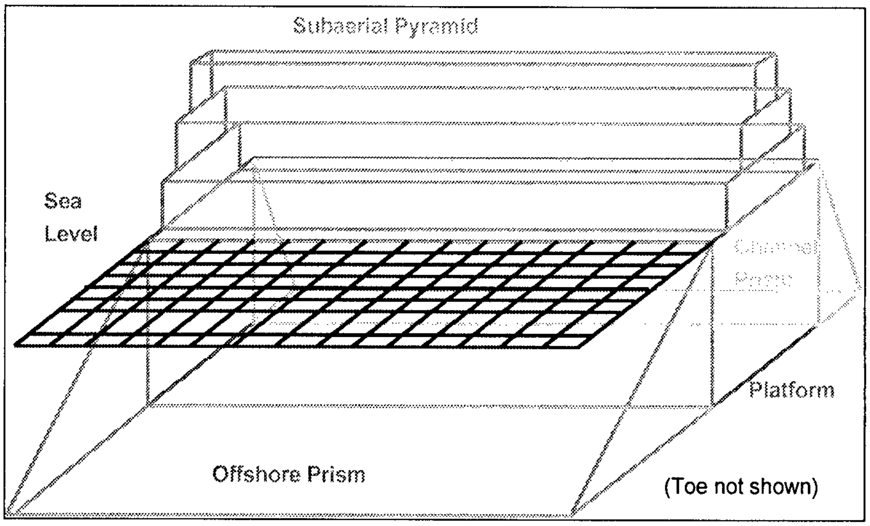

Figure 13. Representation of a spit as a pyramid

With an average annual nearshore wave height of 0.8 m or 2.6 ft (see next chapter), on the assumption that most sediment (predominantly sand) moves alongshore landward of a depth of twice this wave height, or 5.2 ft (which should be referenced to mllw, as this is the lowest water depth typically experienced on the open coast), then the channel depth of 4-ft mlt is close to this value because the mlt datum lies somewhat below mllw. Sediment (sand) will move alongshore at greater depths during times of higher waves and, in particular, during tropical storms and hurricanes. Therefore, it will be assumed that the value of the net longshore sediment rate determined by spit growth at the San Bernard is 75 percent of the total.

Because of the near-constant width of the spit, the change in volume plotted in Figure 14 tracks with the length of the spit plotted in Figure 9. A net longshore sediment transport rate is obtained by dividing the change in volume by the time between the consecutive photographs. Converted to cubic yards per year, these rates are plotted in Figure 15 and run from a minimum of 133,000 cu yd/year to a maximum of 417,000 cu yd/year. The time-weighted average net longshore transport rate is 176,000 cu yd/year, directed to the west. This average is formed as the sum of the products of the transport rate and time over which the rate was measured divided by the total time period (1 April 1980 to 8 July 2001). The average rate is consistent with previously reported estimates and is probably one of the most reliable measurements of a net longshore sediment transport rate available for the Texas coast. The time-weighted value should be divided by 0.75 to obtain an estimate, 235,000 cu yd/year of the total net transport rate to the active depth of longshore transport. However, the 176,000 cu yd/year figure is appropriate if the channel mouth is to be maintained to 4-ft-depth mlt. This value would also be an overestimate for periods when the Brazos River has not experienced a long-duration flood.

From April 1989 to October 1999, Figure 15 shows the net longshore transport rate was less than 176,000 cu yd/year. After October 1999, the annualized rate almost tripled. This notable difference in rates is attributed to the large flood that occurred on the Brazos River in 1992, as described above. The large linear entrance channel shoal created by the flood had a volume estimated to exceed 2 million cu yd, and this feature migrated to the southwest, eventually attaching to the shore. In addition, as discussed in the next section, the new Brazos River delta is approaching equilibrium volume and can thus provide more sand through natural bypassing.

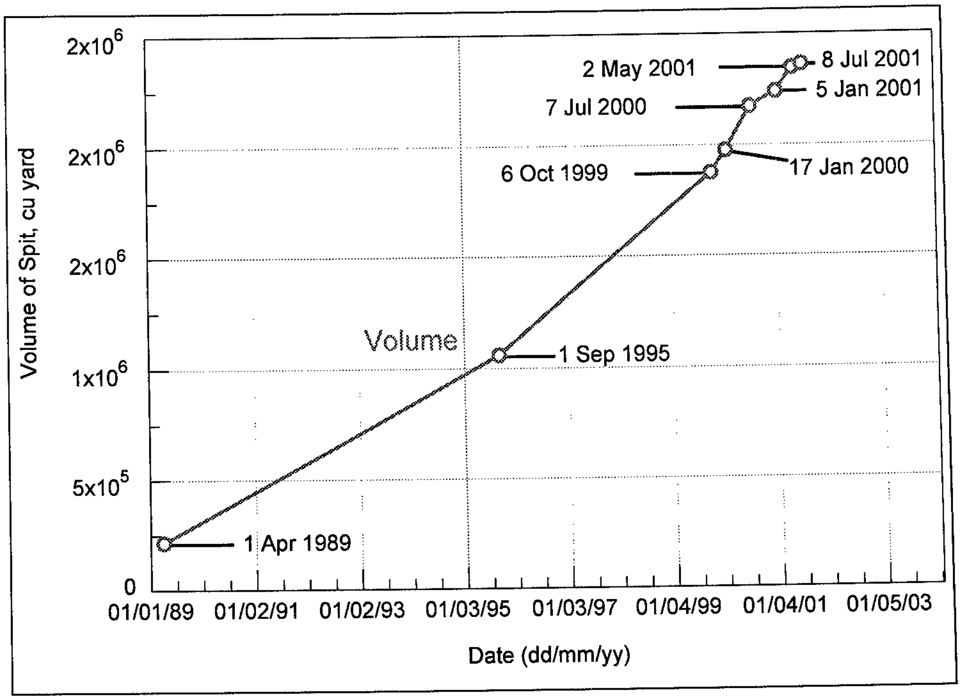

Figure 14. Change in spit volume with time

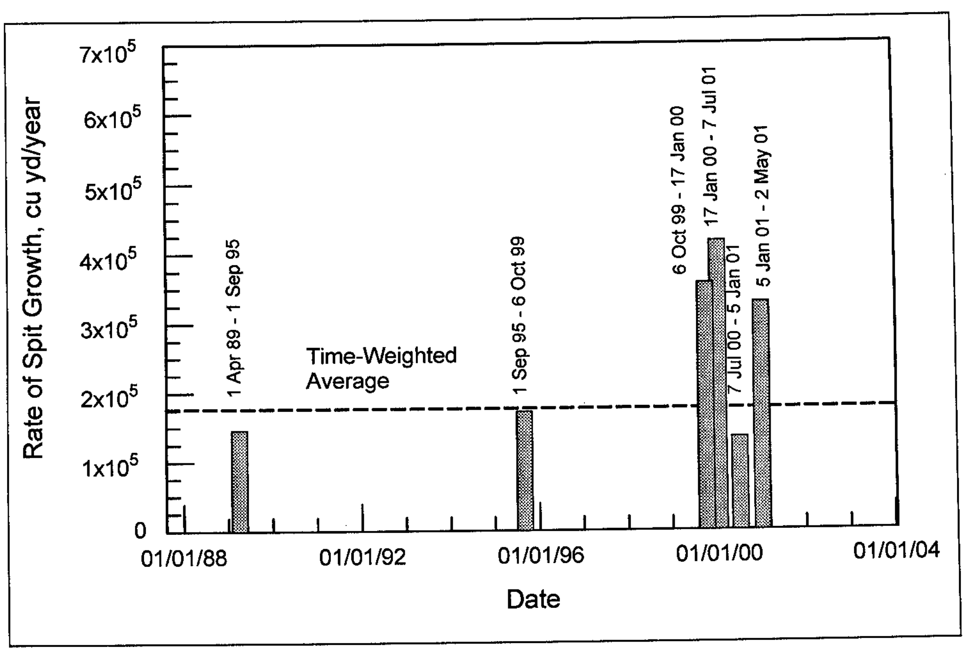

Figure 15. Rates of change in spit volume and time-weighted average

Brazos River Delta and Relation to the San Bernard River Mouth

Fields, Weishar, and Clausner (1988) quantified the volume of sediment stored in the delta at the new Brazos River mouth based on analysis of hydrographic survey charts available for the years 1929, 1931, 1932, 1933, 1934, 1937, and 1985. The 1929 survey chart served as the base, because there was no delta present prior to diversion of the river. The results of their analysis are plotted as the open circles in Figure 16. The volume in the new delta increased rapidly for the first 10 years after the river diversion in 1929, so that by 1960 it had achieved an apparent equilibrium volume of about 28×10^6 cu m (36.6×10^6 cu yd). As described above, the delta does not consist entirely of sand.

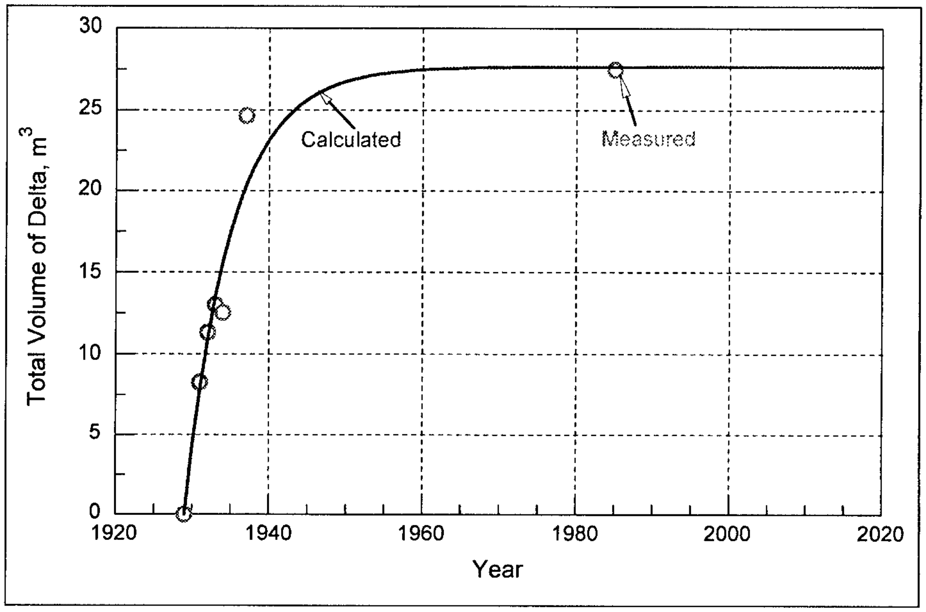

Figure 16. Change in volume of the new Brazos River delta (measurments from Fields, Weishar, and Clausner 1988)

It is expected that the delta of a small river will behave similarly to the ebb shoal of a tidal inlet, in that wave action can remove sediments from it to achieve an equilibrium volume balancing sediment transport by waves and tidal current. Such shoals consist primarily of sand originating from the littoral system. Walton and Adams (1976) found that the volumes of inlet ebb shoals could be predicted based upon knowledge of the tidal prism (volume of water passing through an inlet in half a tidal cycle) at spring tide.

Under the assumption that the ebb delta at the Brazos River attains an equilibrium volume similar to that of an inlet-ebb shoal, its equilibrium volume can be estimated with accepted empirical formulae. It is assumed, in this analysis, that the combined river and ebb-tidal discharge can be converted to an effective tidal prism for making the estimate. This approach was theoretically derived by Kraus (1998) for tidal exchange and will not be described here. To convert maxim tidal discharge D_m to tidal prism P, simple sinusoidal water motion is assumed, which leads to (Keulegan and Hall 1956):

$$P = \frac{T}{\pi} D_m \tag{1}$$

where T = tidal period, which is taken to be 24 hr as a representative diurnal period for the Texas Gulf of Mexico. Hydrodynamic modeling described in Chapter 3 gives a representative maximum tidal discharge of about 100 cu m/sec for the Brazos River. A long-term average river discharge for the Brazos River is 200 cu m/sec, and representative annual and larger flood river discharges are in the range of 1,000 to 2,000 cu m/sec, respectively. Therefore, the tidal exchange is not the dominant flow responsible for building and maintaining the ebb delta. Delta volume is controlled by the flood river discharge. (In contrast, for the San Bernard River, the dominant flow is tidal discharge, as discussed in Chapter 3.)

Walton and Adams (1976) derived empirical formulae for estimating the equilibrium volume of an ebb-tidal shoal. They concluded that the size of a fully developed ebb-tidal shoal depends in part on wave energy at the inlet in addition to tidal prism, and they separated their data for coasts classified as highly, moderately, or mildly exposed to wave action. Data from the coasts of South Carolina, Texas, and the lower Gulf Coast of Florida were categorized as mildly exposed coasts. The empirical formula for the equilibrium ebb-tidal shoal volume V_e on a mildly exposed coast is:

$$V_e = 13.8 \times 10^{-5} P^{1.23} \tag{2}$$

where V_e is expressed in cubic yards and P in cubic feet.

Combining Equations 1 and 2, and assuming that the river discharge can be treated similarly to tidal discharge, Table 2 is developed. (The volume of 36.6×10^6 cu yd listed in Table 2 is fortuitous in being the same as estimated from Figure 16.) The equilibrium volume for the average annual discharge is much too small compared to the volume determined by analysis of hydrographic survey data (Figure 16). In contrast, the volumes determined by the average annual and larger representative flood discharges are comparable to the volume estimated from surveys and give insight into the balance of forces (river discharge and waves) supporting the river delta.

Table 2
Empirically Estimated Equilibrium Volume of Brazos River Delta Based Upon Equation 2

Discharge, cu m/sec	Discharge, cfs	Prism, cf	Equilibrium Volume, cu yd	Equilibrium Volume, cu m
200	7.05×10^3	1.94×10^8	2.16×10^6	1.64×10^6
1,000	3.53×10^4	9.71×10^8	15.6×10^6	11.8×10^6
2,000	7.06×10^4	1.94×10^9	36.6×10^6	27.7×10^6

Kraus (2000) presented a mathematical model called the "reservoir model" that simulates growth of ebb-tidal shoal volume toward equilibrium and bypassing to the downdrift beaches as a quasi-steady continuous-mode transport process. The original model was validated at Ocean City Inlet, Maryland. It was subsequently extended to include the flood shoal and adjacent channels, and validated at Shinnecock Inlet, Long Island, New York. Shinnecock Inlet has a tidal prism on the order of 1.4×10^9 cfs (Militello and Kraus 2001), which is in the range in equivalent average annual flood tidal prism of 0.971 to 9.71×10^9 cfs listed in Table 2. The ebb shoal at Shinnecock Inlet is expected to grow to achieve an equilibrium volume in the range of 15 to 20×10^6 cu yd.

For the present study, to further understand sediment-bypassing processes at the Brazos River mouth, the reservoir model was extended within the framework of a simple analytical solution. In the model, the growth in volume V of the river delta is given by the continuity equation:

$$\frac{dV}{dt} = (Q_{in})_{tot} - Q_{out} \tag{3}$$

where

t = time

$(Q_{in})_{tot}$ = total sediment transport rate into the delta

Q_{out} = sediment transport rate out of the delta.

The total input rate is the sum of the westward longshore sediment transport rate Q_W (neglecting the relatively small eastward transport) and the river input Q_R:

$$(Q_{in})_{tot} = Q_W + Q_R \tag{4}$$

The reservoir model closure assumption is that the output rate of sediment transport is proportional to the product of the volume of the delta at the given time and the input rate as:

$$Q_{out} = \frac{V}{V_e}(Q_{in})_{tot} \tag{5}$$

With the start of formation of the new Brazos River delta as 1929, the river rate of transport is modeled as the sum of a one-time initial discharge Q_{R0} that decreases with time exponentially with decay coefficient β and a steady average-annual rate, Q_{Ra}:

$$Q_R = Q_{Ra} + Q_{R0}e^{-\beta t} \tag{6}$$

The solution of Equation 3 under the stated assumptions is:

$$V = V_e\left(1 - e^{-\alpha t}e^{-a[1-\exp(-\beta t)]}\right) \tag{7}$$

where

$$\alpha = \frac{Q_{in} + Q_{R0}}{V_e}, \qquad a = \frac{Q_{Ra}}{\beta V_e} \tag{8}$$

With parameter values estimated as

$Q_W \ = 3 \times 10^5$ cu m/year

$Q_{R0} \ = 6 \times 10^6$ cu m/year

$Q_{Ra} \ = Q_{R0}/10$

$\beta \ = 0.05$/year

$V_e \ = 28 \times 10^6$ cu m

the solution produces the solid line drawn on Figure 16. Sensitivity tests showed that values of the transport rates and decay coefficient deviating moderately from those listed would not produce the trend of the volume measurements. As the volume of the river delta approaches equilibrium, the output rate of transport will approach the input rate. The total steady input rate consists of $Q_W + Q_{R0}$, which gives a value too high for a bypassed longshore transport rate for this coast. However, not all of the river sediment supply is sand, much of it being fine-grained sediments either buried in the delta or dispersed offshore (Hamilton 1995). In principle, the volume of a delta or alluvial fan can grow in almost an unconstrained manner if the sediment discharge from the river exceeds the capacity of the waves to transport it away.

The model qualitatively predicts the trend in time scale of growth and increase in bypassing rate through time. As the ebb shoal grows and approaches equilibrium, it acts less as a sink of littoral sediments and more as a conveyance area or sediment source for bypassing. In general, the time scale for increase in bypassing toward the potential for longshore transport on the updrift side can take several decades, depending on the equilibrium volume of the ebb shoal or delta and the input longshore sediment transport rate.

Gaudiano and Kana (2001) quantified another type of bypassing, called episodic-mode bypassing, or shoal bypassing, at mixed-energy inlets. In this form of bypassing, shoals periodically split off from the main ebb-shoal complex, migrate shoreward, and attach to the adjacent beach, causing rapid localized accretion. For the nine South Carolina inlets studied by Gaudiano and Kana (2001), the mean bypassing shoal volume was about 1 to 7 percent of the total ebb shoal, and the mean event interval ranged from about 4 to 8 years. A mixed energy inlet is one with moderate tide range and moderate wave heights. The Texas Gulf of Mexico coast is considered wave dominated because of the relatively small tidal range as compared to other coasts of the United States, but the analogy of episodic creation of migrating shoals carries over to river mouth channel bars or shoals created during longer-duration floods.

Sediment-Transport Processes at the San Bernard River Mouth

Based on the information and analysis contained in this chapter, a consistent explanation of sediment-transport processes at the San Bernard River Mouth is developed in this section. The explanation accounts for the relative stability of the San Bernard River mouth prior to the late 1980s and its subsequent migration and tendency for closure observed in recent times.

Prior to 1929, the Brazos River discharged to the Gulf of Mexico 10.5 km northeast of the mouth of the present diversion channel. The San Bernard River mouth was, therefore, located 16 km downdrift of the original river delta and beyond its direct influence. The Brazos River had not yet been dammed, and sediments brought to it were carried relatively far offshore by the river discharge to create a large delta. In the same era, the GIWW had not yet been cut west of the Brazos River, so the San Bernard River flowed unimpeded to the Gulf of Mexico. As a result, it appears that the San Bernard River had adequate tidal exchange supplemented by river discharge to maintain locational and cross-sectional stability of its mouth.

From 1929, a delta began to form at the newly created Brazos River Diversion Channel mouth located 5.4 km northeast and updrift from the San Bernard River mouth. Delta formation and growth in volume toward equilibrium claimed much of the sediment that would otherwise have been transported to the southwest. The San Bernard River mouth, therefore, enjoyed a period of relative absence of arrival of sediment moving alongshore that would otherwise have tended to close and/or translate the mouth downdrift by spit formation on the updrift side. An inlet that experiences less longshore sediment transport than would be typical on equivalent open coast is called a "sheltered inlet." It is known that smaller tidal prisms can maintain more inlet stability than the open (unsheltered) coastal areas (see review in Kraus 1998).

In this period, the late 1930's and early 1940's, the GIWW was extended west from the Brazos River and past the San Bernard. No significant sedimentation problem was observed at the San Bernard River mouth for several decades since that time, making this situation appear to be the norm. However, the "norm" as observed at the San Bernard River mouth during the 6 decades was actually artificially induced by the diversion of the Brazos River and sheltering from longshore sand transport.

As the new Brazos River delta approached equilibrium, it began acting as a natural bypass route for sediment transported alongshore by waves. Thus, from about the 1960's, the delta should have approached full bypassing potential. At the same time, however, because of dam construction, the sediment load on the Brazos River began decreasing. Given the massive infusion of sediment from the 1992 flood, it is likely that the volume of the new delta has reached dynamic equilibrium. If so, the delta will continue to bypass sediment in a semicontinuous manner by wave action and the wave-induced longshore current.

The new Brazos River delta can also bypass sand through the episodic mode, after a substantial flood brings material to the mouth, perhaps to create a channel mouth bar such as during the 1992 flood. The channel mouth bar began to attach to the southwest shore sometime around 1995, creating a sediment-rich, unstable shoreface with sand readily mobilized by waves and transported alongshore toward the San Bernard River mouth.

3 Hydrodynamics and Waves

The hydrodynamics (water level and current) and waves in the vicinity of the San Bernard River mouth were investigated by application of a hydrodynamic model and a wave model. The hydrodynamic model simulates the tidal hydraulics in the river and adjacent inland waters, and interest is in the combined tidal flow and river discharge of the San Bernard River for computing stability of the river mouth. The hydrodynamic model also calculates the current and water level in the San Bernard River, GIWW, and the Brazos River. The wave model provides long-term wave information based on the most recent hindcast and offshore measurements for estimation of the nearshore wave climate and longshore sediment transport rate at the mouth. River mouth stability on alluvial shores is controlled by the river discharge and the rate of littoral sediment supply.

The DYNamic implicit numerical model of 1-D tidal flow through inLETs (DYNLET) was chosen for simulating the water level and current (Amein and Kraus 1991, 1992). This model requires modest effort to establish and is readily transferred to the Galveston District for future investigations at the San Bernard River, Brazos River, and vicinity. DYNLET calculates the current velocity and water level in channels with varied geometry and varying friction factors across the channel. It can also describe a network of channels connecting to the sea, bays, and rivers. The model is well suited for applications involving rivers, inlets, and narrow channels connected to the ocean as compared with 2-D models, because the primary flow directions are known and cross-sectional flows can be simulated at high resolution.

The CHL Wave Information Study WAVE (WISWAVE) model was applied for generating wave information. WISWAVE is a second-generation, time-dependent spectral model that furnishes wave hindcasts along the United States coast (Hubertz 1992). The model is capable of generating wave information in the ocean as well as along the open coast. The deep-water and intermediate-water-depth waves calculated with WISWAVE were transformed to shallow water by a spectral model including dissipation induced by bottom friction.

Establishment of Model

DYNLET is based on the full nonlinear, 1-D hydrodynamic equations to predict the dynamic behavior of the tidal flow at inlets and channels in response to time-dependent boundary and forcing conditions (ocean tides, river discharge, surface winds) provided to the model. It computes water surface elevation and depth-averaged velocity with an implicit finite-difference solution scheme for channels with varied geometry and cross sections. DYNLET is unconditionally stable and efficient for computation of complex flow systems. It is flexible in grid spacing of a network of channels. The model grid consists of a channel network with each channel connected to one or two channels at the junction of nodal points. A channel element consists of a line of nodes. At least three nodes are required in an element. Each channel must have a beginning node and an ending node. Both the beginning and ending nodes must be either a junction node or an external node where boundary conditions are specified to drive the model. The distance between any two nodes is arbitrary, but nodes are best placed at locations where channel properties (width, depth, etc.) change significantly and at locations where output information is sought. At each node, cross-sectional information, including width and depth of the channel and the bottom friction coefficient, is required at stations defined along the cross section.

Figure 17 shows the DYNLET grid for representing the complex flow system of the San Bernard River. The grid consists of 80 nodes distributed in 19 channels. There are four "ocean" boundaries (connections to the Gulf of Mexico), two river discharge input boundaries, and five river end boundaries. The four ocean boundaries are: Node 1 at the mouth of San Bernard River, Node 69 at the mouth of Brazos River, Node 59 at the Mitchell's Cut, and Node 65 at the Freeport Ship Channel (Figure 2). The two river discharge boundaries are at Node 36 at the upper reach of the San Bernard River and Node 80 at the upper reach of the Brazos River. The five river end boundaries are: Node 25 at the end of Jones Creek, Node 39 at the end of McNeal Bayou, and Nodes 43, 50, 56 at the end of Cedar Lake Bayou and Cedar Lakes. The GIWW extends laterally beyond Node 59 at Mitchell's Cut and Node 65 at Freeport. It was assumed that the influence of currents beyond Nodes 59 and 65 in the GIWW is small and can be neglected compared to the current generated by Gulf of Mexico tidal forcing at the two nodes of the flow systems of the San Bernard River and Brazos River.

The Gulf of Mexico tidal forcing was accomplished by input of water surface elevation data from the Galveston Pleasure Pier NOS tidal gauge (29°19'36"N and 94°41'30"W), located approximately 64 km north of the San Bernard River mouth. These data can be accessed from the Texas Coastal Ocean Observation Network, supported by the Galveston District, at the worldwide web address http://dnr.cbi.tamucc.edu. The river discharge input boundary information was acquired from the USGS National Water Information System at the address http://water.usgs.gov/data.html. No-flow boundary conditions were specified at upper ends of the rivers.

The cross-sectional geometrical data were based on National Oceanic and Atmospheric Administration (NOAA) nautical charts and a hydrographic survey performed by CHL. The Galveston District navigation tidal datum mlt was converted to approximate mtl for the modeling by adding 1 ft to mlt values. Kraus et al. (1997) discuss the mlt datum. The depth along the centerline of the San Bernard River around the intersection of the GIWW ranges from 9 to 25 ft mlt. The river becomes shallower approaching the mouth and is effectively unnavigable near the mouth. The greatest depths at the mouth at the time of the survey ranged from 5- to 8-ft mlt and varied with location and time of survey.

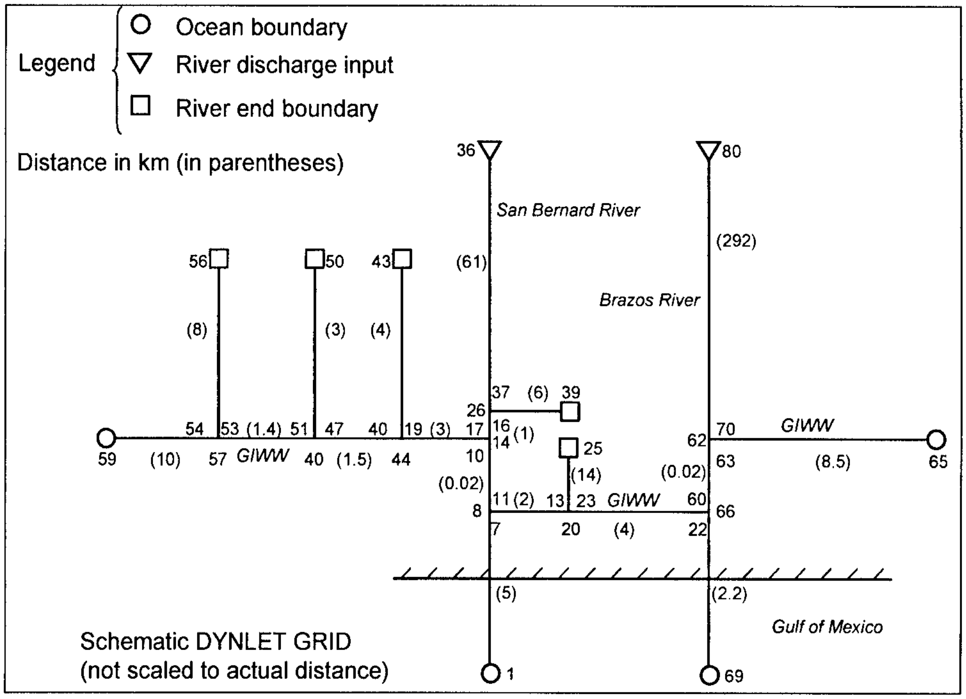

Figure 17. Schematic of DYNLET grid for San Bernard River flow system

The GIWW is maintained to a depth of 12-ft mlt, with provision for 1 ft each of advance dredging and overdredging. The depth in the Brazos River around the intersection of the GIWW ranges from 10- to 20-ft mlt. The water also becomes shallow near the mouth because of sediment shoaling. The average depth along the centerline of the river at the Brazos River mouth was about 8-ft mlt with narrow ebb channels cutting through the shoals according to observations made by the authors on a boat site visit on 18 July 2001. The Brazos River mouth is not maintained as a Federal channel.

Hydrodynamic Modeling

Model validation

DYNLET was configured to simulate the hydrodynamics of the existing channel-and-spit system for three time intervals for which measurements were available. The first interval was for the 2-month period May-June 1993 which corresponds to relatively large discharges in the San Bernard and Brazos Rivers, and the second and third intervals were for the months of January 1994 and August 1999, which had relatively small river discharges. The first interval represents flooding that typically occurs in the spring (see Figure 4 for an example for year 1999), whereas the second and third intervals represents dry conditions that typically occur from July through December. Table 3 summarizes the river discharges as input from the USGS database for the selected intervals.

No significant effort was made to match in detail the model calculations to the measurements because of substantial unknowns in bathymetry at the site, in particular, of storage in the shallow lakes near the channels. The Manning's friction coefficient in DYNLET, the major parameter for achieving calibration, was set to 0.025 sec/m$^{1/3}$ throughout the numerical grid. Sensitivity tests with this coefficient did not produce significantly different results for a reasonable range in values. The floodgates at the Brazos River were represented as being open, following conclusions given by Sanchez and Parchure (2001), as well as by observations by the authors from site visits and aerial photography that indicates the gates tend to remain open.

Table 3
Measured River Discharges for Modeling Time Intervals, cu m/sec

	San Bernard River		Brazos River	
Time	**Monthly Mean**	**Daily maximum**	**Monthly Mean**	**Daily Maximum**
May 1993	40	140	350	900
Jun 1993	80	240	330	1,120
Jan 1994	5	35	70	170
Aug 1999	5	7	30	38

For the first and second validation intervals, the channel cross-sectional depth and width data were obtained from NOAA nautical charts. For the third interval, the model cross-sectional data were taken from a bathymetric survey conducted by CHL on 8 and 9 August 1999. The depth in the NOAA nautical charts is referenced to mean lower low water (mllw), whereas the CHL survey soundings were to mlt. Depths were converted to mtl for operating the model.

Calculations for the first and second intervals for the existing flow situation were verified with water surface elevation measurements made at the San Bernard and Churchill tide stations (locations shown in Figure 18). Data are available at the San Bernard tidal station from 15 February 1993 to 7 March 1995 and at the Churchill tide station from 4 November 1993 to 19 July 1994. Table 4 lists tidal datum and related information for the two tide stations. The tidal range at Churchill, located considerably north (up river) from the San Bernard station, is 22 percent greater than at the San Bernard station. Evidently, the San Bernard River is of such a length and depth to function as an approximate quarter-wavelength resonator for the tidal wave. A numerical model should capture that property, which requires representation of the river to the point of tide or the river's end.

Figure 19 shows the water surface elevation measured at Galveston Pleasure Pier as the ocean boundary condition and the water level measured at the San Bernard and Churchill tide gauges together with the DYNLET calculations for May-June 1993. Also shown in Figure 19 is the water surface elevation measured at the Bob Hall Pier (27°34'36"N and 97°13'00"W) NOS tide station near Corpus Christi. The phase difference of the water surface elevation is almost negligible between the Galveston Pleasure Pier and Bob Hall Pier tide gauges. A small phase difference indicates the water surface elevation measured at the nearby Galveston Pleasure Pier gauge is adequate for the ocean boundary conditions without phase adjustment.

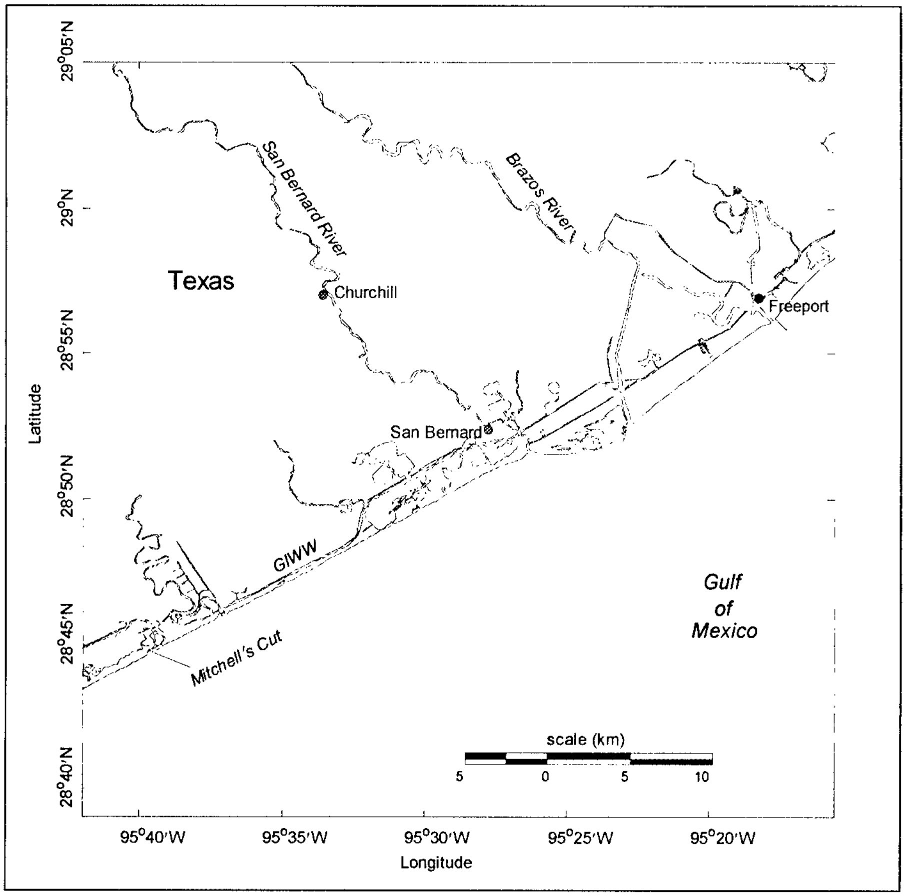

Figure 18. Location map for the San Bernard and Churchill tide gauges

Table 4
Tidal Datums at the San Bernard and Churchill Tide Stations[1]

Quantity or Datum	San Bernard, NOAA 87726891	Churchill, NOAA CBI90050
Latitude	28° 52' 42" N	28° 57' 00" N
Longitude	95° 27' 18" W	95° 33' 18" W
Period of Record	2/93-3/95	11/93-7/94
mhhw, m	0.750	1.309
mhw, m	0.728	1.271
mtl, m	0.613	1.134
mlw, m	0.498	0.997
mllw, m	0.470	0.951
Tidal Range, mhhw-mllw	0.280	0.358

[1] mhhw = mean higher high water; mhw = mean high water; mtl = mean tide level; mlw = mean low water; mllw = mean lower low water.

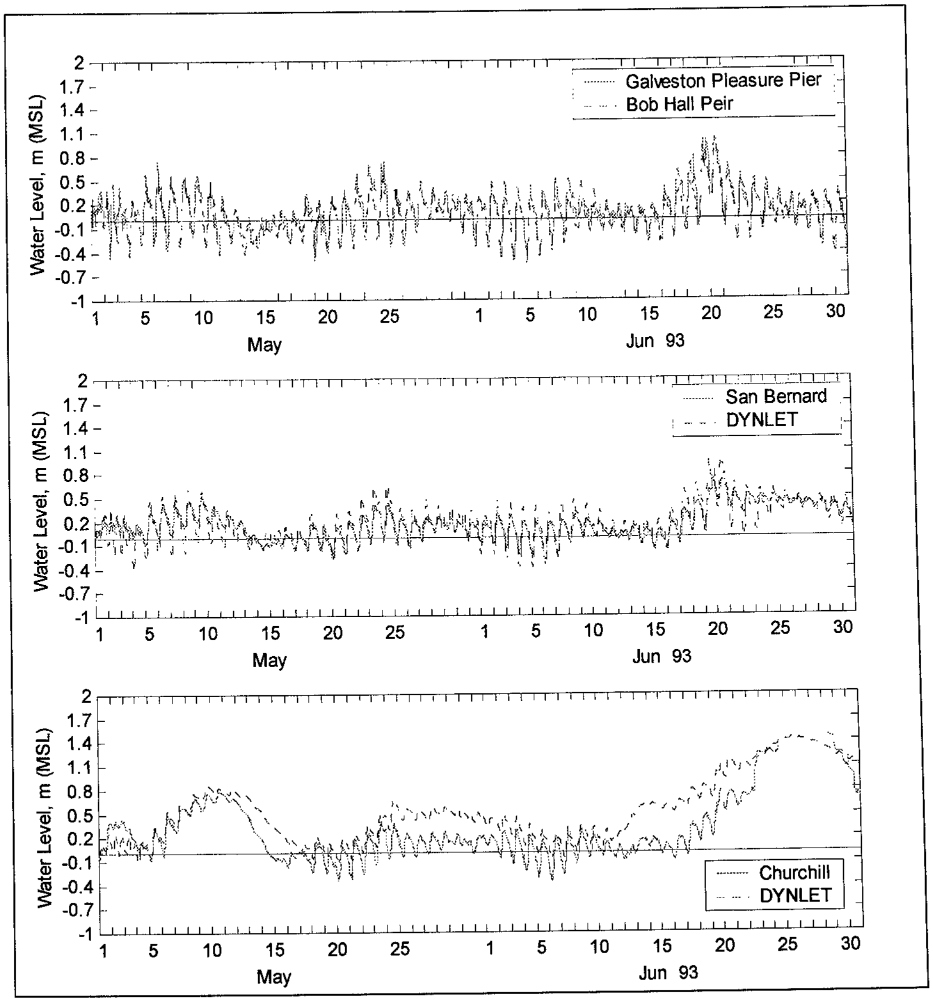

Figure 19. Water surface elevations for May-June 1993

Figure 20 shows the discharge as the input boundary conditions and the discharge at the ocean boundaries for the San Bernard River and the Brazos River. A positive discharge indicates flow directed from the river toward the Gulf of Mexico, and negative discharge indicates flow directed from the Gulf toward the river. Figure 21 shows the water surface elevation measured at Galveston Pleasure Pier and Bob Hall Pier and the water level measured at San Bernard and Churchill tide gauges versus the DYNLET results for January 1994.

Figures 19 and 21 indicate calculations agree moderately well to the water surface elevations measured at the San Bernard and Churchill stations. The magnitude and phase of the signals agree well, and many of the episodic events, which may be caused by storms in the Gulf of Mexico, river discharges, or wind fronts, are often but not always reproduced. The calculated water surface elevation agrees better in the second interval for the dry (weak river flow) condition than in the first interval for the flooding condition. It is more difficult to model a flooding condition because information such as the rate of rainfall and the topography of the flooded area are required in addition to the river discharge input for the model. The calculations could be improved by input of a measured water surface elevation at the Gulf of Mexico boundaries to provide accurate forcing that includes properties of the meteorological conditions experienced locally.

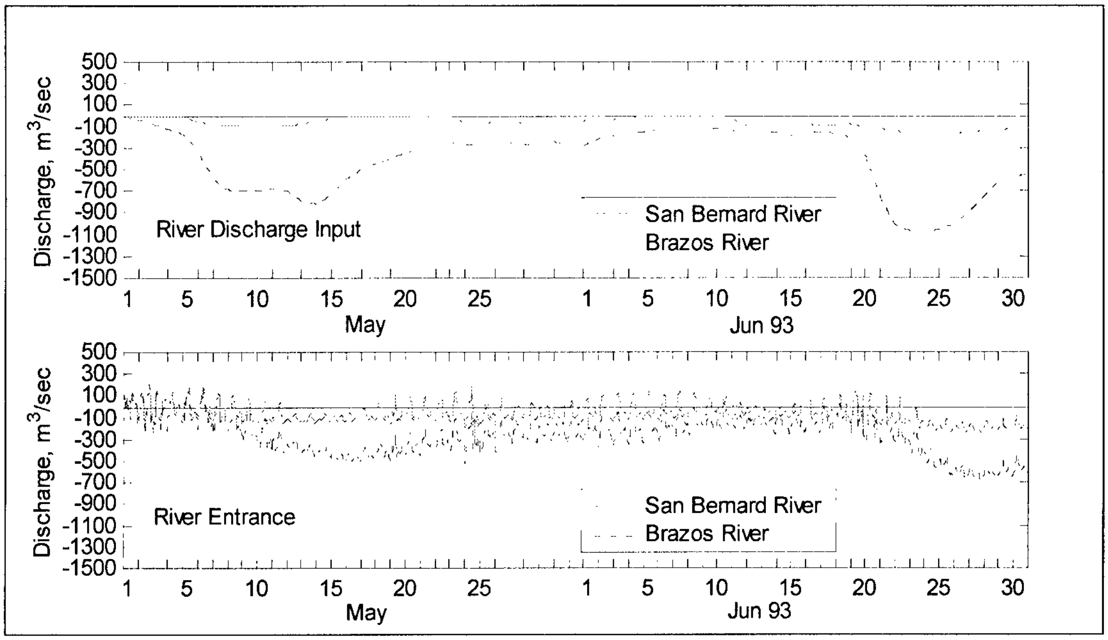

Figure 20. River discharges for May-June 1993

Calculations for the third interval (August 1999) were verified with water surface elevations measured at Stations S04, S06, S12, and S26 (Figure 22) and current data collected at Station S04. Figure 23 compares calculated and measured water surface elevations at Stations S04, S06, S12, and S26, and good agreement is found. Figure 24 compares the calculated and measured current at Station S04. The current was measured for only several hours during daylight in 26 August 1999. Positive values correspond to flood and negative values to ebb.

As a summary of the validation, Table 5 presents the rms error and the percent error, equal to the rms error divided by the tidal range, at each tidal station or location for the three validation intervals. Much of the error is associated with long-duration events not related to the tide.

Calculations for hydrodynamic alternatives

Simulations were conducted to investigate the behavior of the existing flow system and alternative hydrodynamic conditions. Three hydrodynamic alternatives as listed in Table 6 were developed to investigate the potential for improving the flow at the San Bernard River mouth, and a fourth was implemented with river mouth closure. The river mouth is almost closed at the present time, as discussed in Chapter 2.

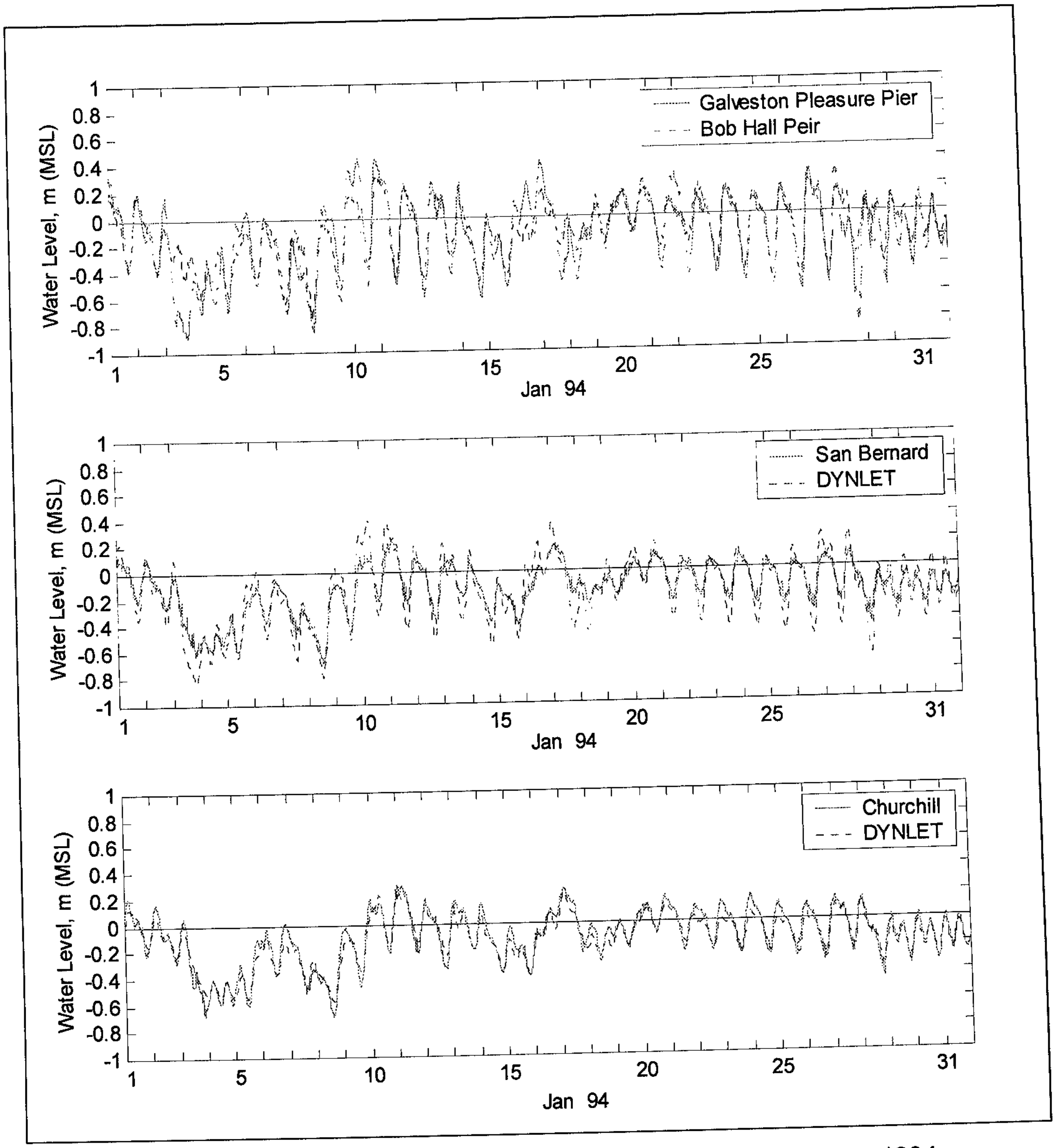

Figure 21. Calculated and measured water surface elevations for January 1994

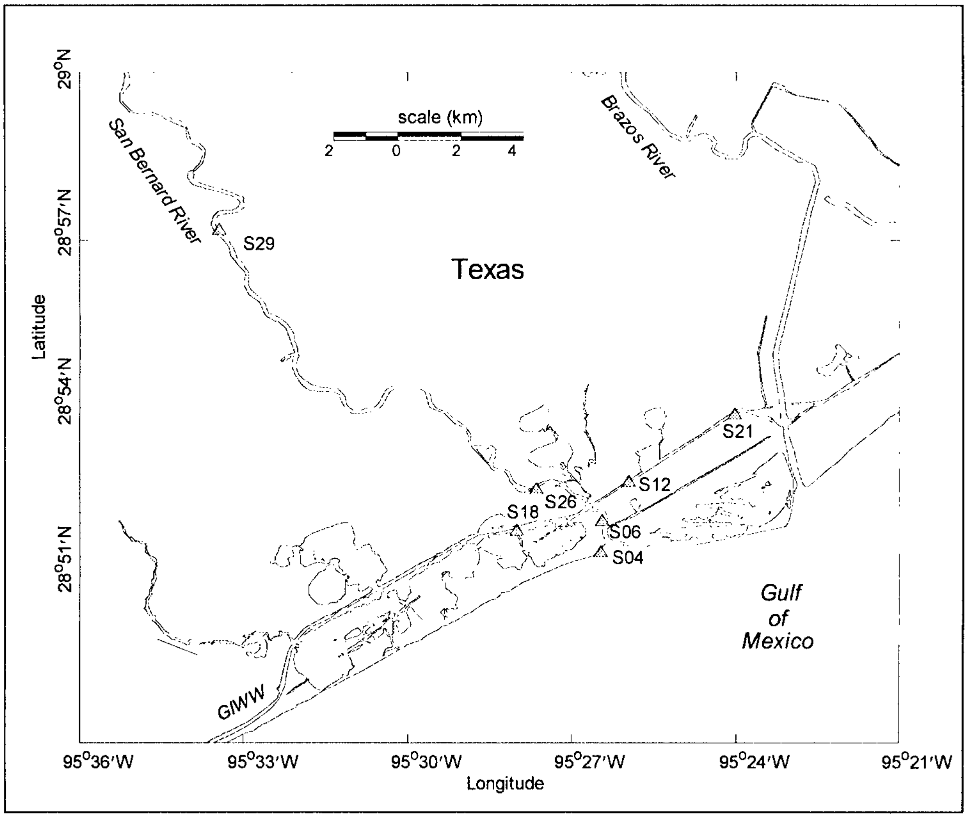

Figure 22. Location map for calculation save locations of interest

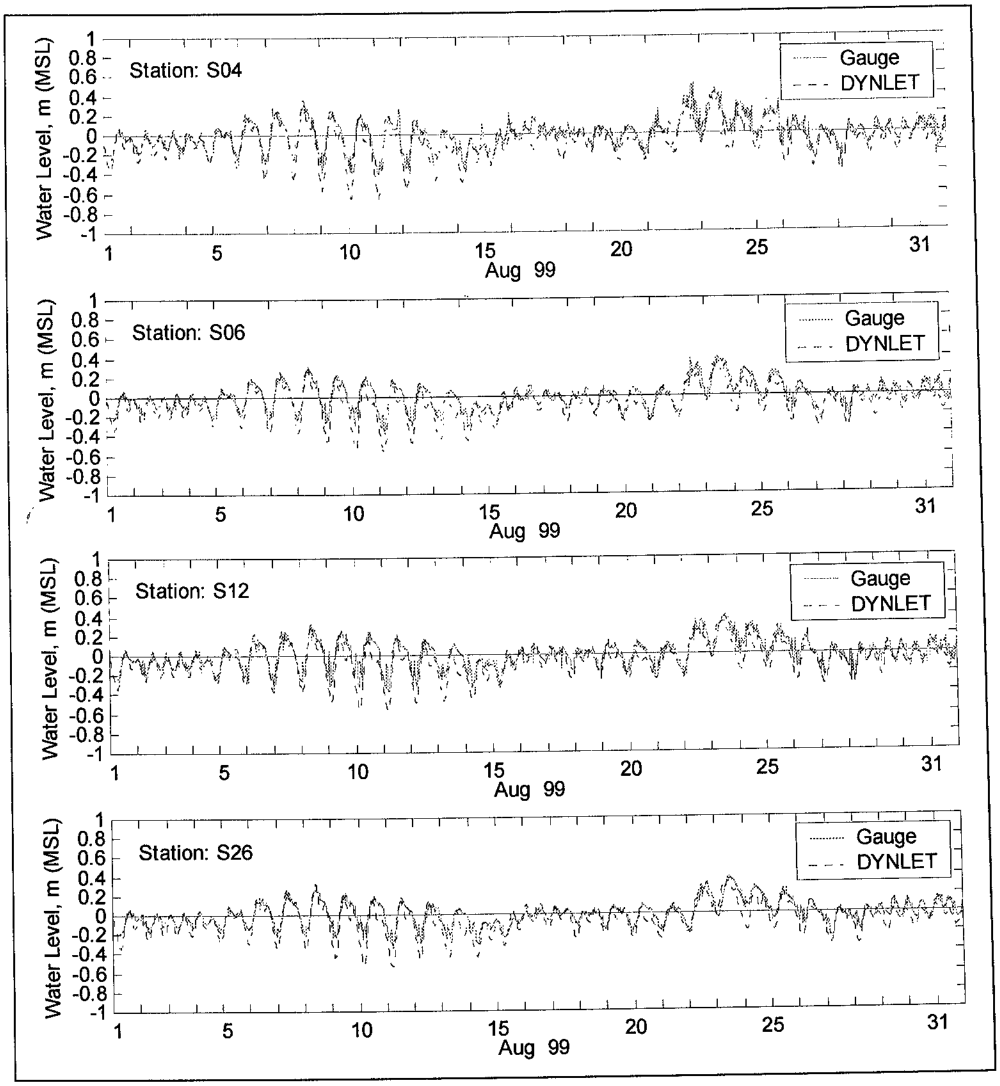

Figure 23. Calculated and measured water surface elevations for August 1999

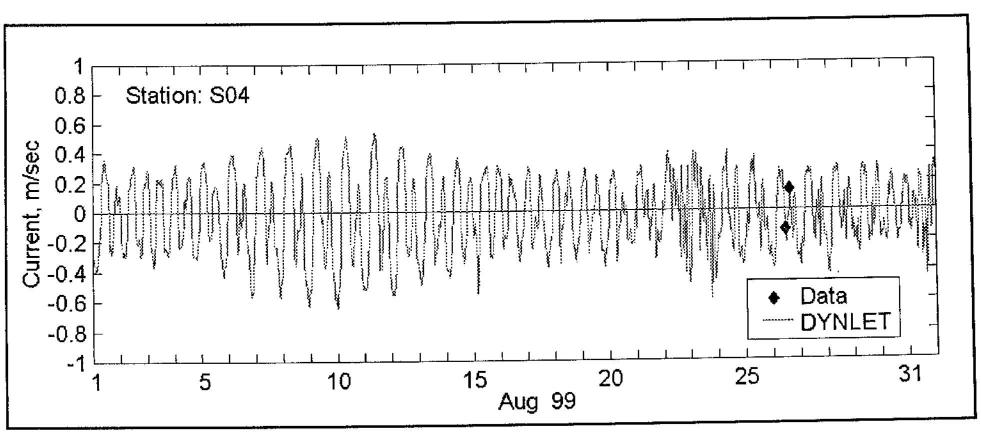

Figure 24. Calculated and measured currents for August 1999

Table 5
Water Surface Elevation RMS Error and Percent Error

Period	Station/Location	RMS Error, m	Percent Error
May-June 1993	San Bernard	0.11	40
	Churchill	0.26	74
January 1994	San Bernard	0.11	37
	Churchill	0.06	17
August 1999	S04	0.12	41
	S06	0.10	37
	S12	0.11	39
	S26	0.10	36

Table 6
River Mouth Hydrodynamic Alternatives

Alternative	Modification
1	Dredge existing San Bernard River to 7.5-ft mlt from the river mouth to the GIWW
2	Dredge new entrance through the spit to 7.5-ft mlt from the mouth to the GIWW
3	Dredge new entrance through the spit to 12-ft mlt from the mouth to the GIWW
4	Close mouth of San Bernard River

The relocated channel was assigned a width of 650 ft, as recommended by Sanchez and Parchure (2001) and calculated based on empirical formulas for a stable inlet (Shigemura 1981). However, the river mouth is not stable, and this width represents an ideal. The width of the river mouth was documented in Chapter 2 from aerial photographs and varied from approximately 1,000 ft in the late 1980's to 200 ft in the late 1990's. Therefore, the 650-ft width is a long-term representative value for a sheltered inlet, which is no longer the situation at the San Bernard River mouth.

Hydrodynamic Alternatives 1-4 were evaluated for the month of August 1999, a typical dry month (Table 7). Calculated water surface elevation and velocity were saved at all cross section stations at all nodes. To understand the flow for the existing conditions and alternatives, calculations were examined at five key locations (Figure 17). These are (Figure 22): (a) Station S06 in the channel between the junction of San Bernard River and GIWW to the mouth of the river, (b) S26 at the San Bernard tide station, (c) S18 in the GIWW about 2 km west of the junction of the San Bernard River, (d) S12 in the GIWW about 2 km east of the junction of the San Bernard River, and (e) S21 in the GIWW located about 3 km west of the intersection with the Brazos River.

Table 7
Average of Local Maxima of Tidal Flood and Ebb Discharges at the River Mouths, cu m/sec

Hydrodynamic Alternative	San Bernard River		Brazos River	
	Flood	Ebb	Flood	Ebb
Existing	41	34	119	126
Alternative 1	69	68	110	117
Alternative 2	70	70	110	116
Alternative 3	89	98	103	109

Figure 25 compares calculated water surface elevations at Station S06 for the existing flow system and with the flow for Alternatives 1-4. Figures 26-29 compare the water surface elevations at S12, S18, S21, and S26, respectively. Figure 30 compares calculated channel centerline currents at Station S06 for the existing flow system and for Alternatives 1-4. Figures 31-34 compare the channel centerline currents at Stations S12, S18, S21, and S26, respectively. Only 15 days of calculated currents ae shown in Figures 30-34 to more clearly distinguish the differences for comparison of alternatives.

Table 7 summarizes the average of the local maxima of flood discharge and ebb discharges at Station S04 for the San Bernard River and the corresponding station at the Brazos River mouth. Figure 35 compares calculated discharges at Station S06 for the existing flow system and Hydrodynamic Alternatives 1-3. Because August 1999 was a dry month, these values correspond primarily to tidal exchange, and the discharge associated with the tide can be compared to selected river discharges listed in Table 3. Both Table 7 and Figure 35 show that the San Bernard River mouth is presently flood dominant. Alternatives 1 and 2 change the mouth to neutral dominance, and deepening the relocated mouth for Alternative 3 produces ebb dominance by the tide.

For most of the year, the tidal discharge exceeds the fluvial discharge at the San Bernard River. In contrast, the tidal discharge typically exceeds the fluvial discharge at the Brazos River from July through December, but during the remainder of the year the fluvial discharge dominates the tidal discharge by as much as a factor of 10 to 20. It can be concluded that river discharge is dominant for stability at the Brazos River mouth, whereas stability of the San Bernard River mouth is mainly controlled by tidal discharge. Whatever the tidal dominance, a flood shoal is expected to occur at the San Bernard River mouth because the discharge is relatively weak.

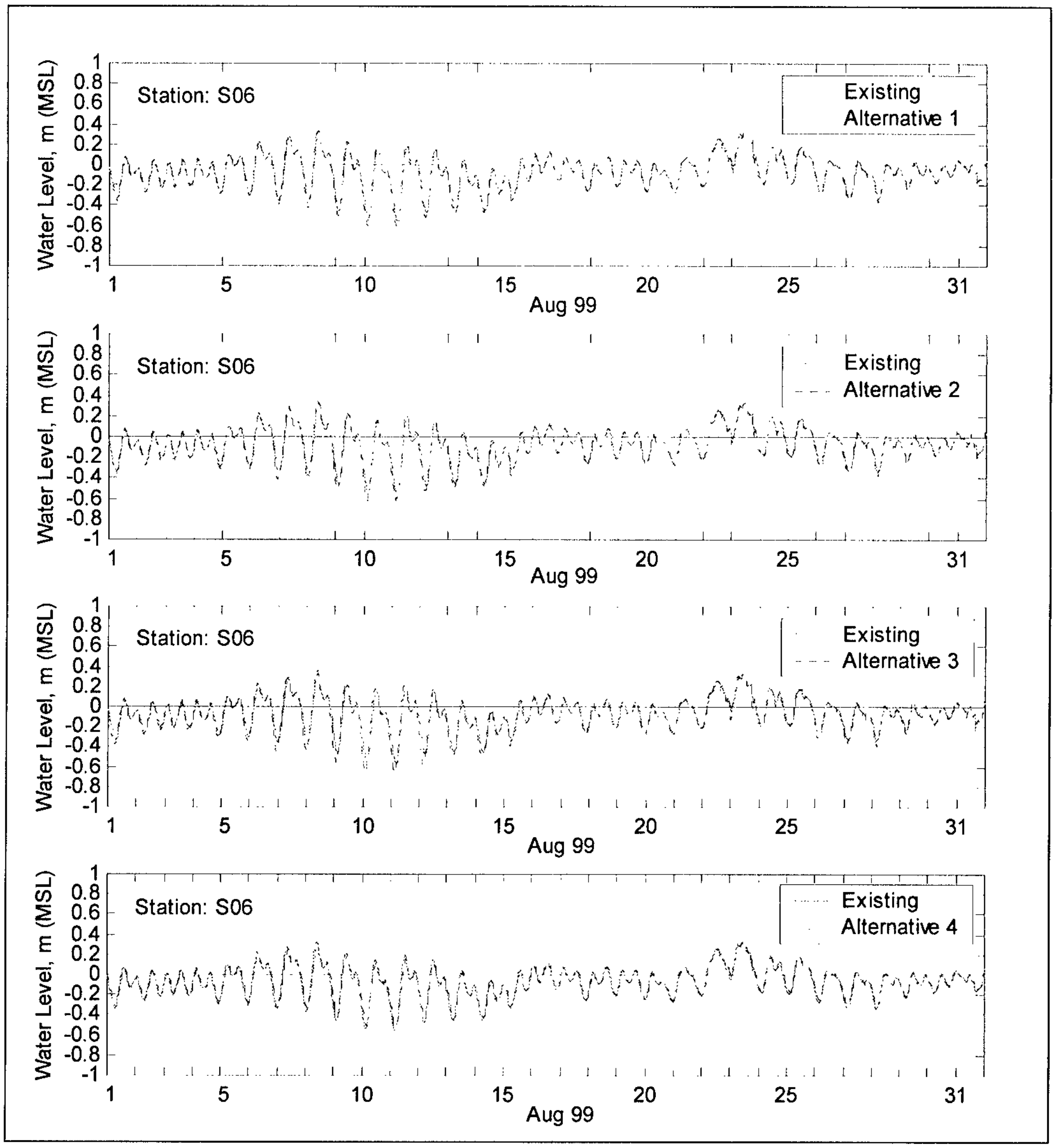

Figure 25. Water surface elevation at Station S06 for August 1999

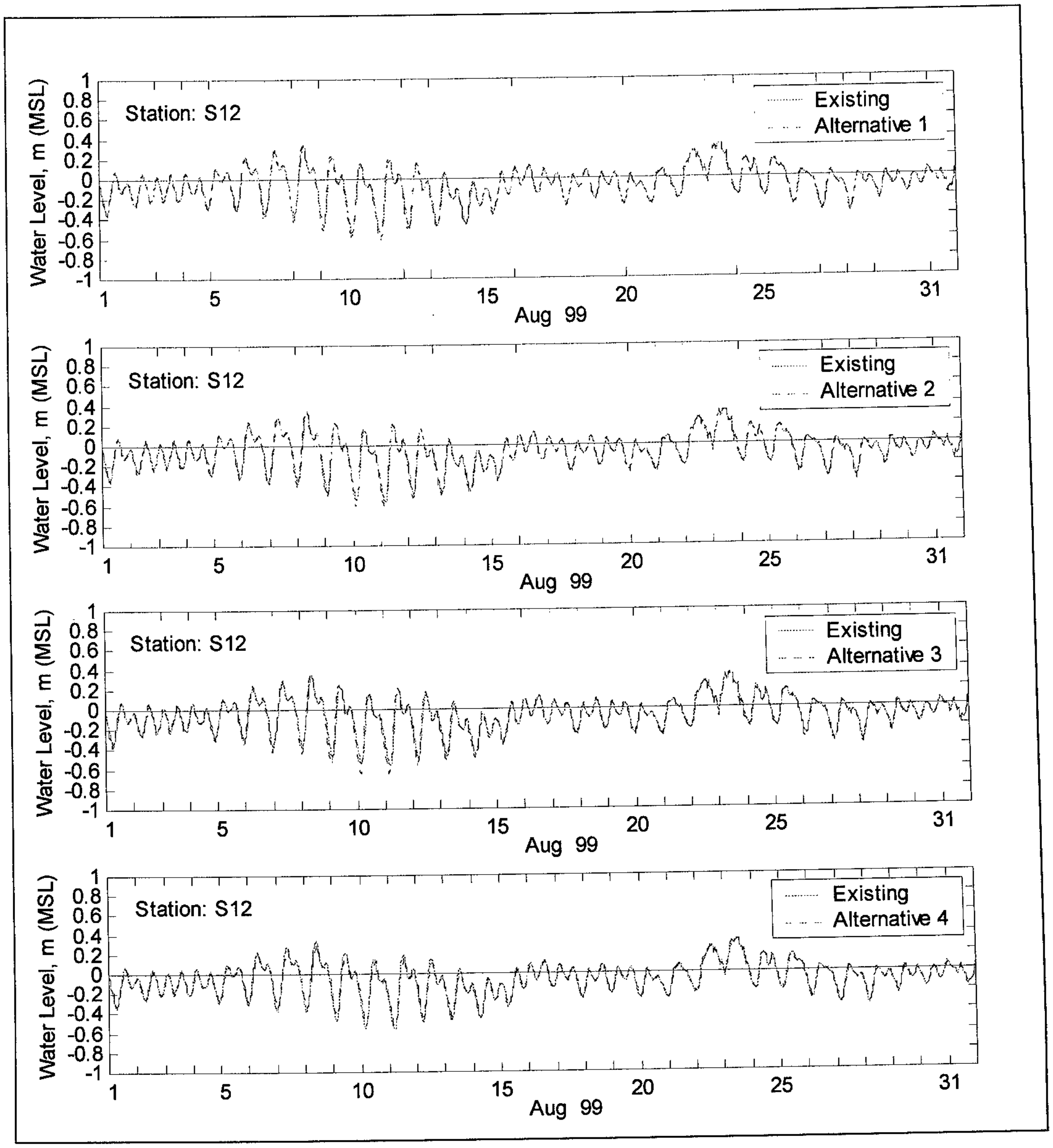

Figure 26. Water surface elevations at Station S12 for August 1999

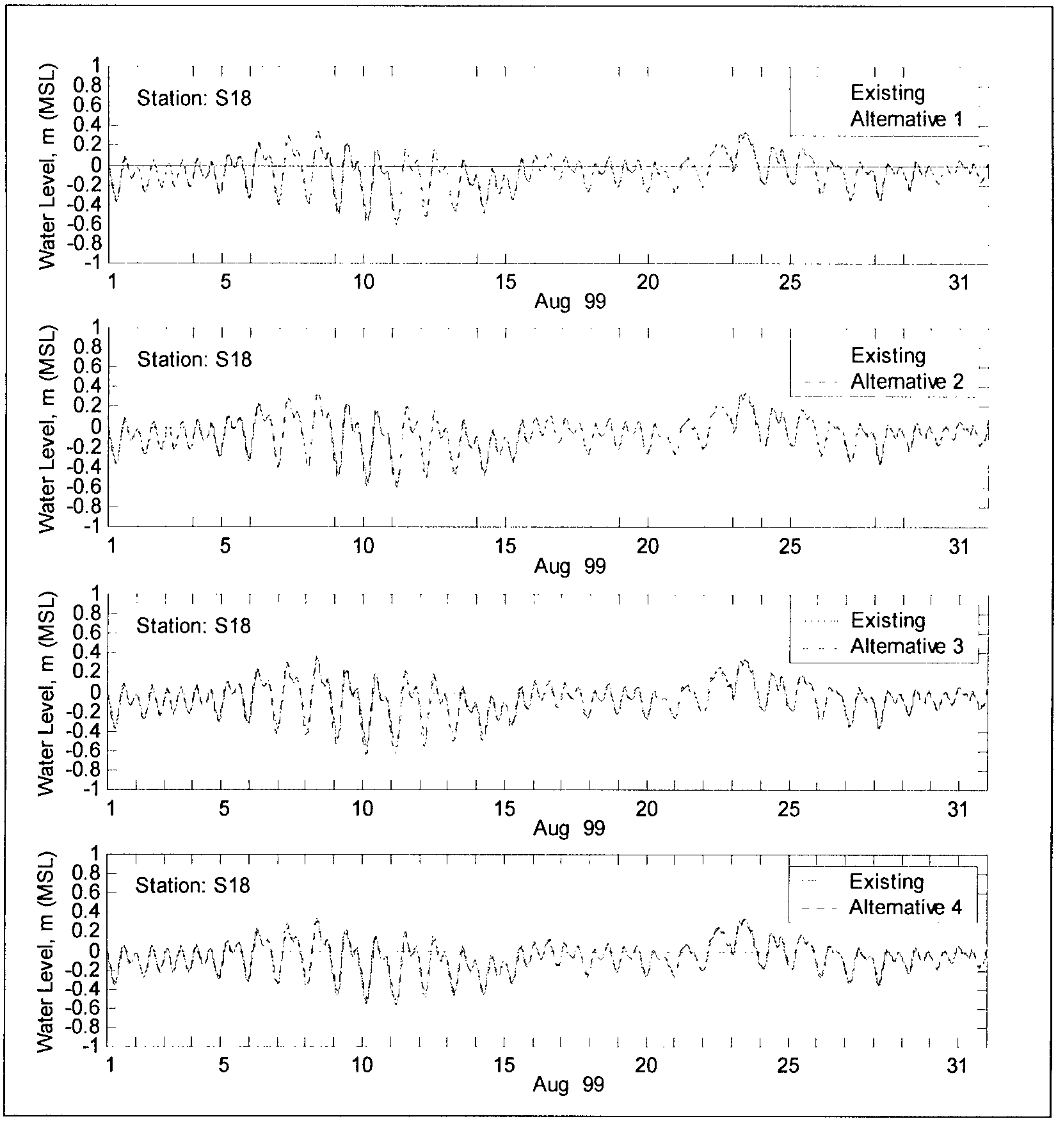

Figure 27. Water surface elevation at Station S18 for August 1999

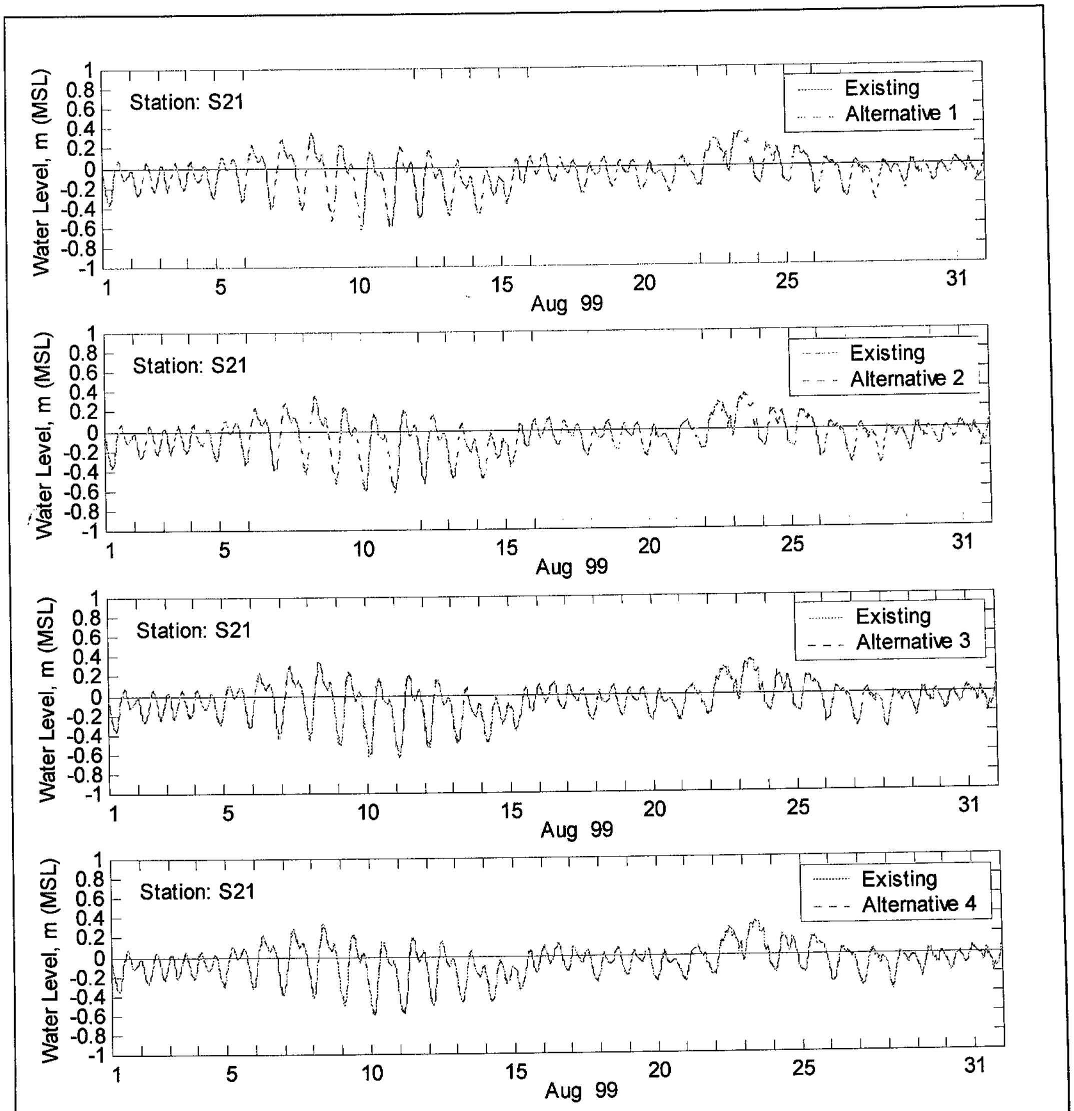

Figure 28. Water surface elevation at Station S21 for August 1999

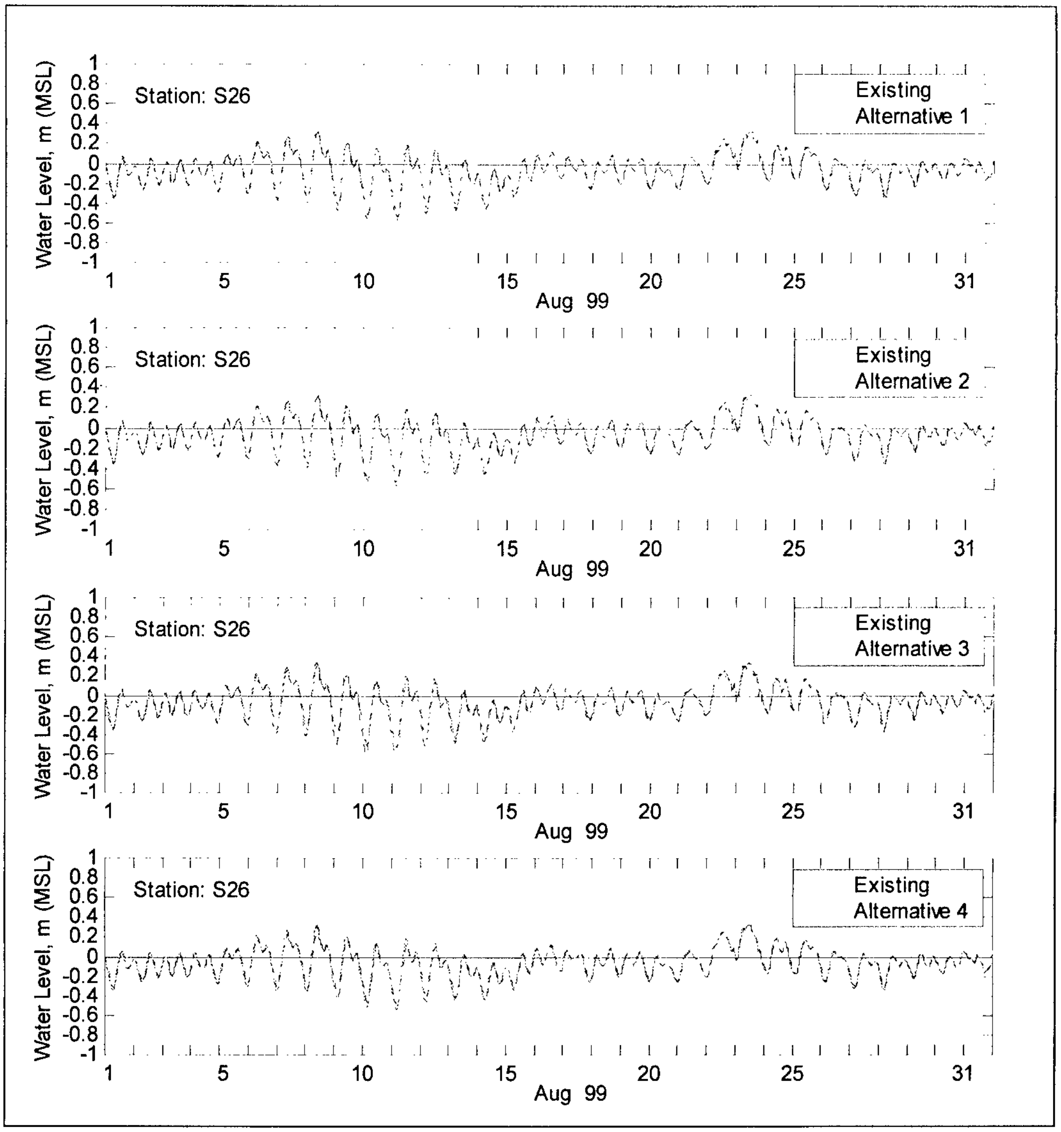

Figure 29. Water surface elevation at Station S26 for August 1999

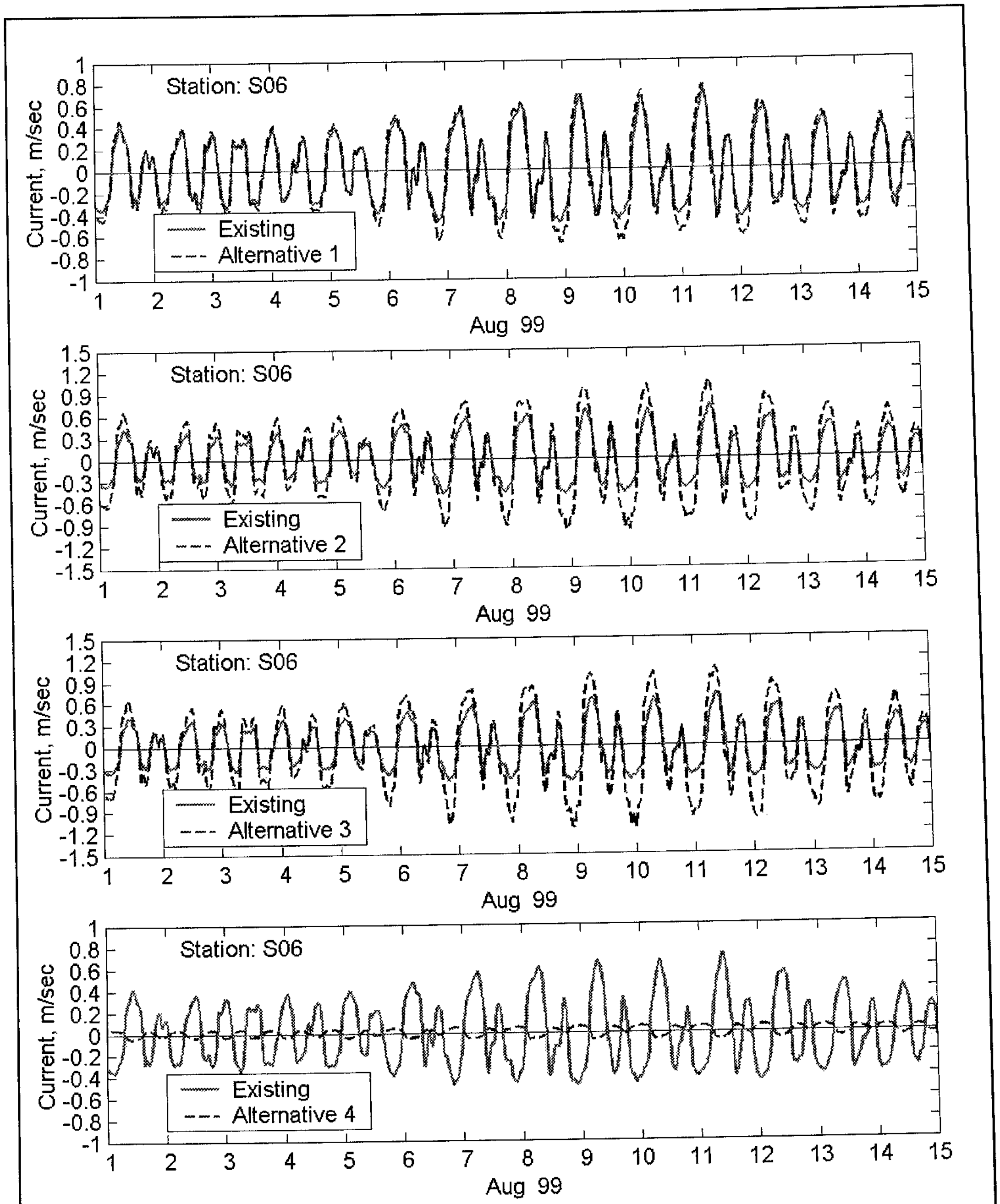

Figure 30. Calculated current at Station S06 for 1-15 August 1999

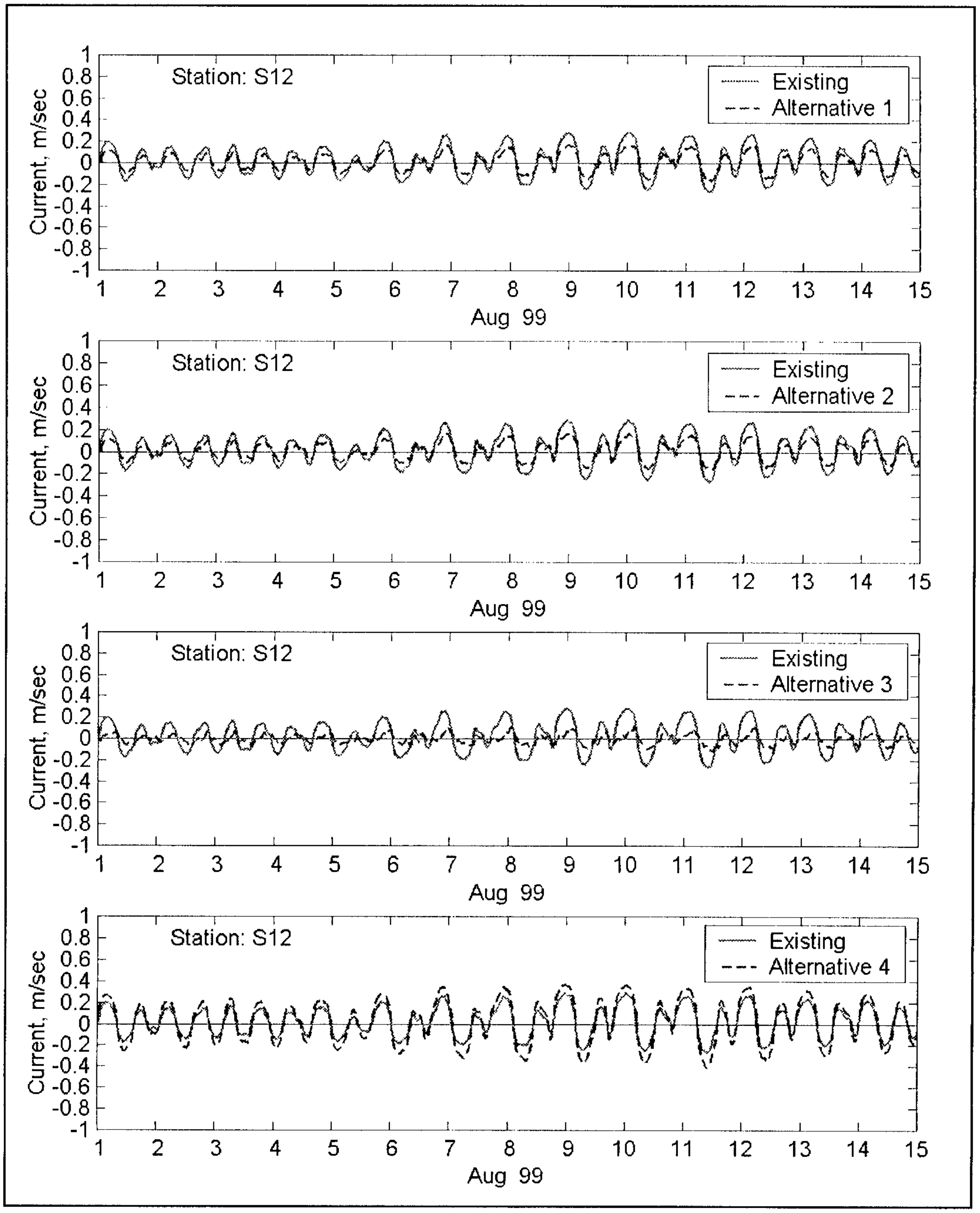

Figure 31. Calculated current at Station S12 for 1-15 August 1999

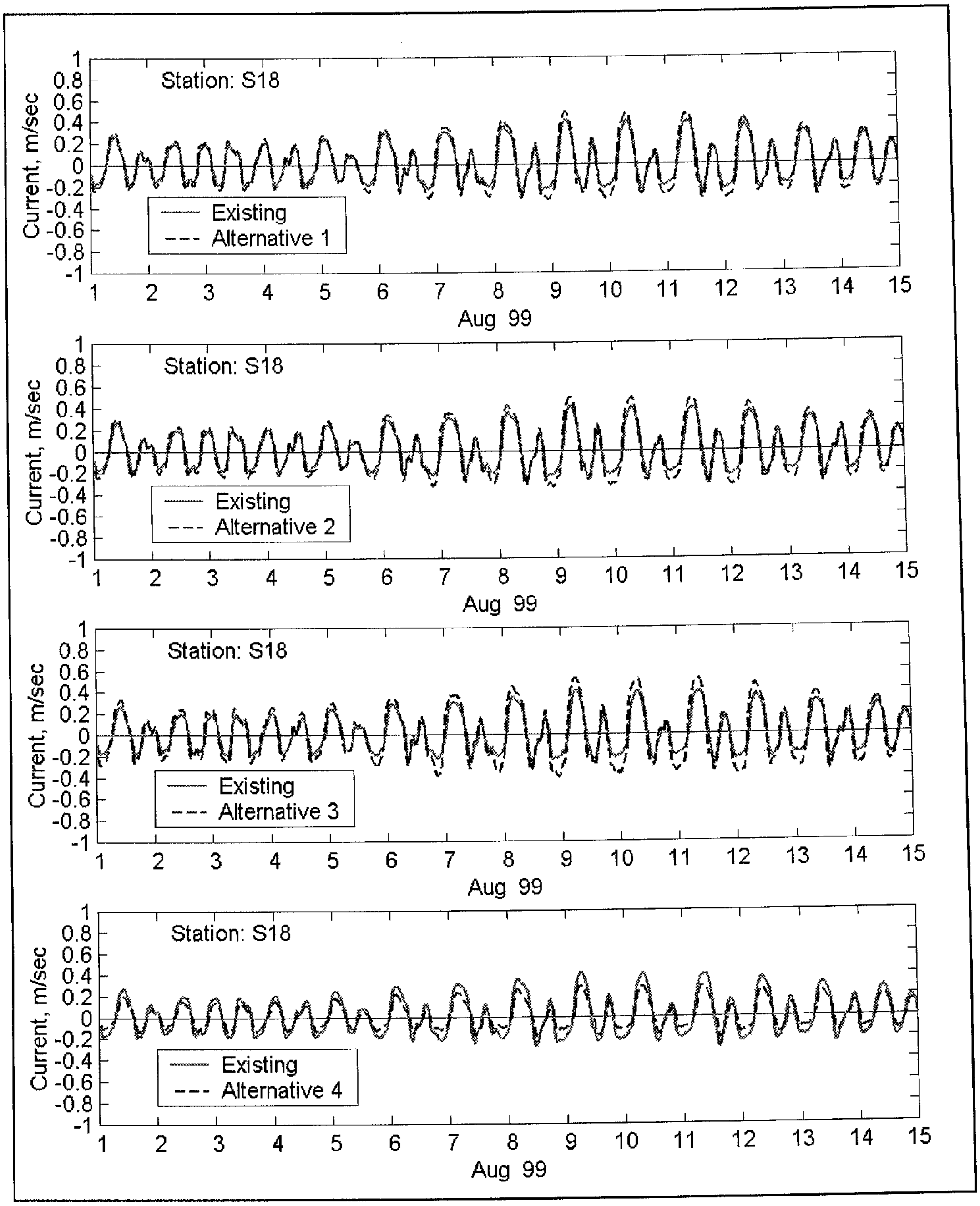

Figure 32. Calculated current at Station S18 for 1-15 August 1999

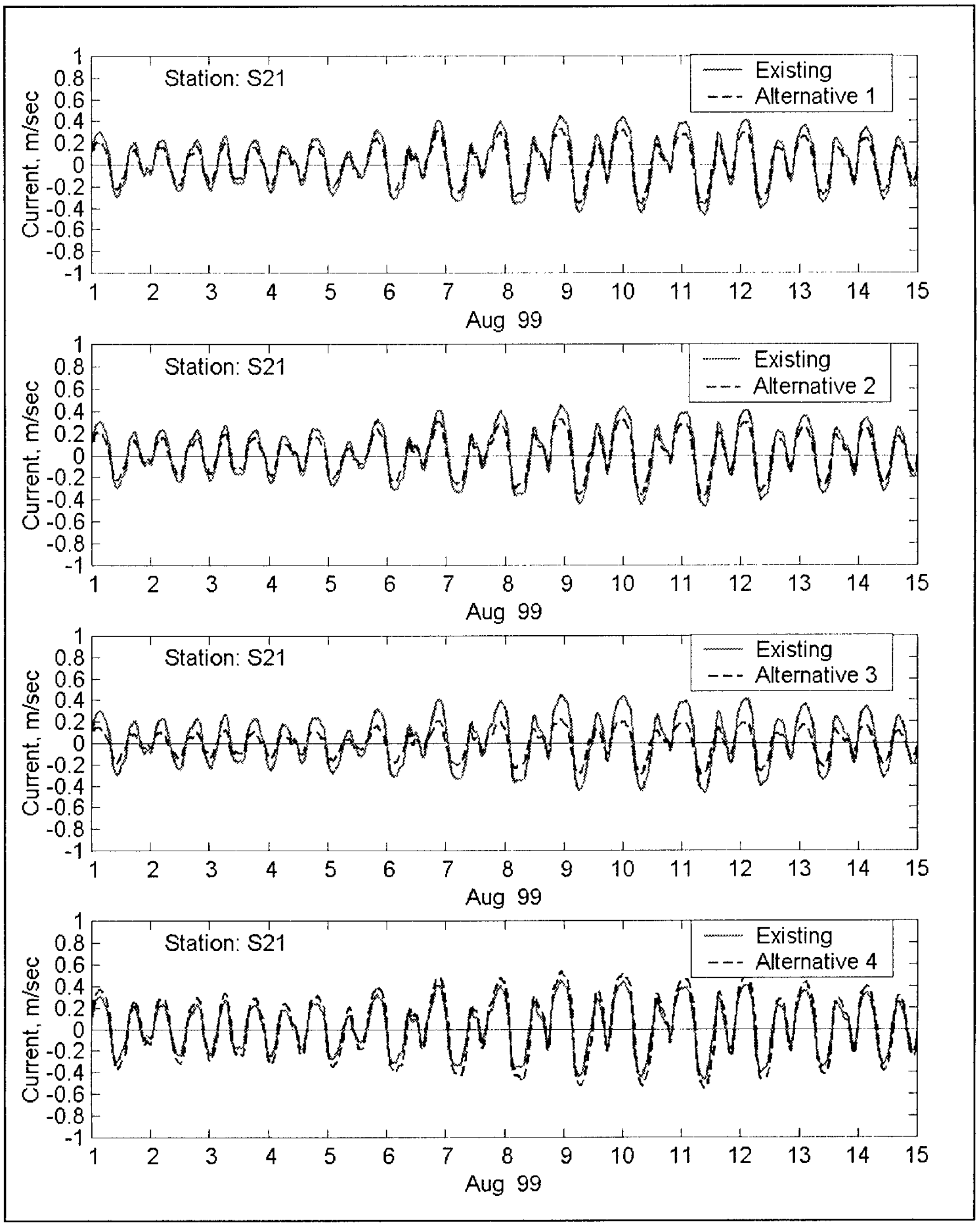

Figure 33. Calculated current at Station S21 for 1-15 August 1999

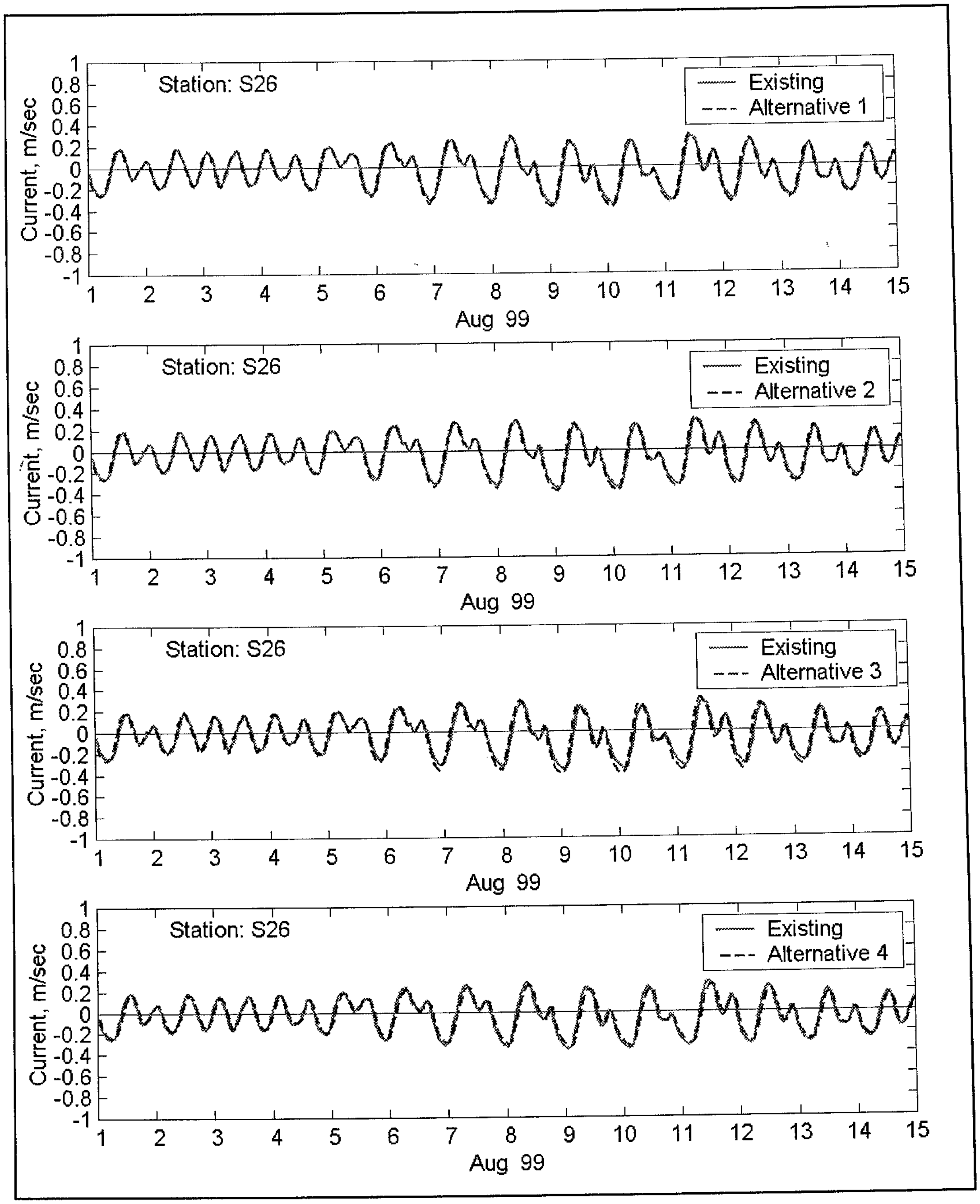

Figure 34. Calculated current at Station S26 for 1-15 August 1999

Figures 25-29 show that the calculated water-surface elevations for Hydrodynamic Alternatives 1-4 are almost identical to those of the existing system, with water level range for Alternatives 1-3 slightly increased. However, slight changes in water surface elevation can greatly change the current velocity. Figure 35 indicates that the current velocity at Station S06 near the mouth of San Bernard River increases significantly (note scale change on vertical axes), with the ebb current velocity almost doubling for Hydrodynamic Alternatives 2 and 3 as compared to the existing condition. The current at S06 for the existing condition is flood dominant. For Alternatives 2 and 3, the current becomes stronger and significantly ebb dominant. For Hydrodynamic Alternative 2, the ebb velocity approaches and, for Alternative 3, occasionally exceeds 1 m/sec. A mean maximum ebb velocity of slightly greater than 1 m/sec is an empirical criterion (O'Brien 1966) for inlet channel stability. This criterion may not strictly hold for river mouths that deliver sediment.

Figures 31 and 33 show that the current at S12 and S21 (both located in the GIWW east of the intersection with the San Bernard River) is reduced for Hydrodynamic Alternatives 1-3, whereas it increases for Hydraulic Alternative 4 (closed mouth). This result indicates that relocation of the San Bernard River mouth will reduce the current velocity in the GIWW where vessels are leaving or entering the locks on the Brazos River, whereas allowing the mouth to close will increase the current, agreeing with conclusions reached by Sanchez and Parchure (2001).

From Figure 32, the current at S18 (in the GIWW west of the intersection with the San Bernard River) increases for Alternatives 1-3, particularly increasing in magnitude of the easterly flow, whereas it decreases for Alternative 4. Figure 34 shows that the four altnernatives do not significantly change the current at S26 (San Bernard River, north of intersection with the GIWW). Modifications in channel location and depth made in Alternatives 1-4 have little influence on the flow conditions in the San Bernard River north of the junction with the GIWW, because the river becomes wider and deeper as compared to the stretch from the GIWW to the river mouth and to the GIWW.

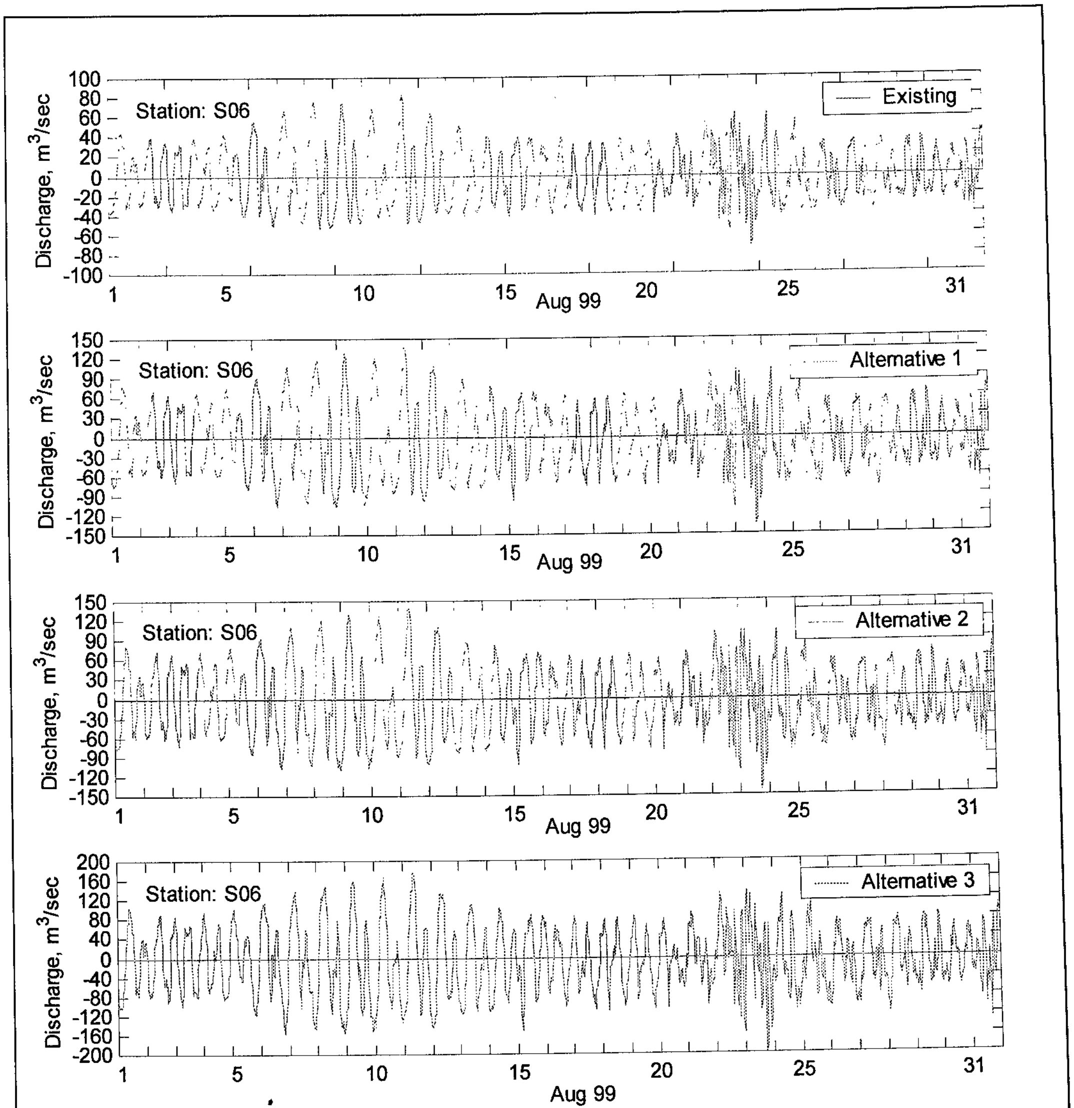

Figure 35. Calculated discharge at Station S06 for August 1999

Wave Model

WISWAVE is a second-generation discrete directional spectral model in which wave and swell computations are based on integration of wave energy components over the discrete frequency spectrum. Calculations are made on a finite-difference grid to simulate the generation, dissipation, and propagation of water waves by wind, including wave-wave interactions. WISWAVE reads in a computational depth grid, wind speed and direction over the model domain, and given wave conditions along the outer boundary of the grid. The model calculates time series of significant wave height, peak (dominant) period, mean wave period, mean wave direction associated with the peak period, and directional spectra at selected output locations. Significant wave height is defined as four times the square root of the total energy content. Peak period is defined as the period associated with the largest energy component in the frequency band. Mean wave period is the energy-weighted average of period over all frequency bands. Mean wave direction is the energy-weighted average of direction associated with the peak period. These quantities are tabulated below.

Wave information for the vicinity of the San Bernard River mouth was available from a recent hindcast made at CHL by WISWAVE for the Gulf of Mexico for the period of 1990-1999. The hindcast was conducted on a nest of two distinct grids: a 1/4-deg coarse grid to cover the entire Gulf of Mexico and Caribbean Sea, and a 1/20-deg fine grid to cover the coast occupied by the San Bernard River and Brazos River. Figure 36 shows the computational domains of the coarse grid and fine grid. The water depths in the coarse grid were obtained from the Digital Bathymetric Data Base 5-min (DBDB5) data set compiled by the U.S. Naval Ocean Research and Development Agency (NORDA) and the Naval Oceanographic Office (see http://ingrid.ldeo.columbia.edu/descriptions).

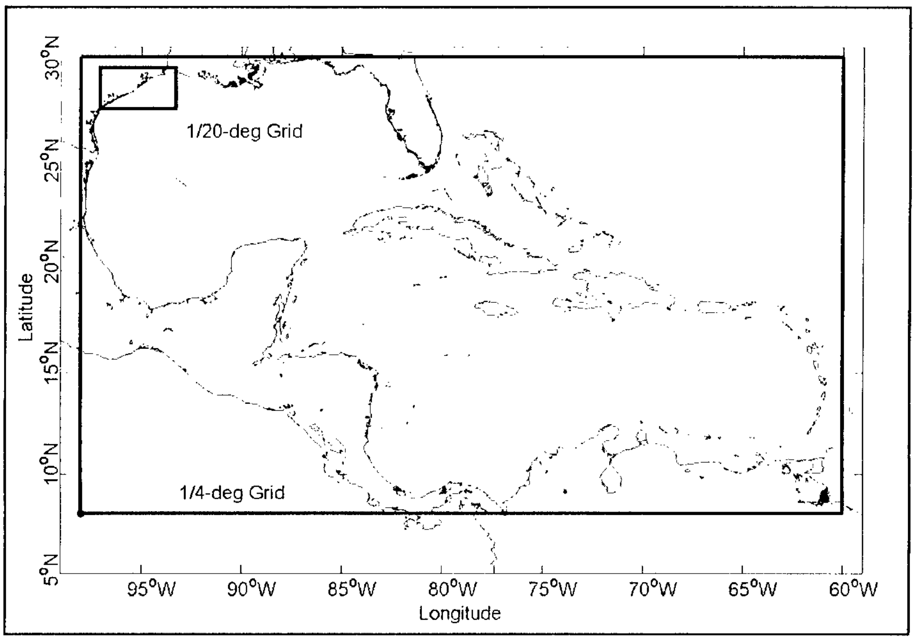

Figure 36. Wave model domains

Depths in the fine grid were taken from the Digital Nautical Chart (DNC) database produced by National Imagery and Mapping Agency, described at the Worldwide Web address (http://www.nima.mil/publications/specs/printed/DNC/dnc.html). The wave hindcast was conducted separately for each of the two model domains in the order of the coarse grid domain first and the fine grid domain next. Directional wave spectra computed from the coarse grid were saved along the boundary of the fine grid to provide incident wave conditions in the fine grid.

The wind input information was from two sources: (a) a reanalysis project conducted by the NOAA National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research, and (b) WIS Gulf of Mexico Wind Database for 1960-1999 (GOM40) developed recently by CHL. The NCEP reanalysis project winds are the global wind field data set available at 6-hr intervals with a resolution of approximately 1.8 deg (Kalnay et al. 1996). GOM40 covers only the Gulf of Mexico at 1-hr intervals, with 1/4-deg resolution. It includes tropical events as simulated from the Planetary Boundary Layer (PBL) wind field model (Cardone, Greenwood, and Greenwood 1992). The GOM40 and NCEP reanalyzed winds were combined as the wind input information to the hindcast that GOM40 used for the Gulf of Mexico, and the NCEP reanalyzed winds were input for the Caribbean Sea area.

Model validation

The WIS hindcast was compared to wave measurements available from Buoy 42019 maintained by the National Data Buoy Center (NDBC). The WIS hindcast wave height was adjusted for the winter, spring, and fall seasons to approach the mean as given by the buoy. Figure 37 shows the location of Buoy 42019 and a nearest save point from model at WIS 42019. Table 8 summarizes background information on NDBC Buoy 42019, and Table 9 lists seasonal and annual statistics from the hindcast and from measurements at Buoy 42019 for the period 1990-1999. Wave direction is in the meteorological convention, i.e., 0 deg corresponds to waves incident from the north, 90 deg from the east, etc. Because directional wave measurements are available at Buoy 42019 for 1997-1999, the mean wave direction can be compared only for this period. From April to September, mean direction is from almost southeast, whereas from October to March, mean direction is east southeast, which would tend to move sediment to the west for a local shoreline orientation estimated to be 60 deg east of north as at the San Bernard River mouth.

Both the hindcast results and the buoy data are available at 1-hr intervals. However, buoy measurements are not as complete as hindcast because buoys require occasional maintenance. In Table 9, the hindcast contains 87,648 records, and buoy measurements contain 66,441 records for 1990-1999. The statistics demonstrate that the hindcast follows the trend in the buoy measurements. Figure 38 shows an example of time series from the hindcast and the buoy measurements for August-October 1999. Figure 39 gives wave roses from the hindcast and buoy measurements for 1997-1999, and Figure 40 summarizes monthly mean wave height for the 10-year period 1990-1999, from which seasonality in the waves is evident.

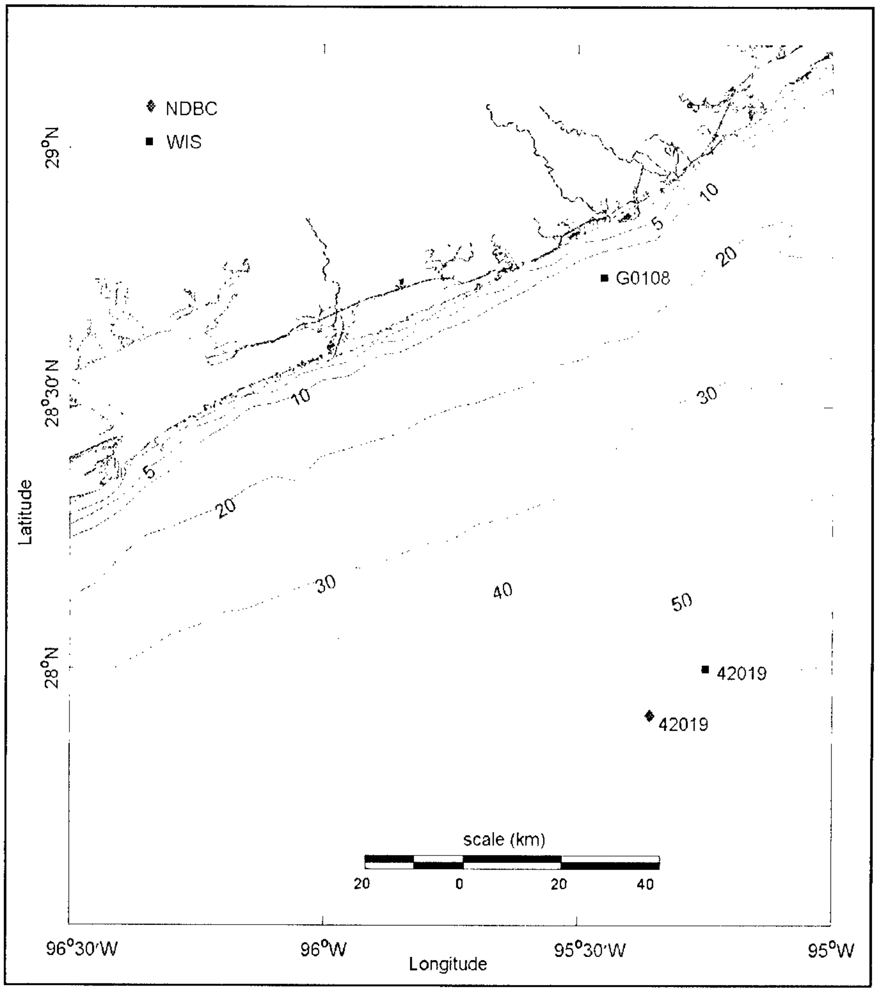

Figure 37. Location map for NDBC 42019 and WIS 42019, G0108 (depth in meters)

Table 8
NDBC Buoy 42019 Information

Buoy ID	42019
Latitude	27°54'36"N
Longitude	95°21'36"W
Depth, m	82
Period of Record	5/90-12/99
Directional Wave Measurements	2/97-12/99

Table 9
WIS 42019 and Buoy 42019 Wave Statistics, 1990-1999

Parameter	Station	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Annual
Mean Significant Height, m	WIS 42019	1.49	1.26	0.93	1.50	1.29
	Buoy 42019	1.46	1.21	0.90	1.47	1.26
Maximum Significant Height, m	WIS 42019	4.93	4.01	5.98	4.79	5.98
	Buoy 42019	5.80	4.30	5.40	5.45	5.80
Mean Period, sec	WIS 42019	6.9	6.5	5.8	6.8	6.6
	Buoy 42019	6.8	6.5	6.1	6.9	6.6
Mean Dir, deg (1997-1999)	WIS 42019	123	133	130	95	122
	Buoy 42019	113	136	140	100	124

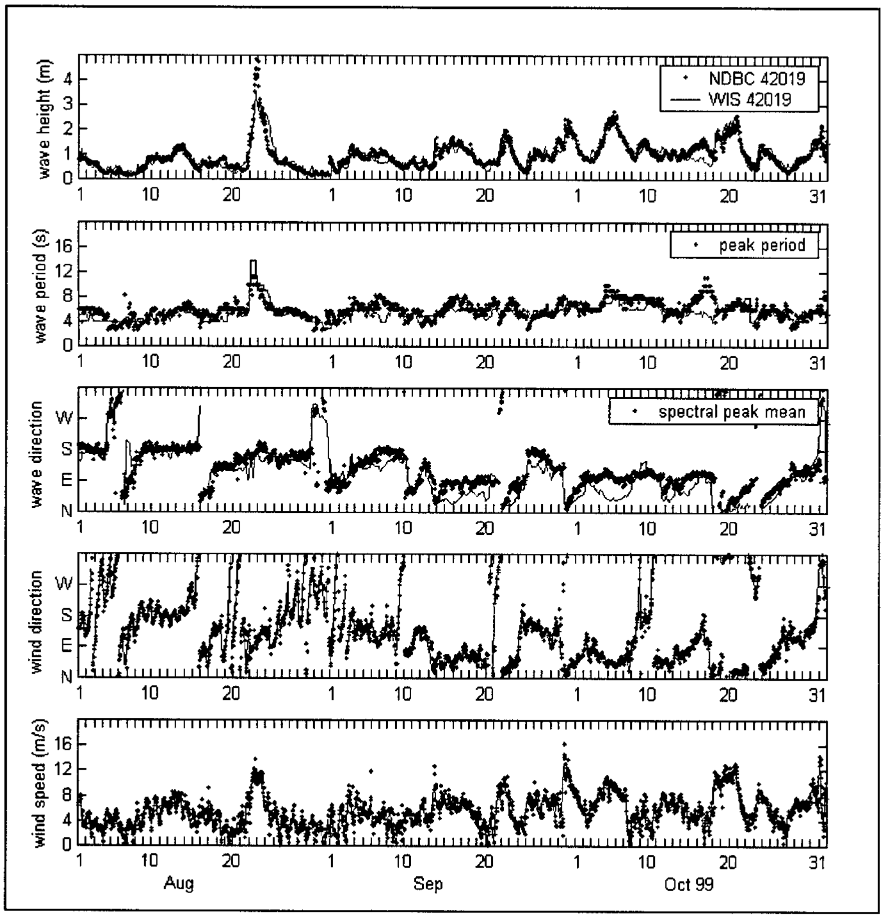

Figure 38. Time series of waves and wind, NDBC 42019 and WIS, August-October 99

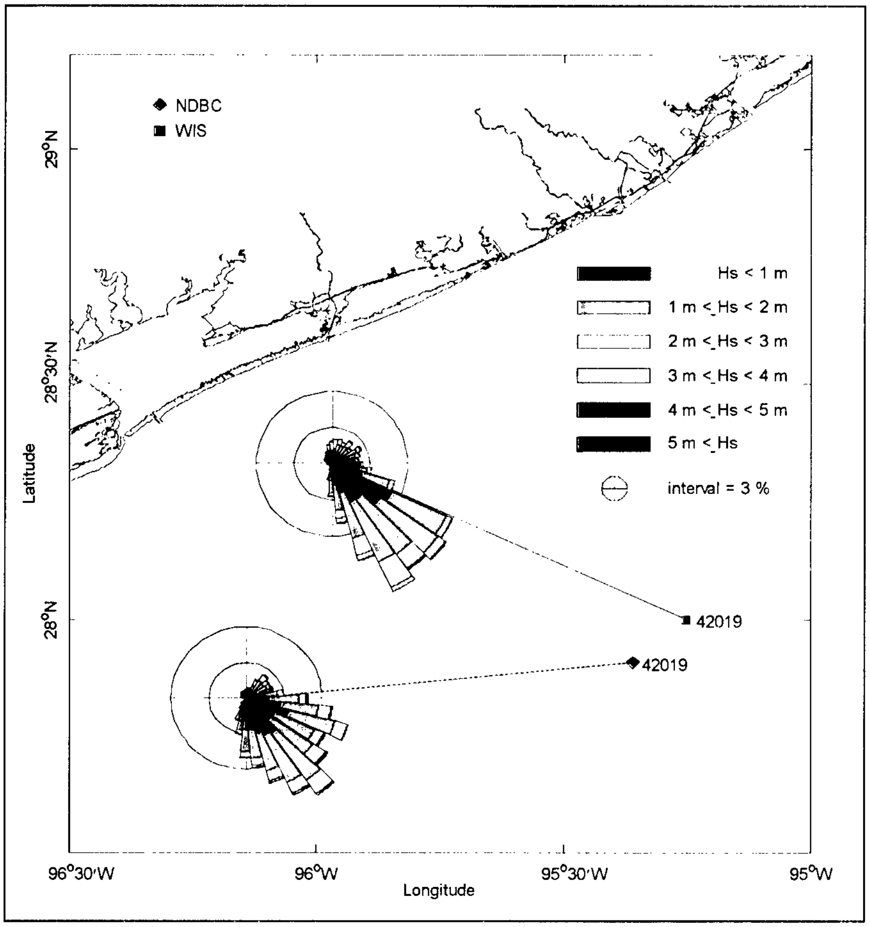

Figure 39. Wave roses for NDBC 42019 and WIS, 1997-1999

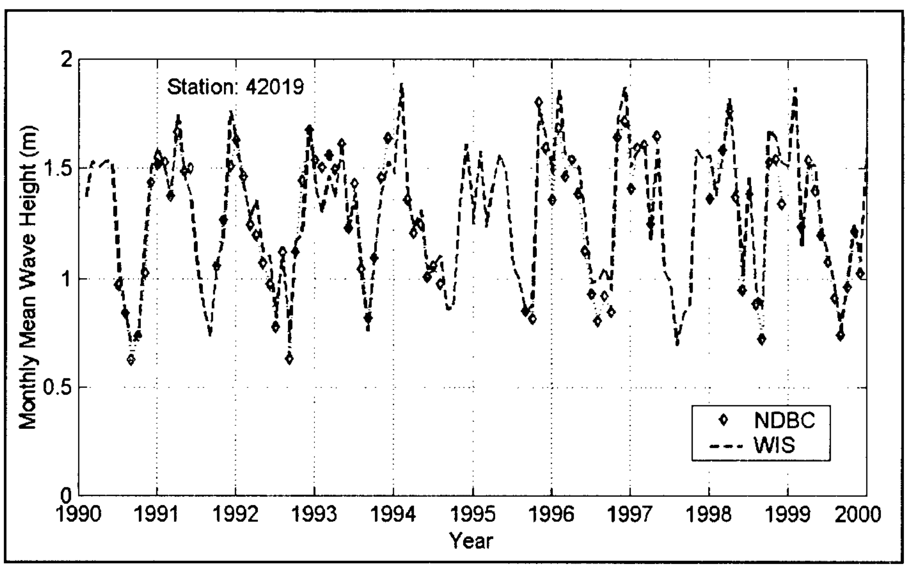

Figure 40. Monthly mean wave height, NDBC 42019 and WIS, 1990-1999

Nearshore wave hindcast

Wave information was propagated and transformed to the 5- and 10-m depths, starting from WIS 42019 and assuming straight and parallel bottom contours. Bottom friction was included in the spectral wave transformation. Figure 41 shows wave information and wind at the two contours for the 3-month period August-October 1999, and Table 10 lists the seasonal and annual nearshore wave statistics for the total record 1990-1999. Wave roses at WIS 42019 and the 10-m depth contour are given in Figure 42.

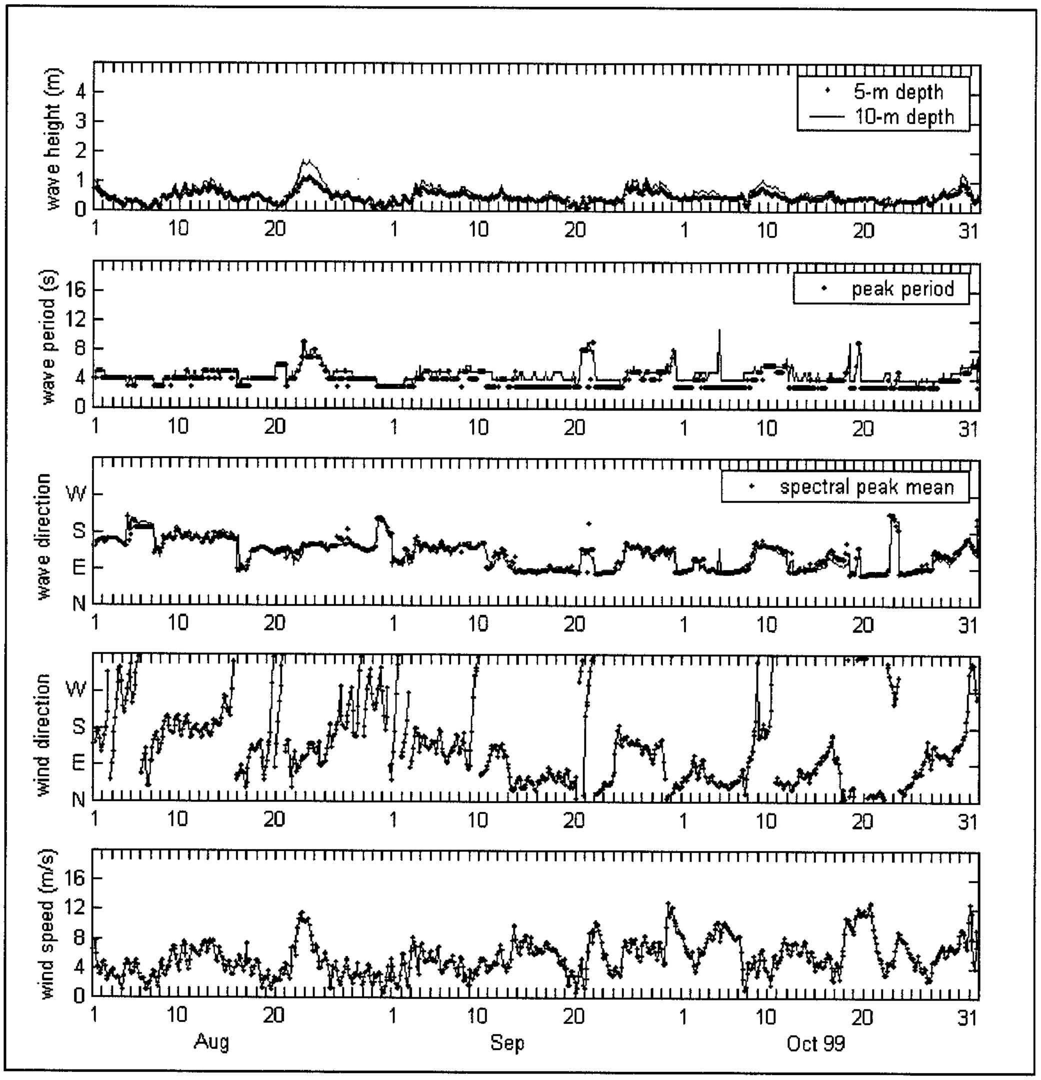

Figure 41. Time series of hindcast wave information at the 5- and 10-m depth contours, 1990-1999, and representative input wind information, August - October 1999

Table 10
Nearshore Wave Statistics at 5- and 10-m Depth, 1990-1999

Parameter	Depth, m	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Annual
Mean Significant Height, m	5	0.59	0.65	0.54	0.58	0.59
	10	0.79	0.88	0.69	0.78	0.78
Maximum Significant Height, m	5	1.43	1.36	1.54	1.39	1.54
	10	2.24	2.06	2.48	2.15	2.48
Mean Period, sec	5	5.7	5.2	4.4	5.3	5.2
	10	6.3	5.8	4.9	6.0	5.7
Mean Dir, deg	5	142	142	142	135	140
	10	141	140	140	134	139

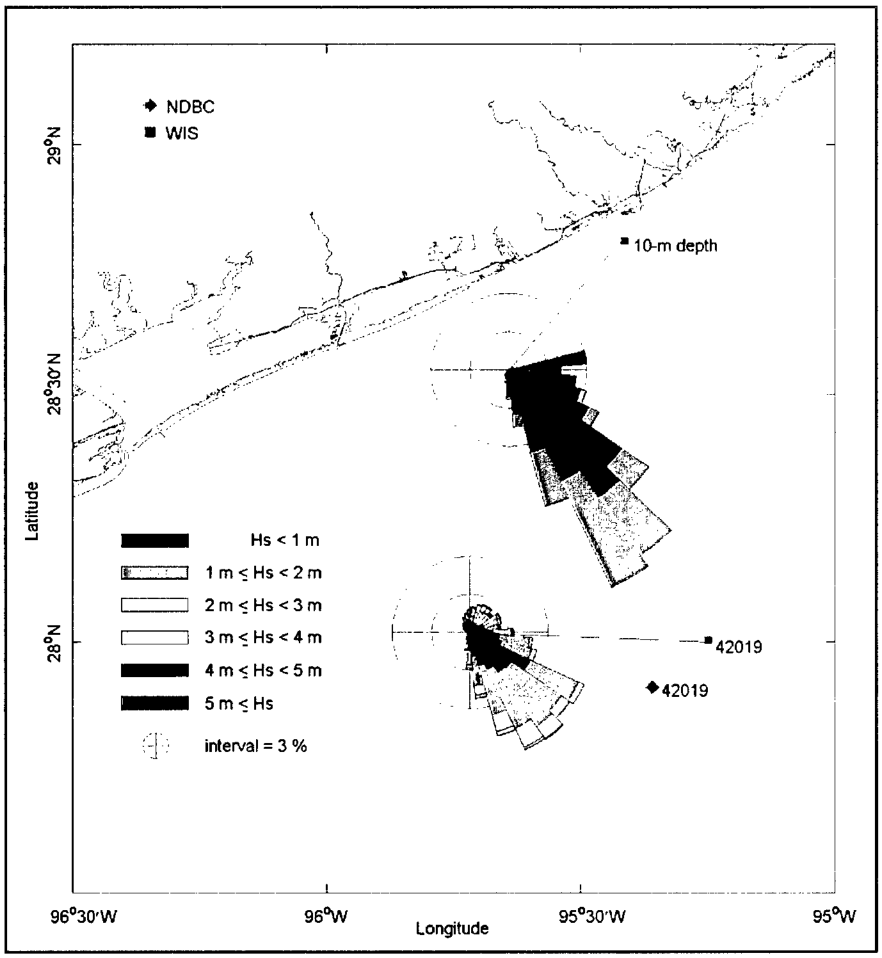

Figure 42. Wave roses for WIS 42019 and the 10-m-depth contour, 1990-1999

The summary statistics for the hindcast of wave height compare favorably with measurements made at the 10-m depth offshore of the Colorado River mouth reported by King and Prickett (1998) for a 17-month period in 1991-1993 containing gaps that would cause a slight underestimate of wave height for the winter months. The nearshore measurements gave a mean significant wave height of 0.6 m and a mean peak period of 5.9 sec. The hindcast mean wave height at the 10-m depth ranges between 0.69 and 0.88 m, whereas height at the 5-m depth ranges between 0.54 and 0.65 m for the 10-year period. Wave direction turns toward shore normal because of refraction. Figure 43 displays the hindcast monthly mean wave height at the two depth contours, for which seasonality is less evident than in the offshore (Figure 40) because of wave dissipation.

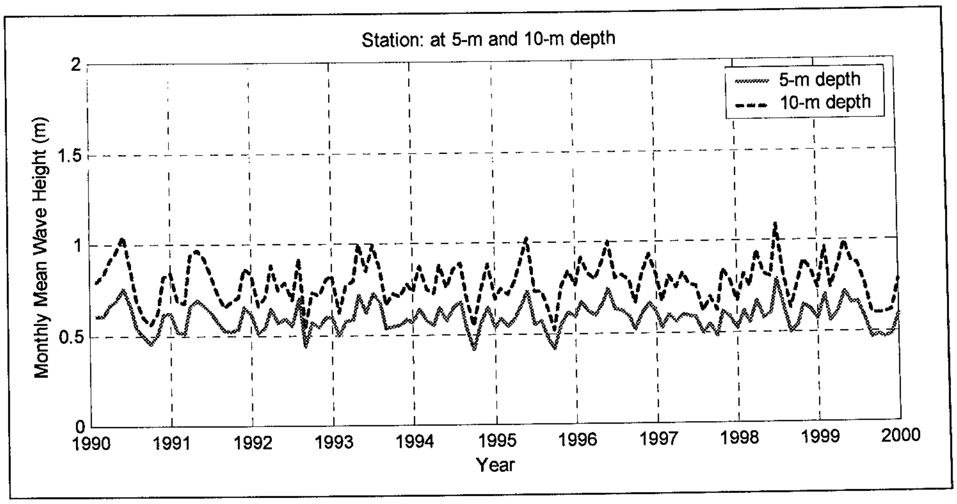

Figure 43. Monthly mean wave height at the 5- and 10-m-depth contours, 1990-1999

Potential Longshore Sediment Transport

The potential longshore sediment transport rate is the rate computed by a predictive formula under the assumption that sediment (assumed to be primarily sand) is available for transport. There is ample sand supply at the San Bernard River mouth, so that the potential and actual rates, assuming the calculated potential rate is accurate, are the same.

The longshore sediment transport rate Q was computed from the 3-hr values of wave height, period, and direction available from the 10-year nearshore WIS time series described above. The trend of the shoreline was taken to be 60 deg east of true north, and the wave data were input to the CERC formula, given by:

$$Q = \frac{K}{2(\rho_s - \rho)ga} F_b \sin(2\theta_b) \tag{9}$$

where

factor K	=	empirical coefficient with value ranging between about 0.1 and 1
K	=	0.77 the standard value specified for the calculations that follow
ρ_s and ρ	=	density of quartz sand and water, respectively
g	=	acceleration of gravity
a (= 0.6)	=	a reduction factor for the void space of sand grains
F_b	=	wave energy flux at breaking (significant wave height)
θ_b	=	angle of the breaking waves to the shoreline

The rates were calculated by month (Table 11) and year (Table 12) and assembled as eastward and westward transport. The calculated net transport is directed toward the west, in agreement with several lines of geomorphic evidence discussed in Chapter 2. The maximum monthly transport occurs in September and October, during which times the waves are incident more from the ESE and can be higher than in other months and when tropical storms have greater probability of occurring. The mean monthly westward rate is 78 percent of the total mean monthly transport rate and indicates that longshore transport is strongly directed to the west in the vicinity of the San Bernard River mouth.

The 10-year average annual rates to the west and east were computed to be 262,550 and 72,530 cu m, respectively, corresponding to approximately 347,000 and 96,000 cu yd/year. These give a net of 248,000 cu yd/year directed to the west and a gross of 438,000 cu yd/year. The standard deviations (SD) of the annual rates are considered to be relatively small. They do not account for all the uncertainty in the estimate, for example, because the wave information was assumed to be completely accurate.

The average annual net longshore sediment transport rate computed from the wave hindcast is comparable to that determined by the geomorphic analysis given in Chapter 2. That analysis, for the 12-year period 1989-2001 and to a depth of 4-ft mlt, gave a minimum of 133,000 cu yd/year to a maximum of 417,000 cu yd/year, with a time-weighted average longshore transport rate of 176,000 cu yd/year directed to the west. It was estimated that this quantity is 0.75 percent of the total, giving 236,000 cu yd/year.

Table 11
Calculated Average Monthly Longshore Sediment Transport Rates, 1990-1999[1]

Month	Eastward, cu m/month	Westward, cu m/month
Jan	9,009	16,419
Feb	7,411	17,549
Mar	6,369	20,551
Apr	3,995	26,356
May	3,197	25,596
Jun	5,381	17,203
Jul	9,362	9,410
Aug	6,696	20,849
Sep	3,432	28,227
Oct	3,989	36,599
Nov	6,842	24,711
Dec	6,694	19,080
Mean	6,044	21,880
SD	2,064	6,977

[1] Significant figures of calculated values do not imply corresponding degree of accuracy and are retained for comparison of values in Table 11 and Table 12.

Table 12
Calculated Annual Longshore Sediment Transport Rates[1]

Year	Eastward, cu m/year	Westward, cu m/year
1990	58,860	259,390
1991	65,250	309,340
1992	74,290	257,050
1993	68,750	253,030
1994	58,630	298,740
1995	81,760	287,800
1996	96,060	208,220
1997	87,660	242,050
1998	60.710	285,370
1999	73,370	224,520
Mean	72,530	262,550
SD	12,730	32,670

[1] Significant figures of calculated values do not imply corresponding degree of accuracy and are retained for comparison of values in Table 11 and Table 12.

4 Synthesis and Recommendations

This chapter summarizes study findings on the causes and rates of shoaling of the San Bernard River mouth. Based on the information and analysis contained in previous chapters, a consistent explanation of sediment transport processes at the San Bernard River mouth is developed here. The explanation accounts for the relative stability of the San Bernard River mouth prior to the late 1980s and its subsequent migration and tendency for closure observed in the past decade. Estimates of volumes of material that must be dredged for implementing the recommended alternative are also given.

Synthesis of Sediment-Transport Processes at the San Bernard River Mouth

Prior to 1929, the Brazos River discharged to the Gulf of Mexico about 10.5 km northeast of the mouth of the present diversion channel. The San Bernard River mouth was located about 16 km downdrift of the original river delta, beyond its direct influence. The Brazos River had not yet been dammed, and sediments brought to it were carried relatively far offshore by its discharge, particularly during floods, to create a large delta. In the same era, the GIWW had not yet been cut west of the Brazos River, and the San Bernard River flowed unimpeded to the Gulf of Mexico. As a result, it appears that the San Bernard River had adequate tidal exchange supplemented by river discharge during floods to maintain dynamic positional and cross-sectional stability of its mouth.

After 1929, a delta began to form at the mouth of the newly created Brazos River Diversion Channel, located 5.4 km updrift of the San Bernard River mouth. Growth of the delta toward an equilibrium volume removed much of the sediment that would otherwise have been transported to the southwest. The predominant direction of longshore sediment transport is to the southwest. The San Bernard River mouth therefore enjoyed a period of relative lack of sediment moving toward it that would otherwise have tended to close and/or translate the mouth downdrift by spit formation from the updrift side.

In this period, the late 1930's to early 1940's, the GIWW was extended west from the Brazos River and past the San Bernard River. No significant sedimentation problem was observed at the San Bernard River mouth for several decades after that time, making this situation appear to be the norm. However, the "norm" as observed at the San Bernard River mouth during the 6 decades was artificially induced by blockage of southwestward-directed longshore transport and sediment capture by the evolving new Brazos River delta.

As the new Brazos River delta approached equilibrium, it began functioning as a natural bypass route for sediment transported alongshore by waves. In the 1960's, the delta appears to have approached full bypassing potential. At the same time, however, because of dam construction, the sediment load on the Brazos River decreased. Therefore, it is likely that the continuous mode of sediment bypassing to the southwest, although increasing in rate, was not at full potential because of the requirement of the delta to reach and maintain equilibrium volume.

The new Brazos River delta can also bypass sediment episodically. The injection of sediment on the coast to the southwest begins to occur a few years after a strong flood brings material to the mouth, perhaps to create a channel mouth bar such as during the 80-day-long 1992 flood. After that flood, this extra supply of sediment in the form of a channel-mouth bar began to attach to the southwest shore sometime around 1995, creating a sediment-rich unstable shore face with sand readily mobilized by waves and transported alongshore toward the San Bernard River mouth. It is noted that the previous major flood was in 1957, with duration of 50 days. Such strong floods are, therefore, relatively rare.

Based on a GIS-based geomorphic analysis of spit growth and river mouth migration as documented in aerial photographs and through land and marine surveys, the following estimates of coastal and river mouth processes were arrived at in this study:

a. From 1989 to about 1995 (after attachment of the entrance bar that developed at the Brazos River mouth during the 1992 flood), the spit at the San Bernard River mouth migrated to the southwest at a rate of approximately 1.2 ft/day. This rate increased after the 1992 flood so that by September 1995 the spit was migrating at a rate of 1.6 ft/day.

b. Above an elevation of –4-ft mlt, the average-annual net rate of longshore sediment transport, which is directed to the southwest, is about 176,000 cu yd/year. This rate can increase to exceed 400,000 cu yd/year temporarily during shoal attachment at the Brazos River mouth. The westward transport comprises about 78 percent of the gross transport. An estimate of the average-annual total net longshore sediment transport rate (to the maximum depth of transport) was estimated to be on the order of 235,000 cu yd/year, which agreed in approximate value to an estimate produced from a wave hindcast.

c. The width of the active portion of the spit (prior to occupation by dense vegetation that would tend to trap wind-blown sand) is about 1,000 ft, and its elevation is about 5-ft mlt.

d. From 1989 to 1995, the width of the San Bernard River mouth was relatively constant at about 1,000 to 1,100 ft. After 1995, the width steadily decreased to reach approximately 200 ft at present. A 1,000-ft width is not sustainable if the new Brazos River delta bypasses sediment alongshore and if floods bring excess sediments to the Brazos River mouth.

e. Depth of the channel at the San Bernard River mouth and running along the north side of the spit is about 4-ft mlt.

f. Because the delta at the Brazos River mouth has now achieved equilibrium, a representative value of 176,000 cu yd/year for the upper limit of the rate of longshore sediment transport can be expected. If a long-duration flood occurs on the Brazos River, the longshore transport rate on the updrift side of the San Bernard River mouth will temporarily increase a few years after the flood.

g. The discharge, including tidal exchange, of the San Bernard River to the Gulf of Mexico is not sufficient to maintain positional and cross-sectional stability of the river mouth. Migration and gradual closure can be expected.

Design Alternatives for Maintaining the San Bernard River Mouth

Although the net longshore sediment transport rate determined in this study, 176,000 cu yd/year on average, is considered to be a reliable number, it is not an estimate of the dredging maintenance requirement. It might only be considered a requirement if the exact location of the channel is to be maintained. The goal of this study is to maintain flow through the San Bernard River so that the current at the intersection of the GIWW and the San Bernard poses minimal hazard. Hydrodynamic modeling (Sanchez and Parchure 2001; Chapter 3 herein) indicated that the flow in the GIWW between the San Bernard River and Brazos River is reduced if the San Bernard River mouth remains open. Because the San Bernard River mouth will not be maintained for navigation, there is no reason to maintain it at a fixed position.

Based upon understanding of the acting coastal and inlet processes at the site as summarized above, the following alternatives were developed:

a. Alternative 1: Dredge at the existing location of the mouth to maintain flow.

b. Alternative 2: Relocate the mouth approximately 6,000 ft to the northeast and stabilize with either rock or geotextile groins, one on each side or possibly just one on the northeast side.

c. Alternative 3: Relocate channel mouth by dredging 6,000 ft to the northeast of the existing river mouth and let the new mouth migrate to the southwest, with the expectation of having to relocate the mouth after 6-12 years.

Alternative 1 is not recommended because the long and shallow river channel running behind the spit has greatly increased hydraulic friction. The friction decreases the ebb current velocity and its capacity to sweep sediments to the Gulf of Mexico; at the same time, the weak current promotes formation of a flood shoal and blockage of the river mouth and channel. The lower portion of the channel is almost full of sediment, probably littoral sediment transported landward during flood tide. A substantial portion of this sediment would have to be dredged to create an efficient channel. Also, further migration of the spit, which is expected, would increase the length of the channel, further increasing friction, thereby increasing the rate of shoaling of the mouth and its tendency to close.

Alternative 2 is a traditional and feasible approach, with the groins serving as stabilization structures in preserving location of the mouth by reducing the amount of sediment transported to it and diverting sediment offshore and away from the river mouth. A single groin placed on the updrift side would halt, at least temporarily, infilling of the channel by the (predominant) westward transport. The river mouth would then tend to adjust to reach an equilibrium width and depth. With only one groin (updrift) in place, the possibility exists that the shore adjacent to the southwest channel bank would erode, widening the channel (which would then become shallower), at least until bypassing around the mouth is re-established. The material impounded by the groin that would otherwise be transported to the southwest would be lost to the downdrift beaches, but this would be a relatively small amount until bypassing is established and is not considered significant for an uninhabited coast. The seaward end of the temporary groin or groins should be placed to a depth of about 7-ft mlt to protect and preserve natural channel depth, yet allow sediment to be transported alongshore by bypassing. The updrift groin would become impounded after several years, but if built to the 7-ft depth, sand would tend to move around it and bypass the channel that tends to have a 4-ft depth. However, some of the bypassed sediment would be swept into the entrance by the flood-tidal current.

Alternative 3 is probably the least-cost approach, and it is more conservative than constructing and maintaining groins at the relocated river mouth. The concept is to relocate the inlet and allow it to migrate. If a major long-duration flood does not occur on the Brazos River, it will take at least 12 years for the channel to migrate 1 mile to the southwest. Therefore, it can be expected that the channel mouth would have to be relocated after 6-12 years, depending on such factors as flooding on the Brazos River, storms and hurricanes, inter-annual changes in wave climate, and the adverse current experienced by vessels traversing the GIWW. After the mouth migrates about 3,000-5,000 ft, it should be relocated again. The amount of material to be excavated during the channel mouth relocation depends on the approach taken to create the opening and is discussed below. Relocation of the inlet periodically by artificial means could be viewed as an acceleration of natural processes, because it is expected that the river would eventually break through the spit some years after the river mouth closes (see concepts in Figure 7).

Recommended Action for Maintaining the San Bernard River Mouth

Alternative 3 is the recommended action, with provision for consideration of groin emplacement should the channel migrate too rapidly or if its cross-sectional area decreases too quickly. The latter possibility is doubtful given the photographic documentation of spit elongation and channel evolution in the past.

Location of new channel and volume of material to be removed

The recommended region for relocation of the river mouth corresponding to Alternatives 2 and 3 is shown in Figure 44, which displays areas of coverage in that region and elevations determined by land and marine surveys made in this study. There is a gap between the land survey of the spit and the nearshore survey, interpolated linearly between the two data sets. The relocated channel should be dredged west of the older and higher sand ridges, which are the more vegetated (and higher) areas seen in the figures. Excavation through the old ridges, as opposed to dredging on the active sandy spit, would require considerably more volume to be removed and cause greater environmental disruption than dredging through the predominantly barren surface of the active sand spit.

Figure 45 and Figure 46, respectively, show widths and cross sections of possible variations of Alternative 3. The three variations are defined by widths of 200, 400, and 600 ft, with possible depths of 4 and 7.5 ft with respect to mean low tide. The existing river channel leading to the mouth has an approximate depth of 4 ft and is the expected depth of the river mouth in an unmaintained state. A 7.5-ft depth represents advance dredging[1] of the channel.

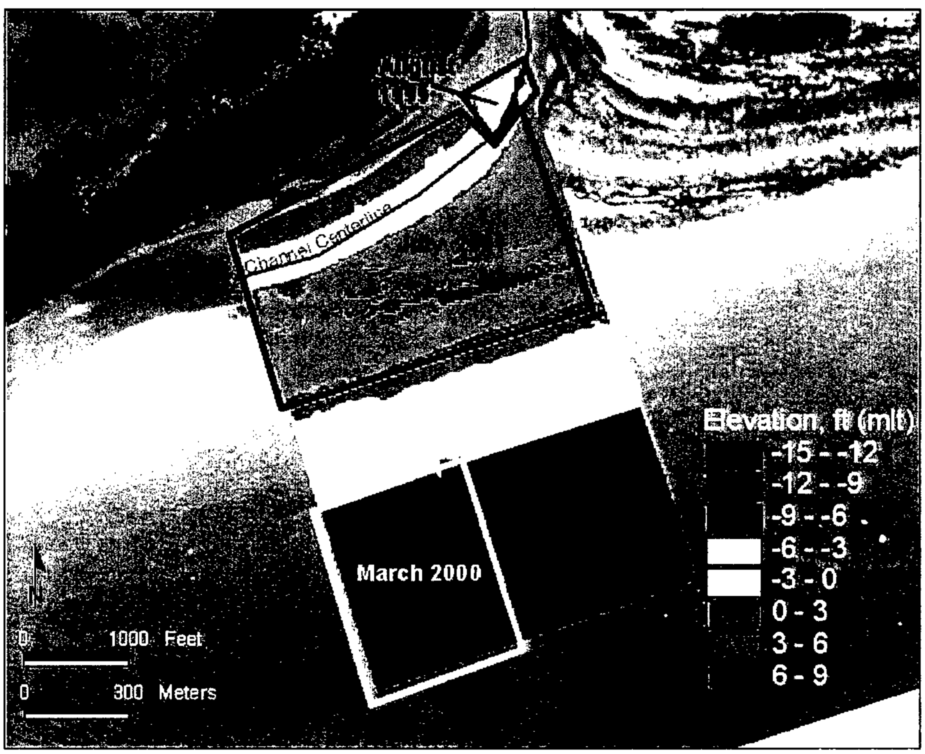

Figure 44. Areas of survey coverage for channel mouth relocation

[1] The term "advance dredging" is not strictly applicable because the channel will not be dredged to a design depth as required for a maintained navigation channel. Usage here is meant to indicate that deeper initial dredging would increase longevity of the mouth.

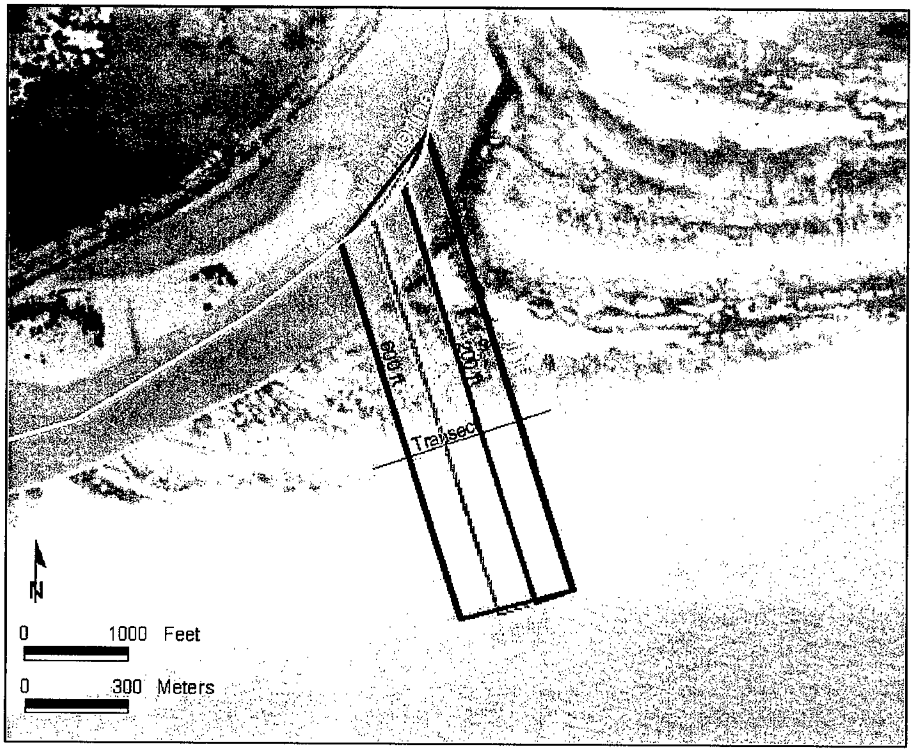

Figure 45. Proposed alternatives for location and width of the relocated channel mouth

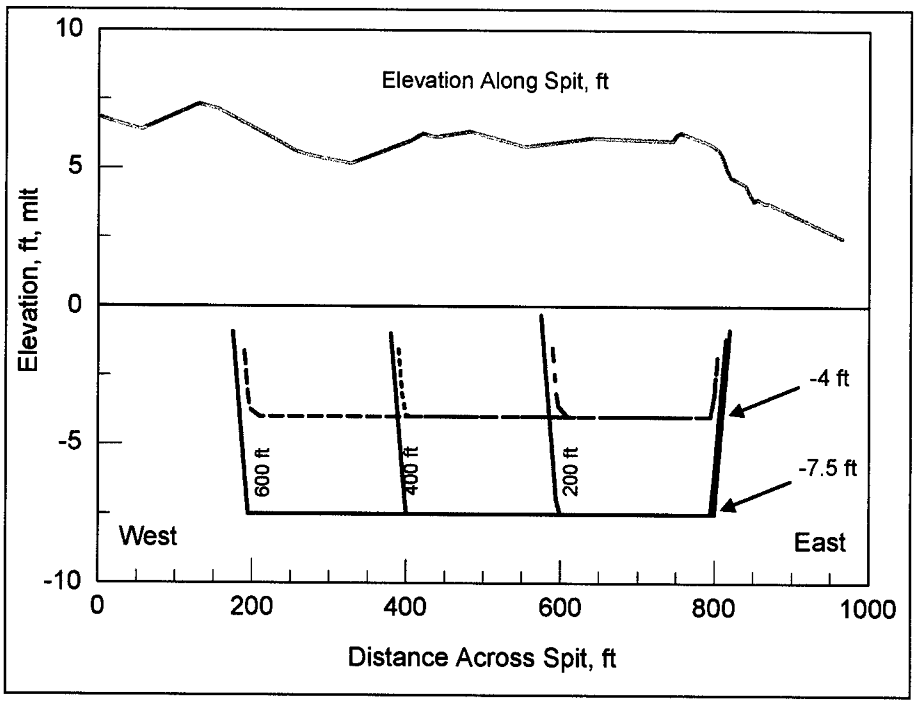

Figure 46. Definition sketch for alternative channel cross sections

Maintenance requirements for the relocated mouth

Initial cut. The channel should be opened during the turn toward ebb tide, so that the initial rush of water will sweep sediment Gulfward and not northward into the river channel. This timing will reduce the tendency for creating a flood shoal with the loose sediments expected to be present in and around the new mouth. It is recommended that the dredging plan be implemented with equipment transported on the GIWW and Route 2918, and then down the river to avoid need for access from the Gulf of Mexico. The new mouth could be opened by dragline dredging, possibly in combination with a backhoe. If the existing river mouth has not yet closed, it is advisable to place some portion of the dredged material in the lower portion of the old channel to close it, thereby eliminating multiple hydraulically competing entrances.

Two general plans can be considered for opening the relocated mouth. Plan 1 is to dredge from the landward side toward the Gulf of Mexico with design dimensions such as given in Table 13. This table lists volumes of the dredged cuts assuming 1:3 side slopes and based upon the survey data as indicated in Figure 44. Upon arrival of ebb tide in the Gulf of Mexico, the last increment of work would open a small channel connecting the main dredged cut and the Gulf of Mexico. Water rushing out of the river would increase the dimensions of the channel. This plan allows for advance maintenance by, for example, dredging to 7.5-ft mlt. Alternatively, a sheet-pile plug could be driven into the beach on the Gulf side and the material removed from the spit behind it. After the new channel is fully excavated, the sheet pile would be removed by crane at ebb tide.

Table 13
Estimated Volumes for Full Excavation of River Mouth Channel

Channel Width, ft	Volume of Sediment to be Dredged, cu yd
4-ft Depth (mlt)	
600	370,500
400	259,000
200	139,152
7.5-ft Depth (mlt)	
600	619,167
400	430,695
200	238,890

Plan 2 for opening the mouth would be to excavate a narrow trench through the spit, as with a clamshell dredge or backhoe, and then make the last cut to the Gulf of Mexico upon arrival of lowest ebb tide. The assumption is that the rushing water and subsequent tidal exchange would continue to open the channel to natural dimensions compatible with the flow conveyed by the hydraulic system. This plan requires less dredging than Plan 1 but entails risk if the rushing water and subsequent tidal exchange cannot cut the quasi-stable mouth. Also, more material will be flushed into the river channel during flood tide than for Plan 1.

Based upon the above considerations, it is recommended to dredge a channel 400 ft wide and 4 ft (mlt) deep (Plan 1), possibly protecting the cut with a sheet-pile wall at the Gulf of Mexico shore. Such dredging would require excavation of approximately 259,000 cu yd of material from the spit, plus any material needed to access the spit from the GIWW. Removal of material from the river channel leading to the mouth would increase hydraulic efficiency of the river mouth and its longevity.

Sediment (consisting predominantly of sand) that is dredged from the spit during the relocation should be moved out of the area and not piled along the sides of the newly cut channel to prevent sediment infiltration by wind. If feasible, it should be placed on the downdrift beach some distance from the new cut. Infilling by wind-blown sand was one cause of closure of the Fish Pass in Corpus Christi, Texas (Kraus and Heilman 1997). Placement of sand fencing along the channel and vegetating the area would mitigate infilling by wind-blown sand.

Maintenance dredging. The site can be monitored by taking aerial photography annually and through site visits by boat. If the spit proves to migrate too rapidly, a geotextile or rock groin could be placed on the updrift (northeast) side, as described in Alternative 2.

Annual maintenance dredging is not recommended. The infilling sediment, coming predominantly from the northeast, will cause the channel mouth to migrate to the southwest at a rate of approximately 1 to 1.5 ft/day. However, the mouth is expected to remain open, similarly to its behavior as documented in Chapter 2 from 1989 to 2001. After an anticipated approximately 6-12 years and migration of the mouth several thousand feet westward, if adverse currents begin to be manifested in the GIWW intersection, the river mouth could again be relocated as described above for "initial cut." Based upon experience with creation of the first relocation of the river mouth, the amount of dredging for the cut could be refined.

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14. ABSTRACT

This report documents an investigation of the coastal and inlet physical processes acting at the San Bernard River mouth, Texas. The U.S. Army Engineer District, Galveston, requested the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), to conduct this study to assist in formulation and assessment of alternatives for improving navigation along the Gulf Intracoastal Waterway (GIWW) between the Brazos River and the San Bernard River and vicinity.

In recent years, a spit has grown from northeast to southwest across the San Bernard River mouth. The migrating river mouth is narrowing, and sediment shoaling landward of it has reduced the river's discharge to the Gulf of Mexico. Riverflow is diverted into the GIWW, increasing the current velocity in an unpredictable way and possibly increasing sediment shoaling at the intersection of the river and the GIWW, as well as to the east at the west floodgate to the Brazos River. The present study was performed to identify and evaluate alternatives for maintaining the San Bernard River mouth.

The San Bernard River is located in north-central Texas and flows through the alluvial valleys of the Colorado River and Brazos River. The central Texas coasts spans several zones from humid in the north to dry subhumid in the south. Average annual rainfall ranges from 104 to 125 cm, with large variations possible between droughts and precipitation brought by tropical storms. The San Bernard River has a much smaller drainage area than either the Colorado River or the Brazos River, with correspondingly much weaker flows and sediment discharge. Therefore, local storms primarily determine its flow.

(Continued)

15. SUBJECT TERMS
Brazos River; Ebb-tidal shoal; Geomorphology; Numerical model; River delta; River mouth; San Bernard River; Spit; Tidal inlet; Texas

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14. ABSTRACT (Concluded)

This study was organized in three components as an analysis of the coastal geomorphology and sediment-transport processes, a hydraulic analysis of the river and tidal flow, and a synthesis of results leading to development and evaluation of alternatives. The geomorphic component includes quantification of spit movement at the San Bernard River mouth and the influence of the Brazos River discharge and delta on the San Bernard River mouth. The hydraulic component consisted of establishing and validating a one-dimensional (1-D) numerical model of the water level and currents in the area. A 1-D model was applied because alternatives at the river mouth could be readily implemented and examined within the scope of this study. The model could also be transferred to and operated at the Galveston District. A wave hindcast was also performed to interpret the coastal processes. Based on these analyses, alternatives were developed and evaluated for maintaining the San Bernard River mouth.

An introduction to the study site and the problem statement is presented, followed by review of the geomorphic setting and changes observed at the spit and river mouth. Results of the hydraulic modeling are discussed. Estimates of the longshore sediment transport rate, of direct consequence to the stability of the San Bernard River mouth and possible maintenance dredging are detailed in this study.