A TIME LINE OF CEDAR BAYOU

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EXECUTIVE SUMMARY

Exchanges with the sea are an important feature of the hydrography of an estuary. For San Antonio Bay, the principal exchanges occur through the Pass Cavallo complex (including the Matagorda Entrance Channel) and through Aransas Pass. The closest inlet to the bay, however, is Cedar Bayou, which separates Matagorda Island and San Jose Island. When open, Cedar Bayou is an effective passage for migratory organisms, so analysis of long-term organism abundance data requires knowledge of the state of the pass.

Cedar Bayou has existed as a channel crossing the barrier island for nearly 2500 years. Authoritative surveys establish that its gross physiographic features, notably its NNE-SSW trend across the island and the washover fan to its west, have not substantially changed since before the Civil War. This project constructed a chronology for Cedar Bayou for 1900-2009. Overall, Cedar Bayou has tended to diminish in size from the surveys of the early twentieth century to the aerial photography of the twenty-first century. The largest recorded cross sections of Cedar Bayou were attained in the late 1960's to early 1970's (during which Texas Parks and Wildlife performed an intensive study of migratory organisms using the inlet), but the inlet has been greatly reduced in cross section, or completely closed in the years since.

While determination of the causes of shoaling of Cedar Bayou is beyond the scope of this study, the chronology includes natural or human activities that could potentially affect the inlet. The mechanisms that scour and maintain Cedar Bayou seem to be operating at roughly the same intensity and frequency during the past three decades except perhaps for freshwater inflow, which is trending upward. Nonetheless, during this period the inlet has been chronically closed, or just marginally open, despite two dredging projects, several hurricanes, and record floods.

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FIGURES

1. BACKGROUND

Cedar Bayou is a small inlet connecting Mesquite Bay to the Gulf of Mexico, see Figure 1. It is the formal boundary between San Jose Island and Matagorda Island. More importantly, it is the closest inlet to San Antonio Bay, which otherwise exchanges with the Gulf of Mexico through Aransas Pass in Aransas-Copano Bay to the south or Pass Cavallo/Entrance Channel in Matagorda Bay to the north. When open, Cedar Bayou serves as a migratory route between the bay and the Gulf for diadromous species (e.g., Simmons and Hoese, 1959, King, 1971), and it is generally expected that the abundance of such a species within the bay will be increased when such a migratory path is available. In anticipation of its function as a migratory access to San Antonio Bay, considerable effort, both physical and political, has been invested in its maintenance over the past seven decades.

Because the status of Cedar Bayou (*viz*., open or closed) potentially affects the abundance of organisms within the estuary, it is essential to construct a timeline of the state of the inlet, so that a time series of organism data may be stratified for analysis. Not only will this information be immediately useful to other tasks in the present project, but it will also support analyses of the distribution and abundance of various species in San Antonio Bay being prosecuted in ongoing projects elsewhere.

Interest in the state of Cedar Bayou, particularly as a migratory access, dates back to the early twentieth century, the first attempt at dredging occurring before World War II. Several time lines of the pass have been constructed in the past, notably the summary by Hoese (1958), largely repeated in Simmons and Hoese (1959), a 1967 report by Turner Collie & Braden (which was not available to this study), and Shepsis and Carter (2007). While the information in these prior studies was employed as appropriate (and available), the general approach of the present study was to seek and document information in the historical record of the status of the inlet that satisfies the following criteria:

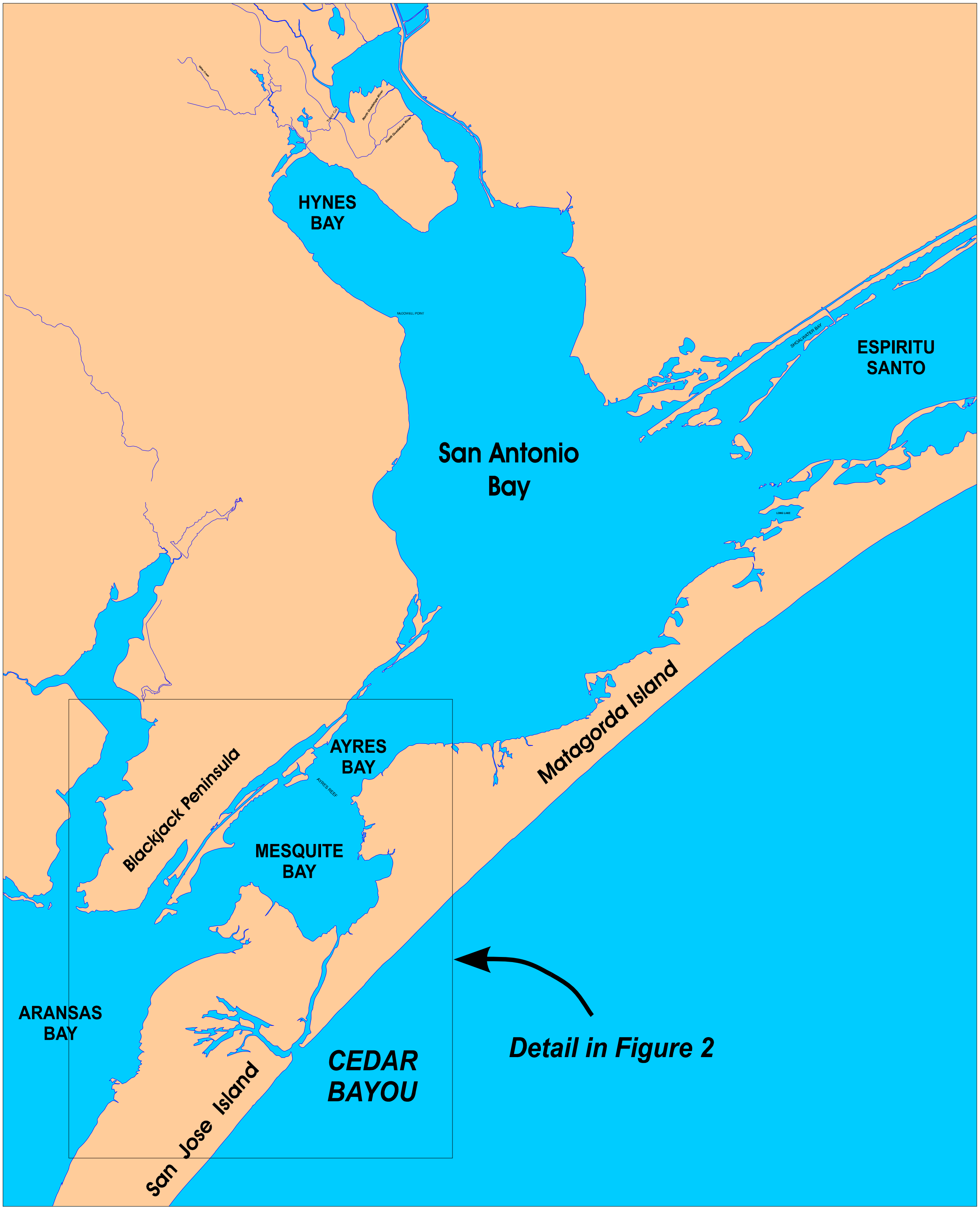

Figure 1 - Location map of San Antonio Bay

(1) the source is authoritative

(2) the information is reliably dated, albeit of variable precision

(3) the information is one of three types:

(a) data on the spatial configuration of the inlet allowing the inference of whether water freely flows through the main channel

(b) measurements of key dimensions of the inlet channel

(c) qualitative descriptions of the capacity of the channel to pass water

By “authoritative” in (1) is meant directly observed by a trustworthy observer and recorded objectively for general use in navigation, coastal management, engineering or science. Two important categories of information itemized in (3) are maps and aerial photography. This information must be capable of being dated, as specified in (2), although the precision of that dating may range from a specific day to a year or more. Many otherwise revealing maps must be discounted if the source date cannot be determined. With respect to the qualitative descriptions of (3c), we make the further distinction of an “observation,” in which the source personally examined the inlet or (say) its photograph, and a “report” in which a third party, presumed authoritative by the source, was responsible for the assessment of inlet status.

The scope of this study was narrow, and the resources were limited. Strictly, the time history presented in Appendix A satisfies—in fact exceeds—the contractual scope. Because it is of considerable interest to explore causes of the inlet’s behavior, in addition to information on the inlet *per se*, records were sought on events that might affect the status of the inlet or influence the interpretation of the above information. These events mainly consist of tropical depressions, heavy rainfall and/or riverine floods, seasonal high waters, and human activities of sediment removal or deposition. However, complete evaluation of the underlying causes for the time behavior of the inlet cannot be undertaken within the scope of the present study. In addition, sources of error or uncertainty were identified, especially where they affect the interpretation of hydrographic or photographic evidence of the status of the inlet.

2. INLET STRUCTURE AND MECHANICS

Cedar Bayou forms the eastern boundary of an extensive washover fan and tidal delta complex that comprises the northern end of San Jose Island. The washover fan contains numerous minor distributaries that carry water only during rare extreme high-water events, most prominent of which is Vincent Slough. The general structure of the Cedar Bayou environment is displayed schematically in Figure 2. Several zones may be identified that are characterized by differing physical processes. The washover fan is the western segment of the lobate end of San Jose Island, made up of mud flats and intervening sand mounds (of aeolian origin). The eastern segment, adjacent to the western shore of Cedar Bayou, is tidal delta, consisting of marsh and irregular ponds. (Andrews, 1970, presents maps of much greater detail, differentiating morphology, sediments, and flora.) Most important for the present purpose is the beach zone, dominated by transports of sand by wind and waves, extending from the shoreface to behind the line of active dunes (the "secondary dunes" in the terminology of Wilkinson, 1973). Beach zone is defined dynamically, but is generally a subset of the geomorphological concept of barrier nucleus (e.g., Andrews, 1970), which includes vegetated dune ridges.

The stability of the Cedar Bayou channel is determined by the interplay of two sedimentary processes: scour by flowing water through the channel, and deposition by gravitational settling from the water column. Scour is initiated when water velocity exceeds a value critical for the texture and cohesion of sediments in the channel bed. Deposition depends upon the concentration of sedimentary particles in the water column, their grain size and density, and the intensity of turbulence created by current or waves. Over the period of time for which inlet data were most densely accumulated, i.e. since the early 1950's, the back-bay reach of the channel appears to be stable. It is the beach-zone reach that shifts position and dimensions, and it is in the beach zone that the channel closes. This implies that it is the littoral transport of sands, overbalancing the scouring ability of water flowing through the inlet, that effects closure of Cedar Bayou. To summarize the mechanics of this inlet, each of these processes must be addressed.

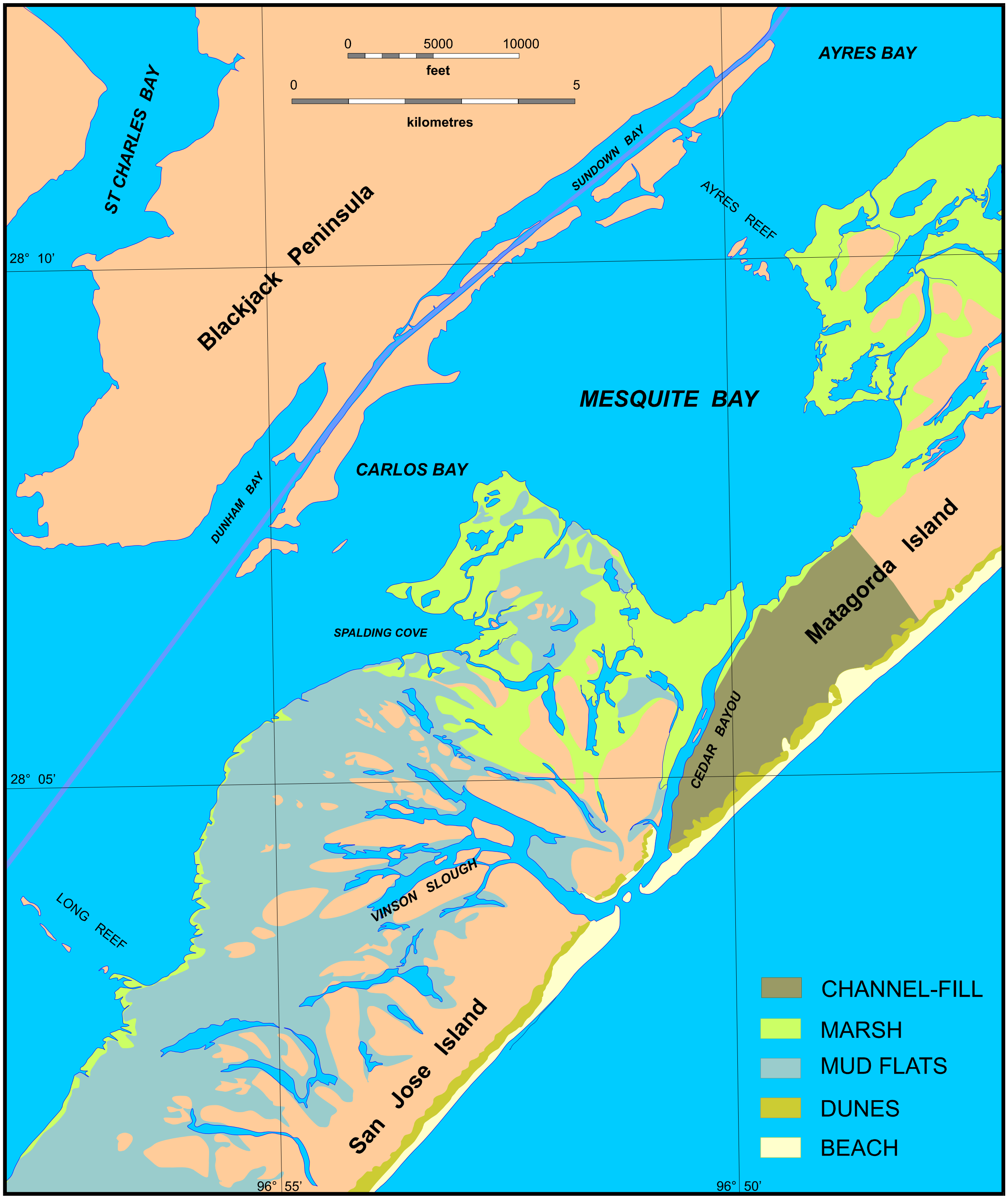

Figure 2 - Cedar Bayou and adjoining barrier island environments (see location map of Fig. 1)

When Cedar Bayou is open, its maintenance needs sufficient flow velocity through the inlet channel to limit deposition. This requires an imposed force to propel water through the inlet. There are two candidates, a slope in the water surface between the two ends of the inlet (more precisely, a gradient in pressure, but practically this will be dominated by the gradient in surface elevation), and the surface tangential stress exerted by wind. The latter becomes important only in the rare circumstance of extreme winds (gale force or more) directed along the axis of the inlet channel. So the former, a water-level slope in either direction between shoreface and backbay, is the primary mechanism, that is, a water-level differential (i.e., hydraulic head) between Mesquite Bay and the Gulf.

Once Cedar Bayou has silted closed, two simultaneous physical factors are required to re-open it: (1) re-establishment of hydraulic continuity between Mesquite Bay and the Gulf, i.e., an open-water connection along the inlet, and (2) an imposed force to drive water through the inlet. For the latter, sufficient head gradient is needed that not only prevents deposition but also achieves scour. Put another way, re-opening the inlet requires that the inlet be inundated over its entire length and that there be adequate water-level differential between bay and Gulf. Some hydrographic events, if sufficiently intense, can accomplish both, e.g., the storm surge of a tropical cyclone, an energetic frontal passage, or a large flood. More modest events can act in combination, i.e., one to create a high water (to achieve inundation) and another to produce a differential water level between bay and Gulf. Such hydrographic events are addressed in more detail below.

Whether the inlet is open, or is closed but temporarily inundated along its length, flow through the inlet is driven primarily by the hydraulic head gradient imposed along the length of the channel, that is, by the difference in water level between the nearshore Gulf of Mexico and that in Mesquite Bay. The effectiveness of this water-level gradient in driving flow depends upon the water depth, in that the greater the water depth, the smaller the frictional resistance to acceleration. The principal physical factors that can force a water-level difference across the barrier island are (1) tides, (2) meteorology, especially variations in wind and pressure, (3) floods into the lagoon behind the barrier islands.

On a day-to-day basis, the most consistent potential generator of flow is the tide, by which is meant the "astronomical tide," the variation of the sea surface induced by the orbital interactions of earth, moon and sun. As an example, the observed sea-level variation during June 2009 is shown in Figure 3 for three Texas Coastal Ocean Observation Network (TCOON) stations, Bob Hall Pier on the Gulf of Mexico seafront, Mesquite Bay (MANERR #1) and Lower San Antonio Bay near False Live Oak Point (GBRA #1). For clarity, these three time traces have been arbitrarily shifted with respect to each other to better display their individual variation. This month was selected because it is relatively free of meteorological disturbances, and the seafront tide is therefore almost entirely astronomical. Features of this figure exemplify several general observations about the astronomical tide on the Texas coast:

(1) The range of the tide varies substantially over a period of about two weeks.

(2) When the range is maximal, the tide has a 24.8-hour periodicity. (This is the length of the *lunar day*, the time required after the moon is overhead for the earth to rotate to bring the moon overhead again.) This is informally called the "diurnal mode" of the tide.

(3) When the range is minimal, the tide has a 12.4-hour periodicity. This is informally called the "semi-diurnal mode" of the tide.

(4) The average water level varies between the times of the diurnal and semi-diurnal modes with a periodicity of about two weeks. This variation in mean water level is referred to as the "fortnightly tide."

(5) The range of the tide is closely correlated with the *magnitude* of declination of the moon, i.e., the angle of the moon above or below the equatorial plane of the earth. The greatest declination is the angle between the equatorial plane of the earth and the orbital plane of the moon (which varies slowly as the orbital plane rotates, with a period of about 18.6 years). During its one-month orbit, the moon has a maximum (positive) declination at the top of its orbit, then a zero declination as it crosses the earth's equatorial plane, then a maximum – but negative – declination at the bottom of the orbit, then another zero declination as it once again crosses the equatorial plane.

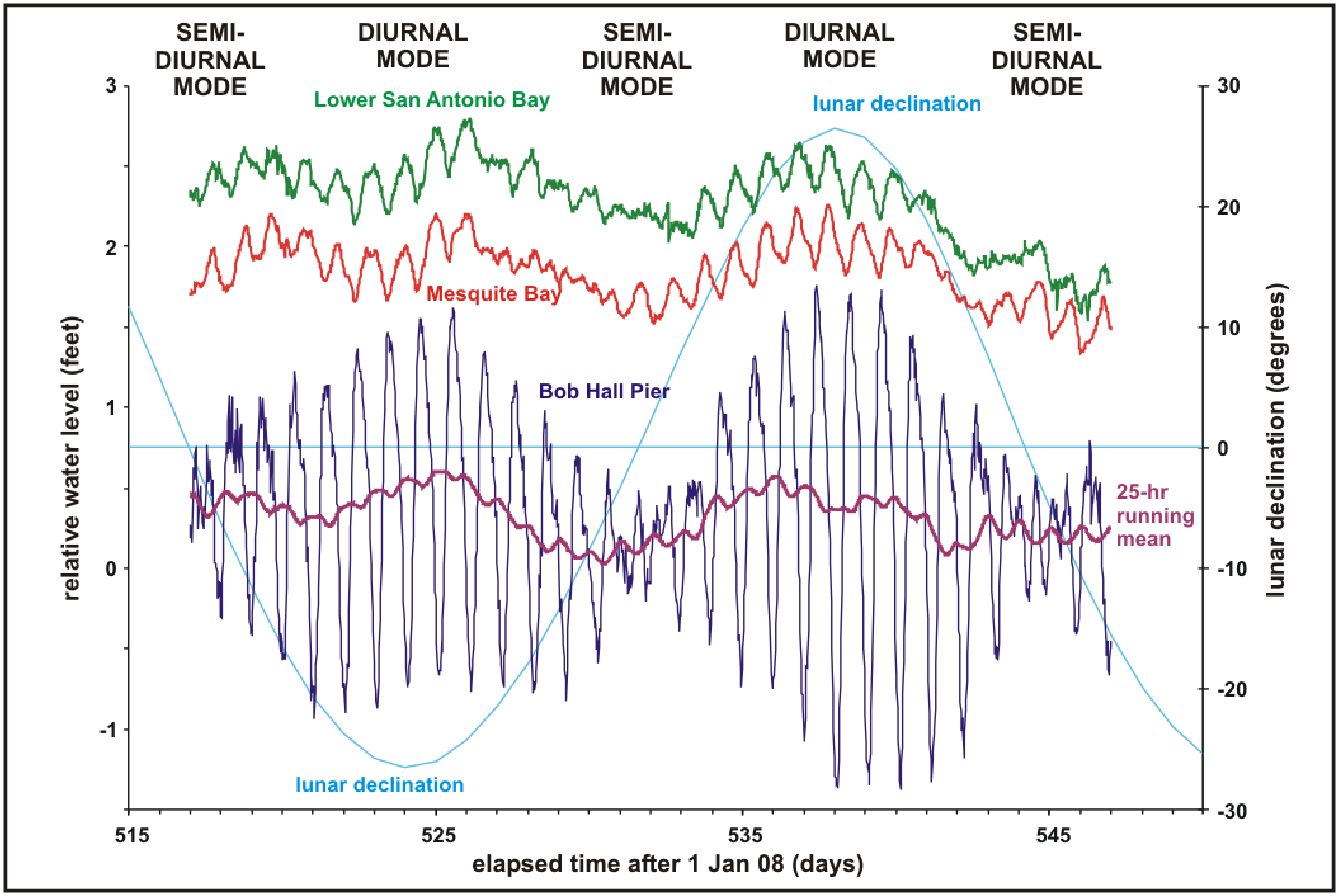

Figure 3 - Tides in vicinity of Cedar Bayou, June 2009. Data from Texas Coastal Ocean Observation Network. Tide traces are displaced vertically by arbitrary shifts for clarity.

(6) The maxima in absolute value of lunar declination correspond to the diurnal tides, with maximal tidal range. The zeroes of lunar declination correspond to the semi-diurnal tides, with minimal tidal range. For this reason, the diurnal mode of the tide is sometimes called the "great-declination tide," and the semi-diurnal mode, the "small-declination tide."

The Gulf seafront tide has been succinctly described as a superposition of a 12.4-hour semidiurnal and 24.8-hour diurnal tide, modulated by a 27.2-day signal tied to the declination of the moon (Ward, 1997). It is worth noting in passing that, despite the physical elegance of the relation between spring and neap tides and the phases of the moon—a relation which appears in standard oceanography textbooks and piloting manuals—and despite the frequent description of the variation in range of Texas tides as the spring-neap cycle, including some local guidebooks, lunar phase has little effect on the tide on the Texas coast.

There is one more component of sea-level variation in the western Gulf, which like the above tides is cyclic and relatively predictable, and is an important mechanism for the exchange of water between the bays and the Gulf, namely the secular semi-annual "tide". This is exposed by averaging water levels over a long enough period that the semidiurnal, diurnal and fortnightly tides are removed. Figure 4 displays the observed water levels at Bob Hall Pier after being subjected to a running 29-day average, then being further averaged over the 1990-2010 record for each day of the year. The resulting, greatly-smoothed annual variation exhibits two maxima and two minima, whence the name "semi-annual". High waters occur in the equinoctial seasons, the higher occurring in the fall, and low waters occur in the solstitial seasons, the lower being in winter. The smoothed curve of Fig. 4 correctly depicts the calendar occurrence of these events but greatly suppresses the extent of water-level variation, as demonstrated by the superposed annual extrema (from the 29-day mean smoothed annual variation for each year). While the mechanics of this "tide" are not well-understood, there is no doubt that climatology plays some rôle in the annual signal, including but not limited to a steric response to the solar cycle, and that meteorology contributes both inter-annual and intra-annual variation. When the seasonal high water, most notably that of the fall, coincides with other factors that elevate sea level, e.g., a great-declination tide or an intensification of the trade winds, beaches and nearshore structures

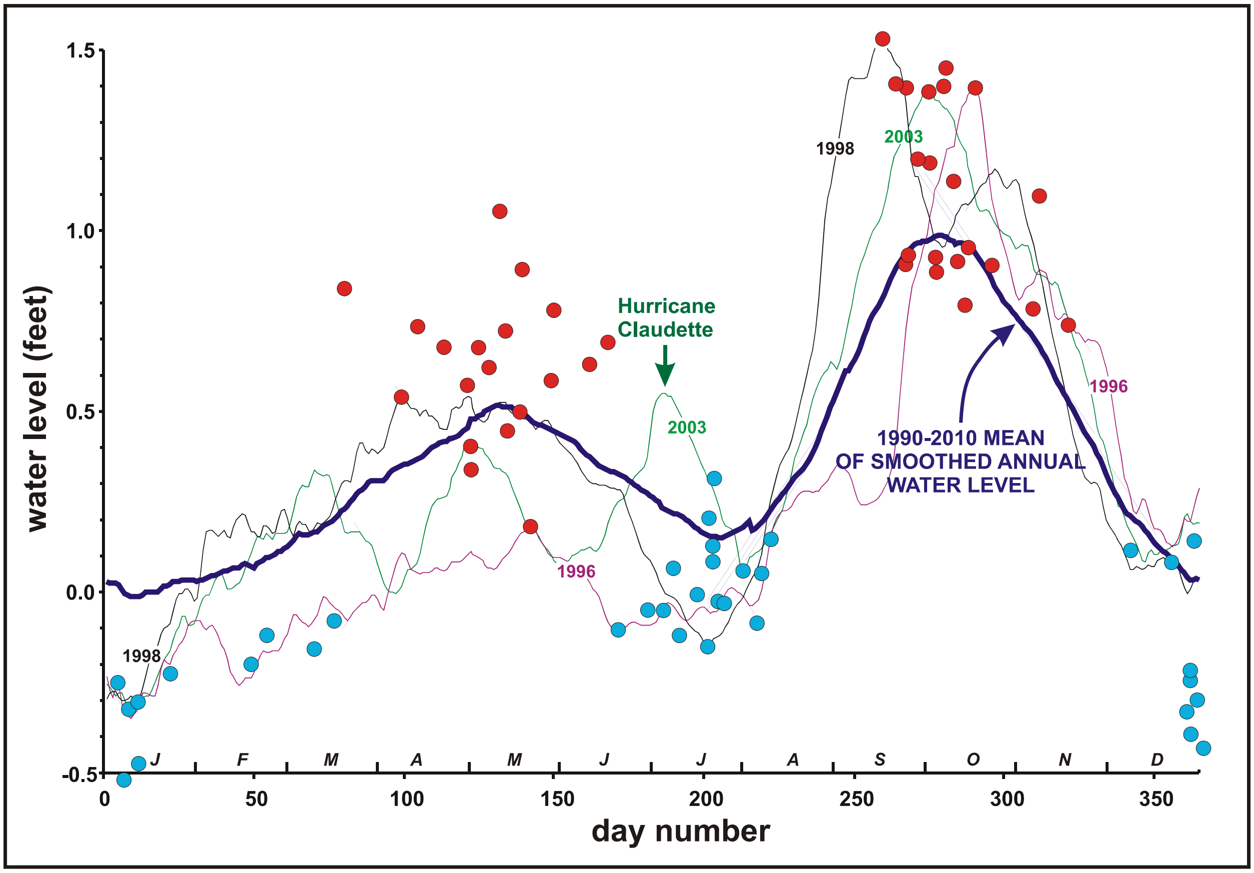

Figure 4 - Annual water-level variation at Bob Hall Pier after 29-day running mean, 1990-2010 average and selected years. Extrema of individual years plotted as red circles (maxima) and blue circles (minima).

such as the JFK Causeway may be flooded. The conventional practice of the local news media when this occurs is to ascribe the cause to a tropical storm in the Gulf of Mexico, no matter how feeble or remote (see Ward, 1997).

The Gulf tide described above is considerably modified as it passes through the inlets into the Coastal Bend bays, a manifestation of the "stilling well" effect, in which the inlet behaves as a small port or ajutage connecting a large oscillating chamber of water (the Gulf of Mexico) with a much smaller chamber in co-oscillation (the bay behind the barrier island). For example, the 24.8-hr diurnal tide loses about 75% of its energy in passing through Aransas Pass, and the 12.4-hr semidiurnal tide loses nearly 90% of its energy (Ward, 1997). Similar losses occur through Pass Cavallo and the Entrance Channel. The effect is a considerably reduced tidal range at these frequencies within the bays. As the tide passes from the main body of the bay into the secondary bays, e.g. through the ajutages of Nueces Entrance into Nueces Bay, Copano Pass into Copano Bay, or Espiritu Santo into San Antonio Bay, its semidiurnal and diurnal variations are reduced even further in amplitude. This is evident in the tide traces for San Antonio Bay and Mesquite Bay in Fig. 3. However, the fortnightly and semi-annual tides, being of longer periods, lose very little energy in passing through the inlet. In Fig. 3, it should be noted how closely the Mesquite and San Antonio Bay tides track the 25-hr running mean of the seafront tide. A stilling well, it will be recalled, filters out the short-period variation due to surface waves, so that the water surface in the well follows the average level of water outside.

While the astronomical tide (including, for convenience, the semi-annual "tide") is an important regular mechanism of water-level variation, the Gulf and the interior bays are dominated by atmospheric forcing, especially arising from time variations in wind and atmospheric pressure. The wind regime in the Texas coastal zone can be characterized as a sustained onshore flow from the Gulf of Mexico, interrupted by frontal passages, and modulated by the sea-land breeze circulation (Ward, 1997). The operative agent is the wind stress on the water surface, which accelerates the water in the direction of wind and increases its elevation along the windward shore. Informally, the water is said to "pile up". (The technical term is *denivellation*, the distortion of a free fluid surface by an applied stress.)

Under strong trade winds, characteristic of summer, water levels are gradually increased on the Texas Gulf shore. Within the bays water levels are raised on the interior shore and depressed on the shoreline behind the barrier islands. The inlets see a water-level differential from Gulf to bay, and water is driven from the sea into the bay. Under strong northerlies, such as following a winter frontal passage, these relative elevations are reversed, the Gulf being set down along the shorefront and the water surface within the bays tilting up from the inland shore to the barrier island. Water flows, often at a relatively fast rate, from bay to sea through the inlets, reducing the water volume within the bay. Direct measurements show that this volume driven from the bay by a frontal passage is typically greater than the great-declination tidal prism (Ward, 1980). While a vigorous front can evacuate half the volume of the bays on the upper coast, those on the lower coast, including San Antonio and Aransas-Copano, exhibit a more limited response to frontal passages.

The largest proportion of volume exchange was found by Ward (1997) to be about 10% of the bay volume. This more modest response to frontal passages on the south and central coast, compared to the upper coast, is probably due to the more constricted inlets of Matagorda and Corpus Christi Bay, and their reduced hydraulic capacities, and additionally to the reduction of energy of the frontal system in penetrating to the more southerly latitudes of the Coastal Bend area. Notwithstanding, the response of the bays and inlets to frontal passages dominates the astronomical tide and is a major mechanism of exchange between the bays and the sea.

An additional effect of wind that must be mentioned is that of the seabreeze. This is a diurnal variation in the onshore wind induced by the differing heat exchanges with the atmosphere over land and ocean, most prominent in the summer. Due to the rotation of the earth, the seabreeze *component* of the wind turns clockwise, describing a circle every 24 hours. Because this component is of smaller magnitude than the normal onshore flow, it is manifested as a variation in the windspeed, which directly at the coastline amounts to a change of a factor of three in windspeed, from about 0600 CST (when the seabreeze component is opposed to the onshore flow and reduces the total windspeed) until about 1800 CST (when the seabreeze reinforces the onshore flow). In confined bays with a suppressed astronomical tide, the seabreeze can induce a pure 24-hour variation in water level (see Ward, 1997).

Probably the most dramatic meteorological response of the Texas coast is that due to wind and surge of a tropical cyclone. (These systems also generate waves and mobilize sediment, but these processes are considered later.) These storms are large-scale atmospheric vortices driven by the release of heat energy when water vapor, evaporated from the warm ocean surface, is condensed into ice and water. The circulation around these storms is counterclockwise. Relative to the point of landfall, the wind to the right (looking inland, in the direction of storm movement) is onshore, and to the left, offshore. The zone to the right is therefore favored for wind stress and wave run-up, both of which contribute to the elevation of water referred to as the “surge”. It is, however, more complicated than this. Water is also elevated by the depressed pressure within the storm (the “inverse barometer” effect), at a rate of about one foot per 30 millibars depression. There is an additional inward (radial) component of wind at the surface that feeds the convection in the storm and moves seawater toward the eye (e.g., Anthes, 1982). These processes create a mound of water beneath the storm that evolves as the cyclone moves. When the storm enters the continental shelf zone, water depths become shallower and this mound of water, conserving its volume, is forced upward. Far offshore, its elevation above the surrounding sea level may only be one or two feet for a moderate hurricane, but as the storm moves into the nearshore zone, its elevation increases markedly to exceed ten feet or more.

A large zone of the coast, extending both to the left and the right of landfall, is potentially exposed to surge, though wind and surge will be greater to the right. The influence of the storm is dictated by its intensity (measured by central pressure anomaly and maximum sustained windspeed), size, trajectory and speed of movement. To pick one illustrative example, Carla in 1961 was a Category-4 hurricane (McAdie et al., 2009), whose impact was augmented by its relatively slow movement into the Texas coast. Landfall was at Pass Cavallo, where the surge (as determined by high water marks, see Harris, 1963) was about 12 ft, and in the Cedar Bayou area, to the left of landfall, the surge was around 10 ft. (Of course, much higher surges were experienced within the bays due to the convergence of cross section, the maximum being 22 ft at Port Lavaca.)

Appendix B presents a summary timeline of tropical storms and hurricanes that potentially could have affected the Cedar Bayou area, drawn mainly from the authoritative compilation of the National Climatic Data Center (NCDC) and the National Hurricane Center (NHC), published in McAdie et al. (2009).

It is difficult to offer a definitive statement on the ability of river flow to open or maintain Cedar Bayou from mechanical considerations. Delivery of a large volume of flow from the San Antonio Bay watershed into the bay will raise water levels throughout the adjacent bays of Espiritu Santo and Mesquite (in addition to San Antonio Bay itself), but Aransas Bay to the south and Matagorda to the north offer large cross sections opening onto enormous surface areas, so would represent the path of lesser resistance for the majority of the river flow. Nonetheless, a flood large enough might still raise water levels sufficiently in Mesquite Bay to inundate Cedar Bayou. The best guide to what level of flow would be required would be observational

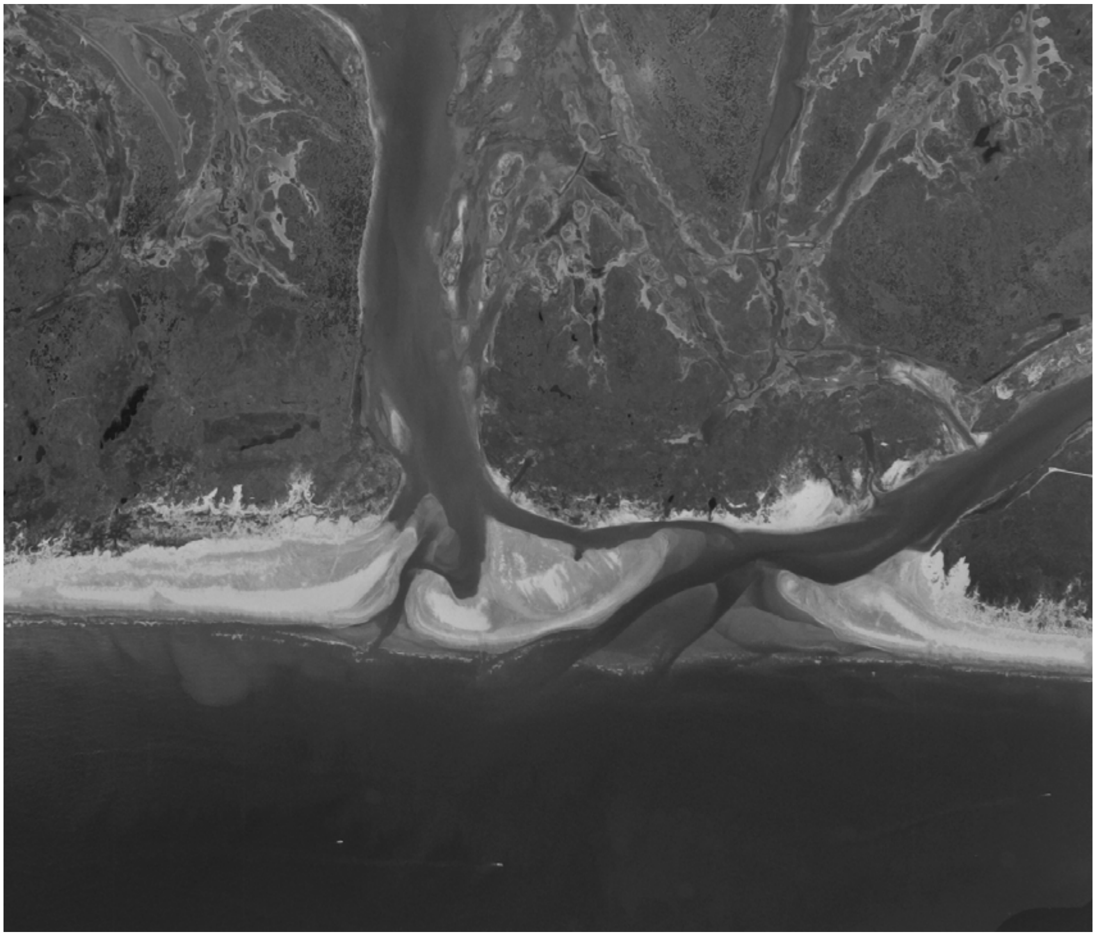

Figure 5 - Detail of Cedar Bayou beach zone during high flow event, 22 April 1969. (From USGS AR1VCFI00010053 Roll 1 Frame 53)

experience. Two vertical aerial photographs are available under high flow conditions, USGS 1 Feb 1979 and USGS 22 Apr 1969 (see Appendix C). In each of these the date of the photograph is embedded in a 3-4 month period of high flows. In the 1979 photo, while the inlet is open, there is no indication of elevated water levels. In the 1969 photo, shown in Fig. 5, it is apparent that much of the beach area is underwater, as evidenced by the extensive shallow (but submerged) bars. The flow conditions for the 1979 photo exceeded about 80% of the period of record data*, while those for the 1969 photo are higher, exceeding about 90% of the data. Since

* Based on the Texas Water Development Board compilation of total monthly flows into San Antonio Bay for the period 1942-2008.

this photo was taken in mid-April, it is possible that the water-level elevation is more associated with the spring high-water (the semi-annual "tide" of Fig. 4) rather than with river flow. This photo is consequently rather flimsy evidence for drawing any conclusion, but provisionally it appears that a flow well in excess of the magnitude of that of April 1969 (about 400 Taf/mo) would be required to inundate the inlet through the beach zone. Of course, the question of whether this level of inflow would be additionally sufficient to force a flow through the inlet is a separate matter, to be addressed in Section 4. We observe that in Fig. 5 the channel out from Cedar Bayou is clear, as well as the opening out from Vinson Slough. There is no indication of sediment discharge through the inlet, i.e., no plume in the nearshore Gulf and no turbidity difference between Vinson Slough and Cedar Bayou, which would have been expected if there were a substantial seaward flow through the inlet.

As noted at the beginning of this chapter, the maintenance of Cedar Bayou depends upon the ability of flows in the inlet to scour and erode sediments during high velocities that settle to the bottom of the inlet during low velocities. The fact that the inlet is observed to close in its beach zone means that the source of sediments (notably, the fine sands making up the beach) settling in the inlet channel exceeds the scouring ability of inlet throughflow. A primary source of sands in this zone is littoral transport into the inlet mouth by longshore drift, driven in turn by waves (primarily swell) whose crestlines approach the beach at some acute angle. (There is a vast literature on beach sediment dynamics, of which the work of Bagnold is fundamental, e.g., Bagnold, 1963, Inman and Bagnold, 1963. The *Coastal Engineering Manual*, née *Shore Protection Manual*, of the U.S. Army Corps of Engineers is a comprehensive source, USCE, 2008, especially Part III Chaps 2 & 6, Part IV Chap 3. While much work has been done on conditions for settling and incipient motion by flowing water, and on the mechanics and sense of littoral transport, the computation of the actual volumes of sand transported in either process remains elusive.)

It has been long recognized that—assuming the crestlines of swell propagate in the direction of the wind—the prevailing onshore winds impingent upon the concave Texas coastline create a zone of *net* littoral drift convergence in the general vicinity of Aransas Pass (e.g., Carothers and Innis, 1960, Watson, 1971), exemplified by the asymmetric accumulation of sand at barriers such as jetties along the coast. As the onshore winds range from E to S over the course of the summer season, the actual zone of convergence migrates along the coast. Cedar Bayou lies within the region through which the point of convergence passes. Like almost all of the Texas shoreline, this region evidences long-term retreat, but at a much more modest rate—about a foot per year—than the beaches farther south or north, according to BEG (2010). An earlier study by Morton (1977) found a net shoreline accretion over the period from the 1880's through the mid-1970's. This net long-term accretion was the integrated effect of two very different shoreline behaviors: until the 1930's this shoreline was accreting at a substantial rate, but this reversed in the 1930's, the shoreline eroding thereafter. That Matagorda Island is not eroding as quickly as the beaches upcoast and downcoast may be attributable to the longshore transport of these eroded sediments into the area, especially from upcoast. For Cedar Bayou, unlike the larger, jettied inlets of Matagorda Entrance Channel or Aransas Pass, this exposure to longshore littoral drift is probably more than enough to overbalance the relatively low flows through the inlet.

3. EVOLUTION OF INLET

The segment of the Texas coast containing Cedar Bayou has received considerable attention from geologists over the years. Of immediate relevance to the evolution of the inlet is the American Petroleum Institute Project 51 (Shepard and Moore, 1955, Shepard et al., 1960). The study area of this project ("Area 51") included San Antonio, Aransas and Copano Bays, and the adjacent barrier islands, Matagorda and San Jose. More recently, the washover fan adjacent to Cedar Bayou to its south (Fig. 2) was given detailed study by Andrews (1970), and Matagorda Island by Wilkinson (1973), see also Deal (1973) and Wilkinson (1975). From these, a picture of the geological evolution of Cedar Bayou and environs emerges, as follows:

(1) After the close of the Pleistocene, about 12,000 years BP, the nascent Matagorda Island was a sand shoal, which migrated inland as sea level swiftly rose with the retreat of glaciers. During this period, the Pleistocene river valleys were inundated by rising sea level and filled with sediment.

(2) Around 4000-5000 yrs BP, the rate of sea-level rise sharply declined, and the island stabilized in more-or-less its present location, as a low sandbar with numerous passes between the Gulf and an elongated lagoon, or sound, behind the sandbar.

(3) With sea-level rising much more slowly, the Matagorda Island began prograding seaward, and by 3000 yrs BP, it had nearly doubled its width. At this time, three major passes through the island remained active, all of the others being filled. There was an even larger pass at the southern end of the island, whose location was in the vicinity of the present washover fan to the south of Cedar Bayou (Fig. 2).

(4) The island continued to prograde, creating a present-day sequence of dune ridges separated by swales, now in its interior, marking successive positions of the island dune chains.

(5) At some point in time after 3000 BP, a narrow channel, the primordial Cedar Bayou, opened between the pass at the southern end of Matagorda Island and the next pass to the north, at the eastern boundary of the channel-fill area of Fig. 2. There is a suggestion by the recurvature of the dune ridges just to the east that this was the site of a much older tidal pass, dating back to the early progradation phase of the island (Wilkinson, 1973).

(6) After Cedar Bayou formed, probably around 2400 yrs BP (Andrews, 1970), the accretion of a tidal delta began on the west side of the inlet. Interestingly, this predates the *oldest* sediments in the washover fan (ca. 1700 yrs BP, Andrews, 1970).

(7) Around 2000 yrs BP seaward progradation ceased. All of the passes through Matagorda Island filled. The pass at the south end of the island (as well as that at the north end, Pass Cavallo) remained active.

(8) Approximately 1700 yrs BP, the washover fan adjacent to present-day Cedar Bayou began to form, associated with the tidal pass to the south, at first rapidly prograding into the bay.

(9) About 1500 AD, around the time of Columbus, the major tidal pass at the south end of the island silted closed. Progradation of the washover fan ceased at this time (based on the youngest radiocarbon dates found in bayside fan sediments by Andrews, 1970). Subsequently, Cedar Bayou migrated to the south, in the process obliterating the earlier ridge-and-swale topography, and creating the channel-fill zone of Fig. 2.

(10) Certainly since before the Civil War (given the 1858 reconnaissance of the U.S. Coastal Survey, *cf*. the 1867 chart of Felix Blucher), most likely earlier, the gross physiographic features of Cedar Bayou channel, notably its NNE-SSW trend and the washover fan to its west, have not substantially changed.

(11) Sometime after 1900, the fore-island dune chain on Matagorda Island began migrating inland, to form the present maximum-elevation ridge of the island. These are much higher than the relict dune ridges (now stabilized). These dunes reached their present position around 1935 and have become stabilized

> by vegetation. Since 1935, a new line of dunes has formed just inland from the backbeach.

The earliest technical mapping of Cedar Bayou is evidently the reconnaissance survey undertaken by the Coast Survey in 1858, reported by Superintendent Bache (1859). In March-June, the field party led by Assistant S. A. Gilbert, assisted by C. Hosmer, worked its way from Pass Cavallo to Aransas Pass mapping the interior bay shoreline by plane table, a preliminary to the later triangulation of this section of the Texas coast. The depiction of Cedar Bayou is strikingly similar to the maps of the twentieth century, e.g., Figure 6. The following year, Gilbert's party returned to the area to complete triangulation and shoreline mapping, joined by a second survey party that carried out topographic mapping. In his report to the Survey, Gilbert (1859) described Mesquite Bay and Cedar Bayou as follows:

> Mezquit *[sic]* bay is about five miles long, northwest and southeast, and about three miles wide, with an average depth of four feet throughout, and soft muddy bottom. It has direct communication with the Gulf of Mexico through Cedar bayou, into the north end of which there is but one foot of water, through the bayou about ten feet, and at the Gulf outlet, or south end, about four and a half feet. Its length is three miles, and average width about a hundred and sixty yards. The oysters of this bay are noted as being the best on the coast. Fish are abundant, and to be had at all seasons of the year.

Figure 6 displays a detail of the Cedar Bayou channel showing three mapped shorelines from the twentieth century. Sources for these shorelines are:

1934 -	Nautical chart, U.S. Coast & Geodetic Survey 1285
1952 -	USGS 1:24,000 topographic quadrangle St Charles Island SE
1973 -	USGS 1:24,000 topographic quadrangle St Charles Island SE photorevised

While such map sources are generally regarded as authoritative, the applicable dates have considerable uncertainty. The 1934 nautical chart, for example, is based upon surveys in the area in the early 1930's and earlier. It would be necessary to consult the USC&GS reports (*viz.* descriptive reports filed by the survey parties, chart letters or field examination reports, and history sheets, archived at the National Oceanic and Atmospheric Administration) to establish the applicable date for this shoreline. The 1952 USGS map is compiled from a combination of

Figure 6 - Detail of Cedar Bayou showing three shorelines from the twentieth century, see text. The least back-island width and the throat width are based on the 1973 shoreline.

photogrammetry based on photography in the 1940's, after WWII, and plane-table surveys in the area in 1952. Which of these sources (and in what combination) are the basis for the shoreline, and therefore the corresponding applicable date(s), are unknown without extensive archival searching. Finally, the 1973 photorevision is the publication date, not necessarily the date of the photography source. We can be sure that the date is no later than 1973, and probably from the late 1960's or early 1970's. Again, a considerable effort of accessing the photography used by USGS would be necessary to establish this precisely. (The image of Fig. 5 was no doubt one of these sources. However, the emergent islet in the inlet mouth shown on the 1973 quadrangle is absent or underwater in Fig. 5, and the open pass to the south, connecting Vinson Slough is not depicted on the map.)

There is exactly one (1) historical survey of Cedar Bayou in which cross sectional profiles were measured, namely the February 1954 survey performed by Lockwood and Andrews (1954). It is worth noting that, excepting the Lockwood & Andrews survey, the 1934 map of Cedar Bayou is the *latest survey* including both widths and soundings of the channel *in an open state* available to this study, and perhaps extant. This is a frustrating information deficit. Even a simple measurement of controlling talweg depth (and approximate location in the channel) at various intervals over time would have been of immense value to the present study. Such data would be easily and inexpensively obtained, especially given the frequent visits to Cedar Bayou by technical personnel as well as knowledgeable boaters.

Despite the imprecision in dates, these shorelines illustrate that the back-island configuration of Cedar Bayou has remained fairly stable in the twentieth century, while the beach zone has exhibited considerable variation. Two quantitative measures in the horizontal plane are indicated in Figure 6, the least width in the back-bay reach, and the throat width in the beach zone. The least back-bay width, as the name suggests, is the minimum width of the Cedar Bayou channel anywhere in the reach from approximately Grass Island to the opening of the channel in Mesquite Bay. This least-width location generally falls in the vicinity that is shown in Fig. 6. In the beach zone, the "throat" is defined for present purposes to be the least width in the channel segment that trends southwest from the dune line, i.e. from the dune line to the point at which the

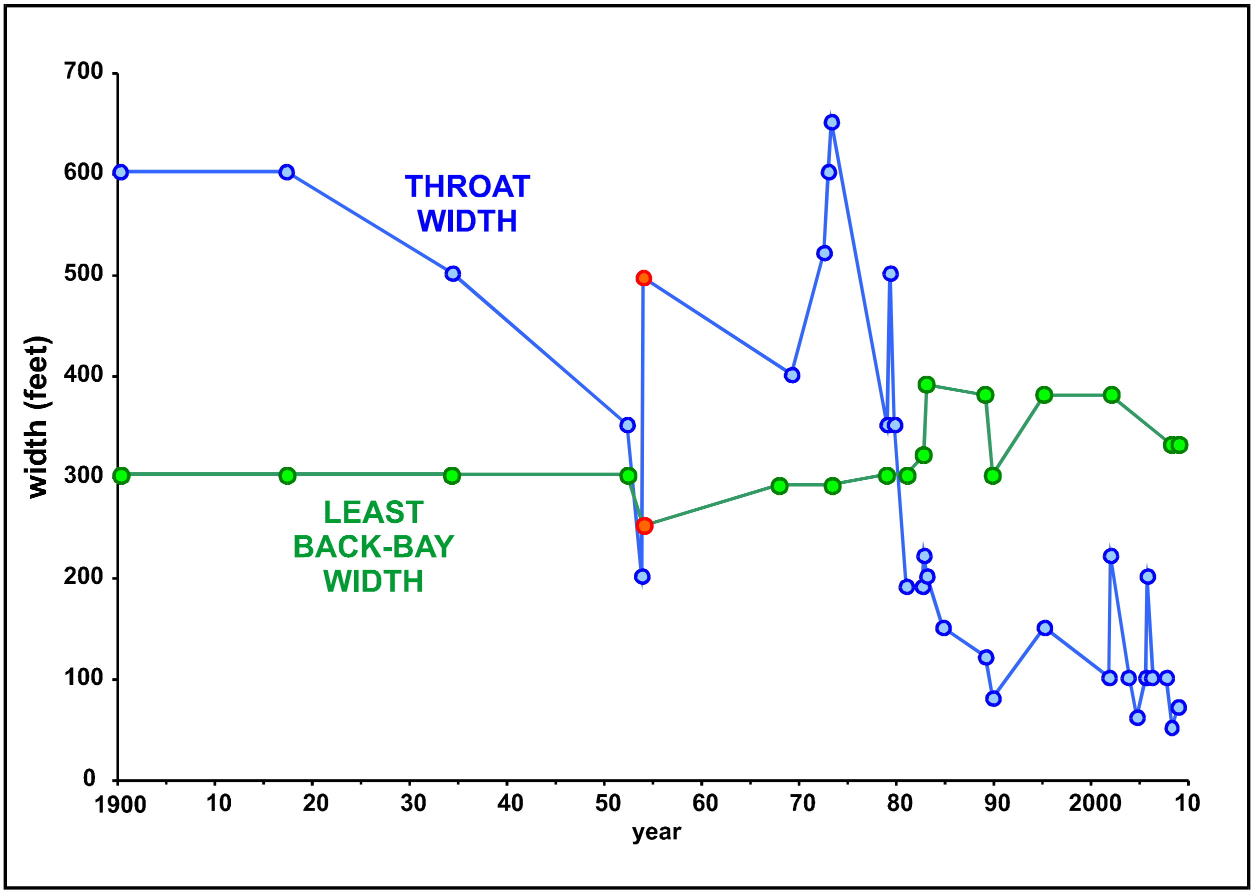

Figure 7 - Time history of width measures for Cedar Bayou.
Red data points are from Lockwood & Andrews (1954) survey.

channel turns seaward. For the 1973 shoreline, the least back-bay width is 290 ft, and the throat is 650 feet.

The variation over time for each of these width measures is shown in Figure 7. The stability of the least back-bay width is clearly demonstrated, ranging 300-400 ft over the century, while the throat width is much more variable, but generally trends downward. Not all of this variation in width is natural. The channel has been dredged in its entirety, or in limited reaches, four times in the past century, in 1939, 1959, 1987-88 and 1995. Unfortunately, there was no reliable information available to this study as to the specific reaches dredged or the volumes removed. In addition to these dredging events, the Gulf entrance has been opened by dragline (1956) and closed by bulldozer (1979).

4. INLET TIME SERIES 1900-PRESENT

In assembling a timeline on Cedar Bayou from the various information sources, the objective was to render the status of the inlet quantitatively. Unfortunately, many of the historical *observations* about the status of the inlet are qualitative, e.g., “open” or “open at high water”. Moreover, the typical *data* are either a map (without depths), a reported depth (without a map, or specific location), or an aerial photograph. The best single source of information is a set of cross sectional profiles along the channel. There is but one such survey extant for Cedar Bayou, from 1954. Next best is a hydrographic survey chart with soundings. As remarked above, the *latest* such survey available of Cedar Bayou *in an open state* is the 1934 USC&GS nautical chart.

The U. S. Coast and Geodetic Survey (USC&GS, formerly the Coast Survey, now the Office of Coast Survey of the National Ocean Service) has historically been responsible for precise determination of the nation’s shoreline, as well as operation of tide gauges, prediction of tides, and establishment of horizontal and vertical control. Prior to WWII, shorelines were surveyed by the use of plane tables. The procedures and field protocols of the USC&GS are detailed by Shalowitz (1964). While USC&GS references bathymetry and submerged hazards to some low water datum for navigation purposes, such as mean low water or mean lower low water, the shoreline position on its maps is at mean high water. USGS apparently follows a similar convention. Only since WWII has photogrammetry become incorporated into the process, so that modifications to the shoreline can be readily incorporated into new maps. Earlier surveys were performed infrequently and therefore provide only a very spotty record of shoreline history.

The primary source of information on shoreline position in the present study is aerial photography, mainly vertical photography. From these, the shoreline can be identified, and if an accurate scale can be constructed, key dimensions may be measured. Oblique photographs are difficult, sometimes impossible, to rectify and assign an accurate scale, so were given only limited use to qualitatively establish features of Cedar Bayou.

Aerial photography offers, in principle, a superior data source on shoreline position because the photograph can be precisely dated (presumably). This precision is limited to the calendar date, because the clock time is generally omitted from the readily available metadata. For several otherwise excellent photos, the date was given only to the month.

An instantaneous shoreline position, such as exhibited by photography, is subject to considerable uncertainty arising from the unknown variation in water level in coastal regions. Ideally, tide data would be obtained from the nearest gauge and translated to the Cedar Bayou area, then used to adjust the photographed shoreline position to that of mean high water. This is a complex procedure for which the extant tide information is often inadequate. While this was manifestly beyond the scope and resources of this study, without an accurate acquisition time for the photograph, it is impossible to relate an aerial photo to concurrent water level. Therefore, the stage of the tide, including meteorological effects, remains a source of uncertainty in interpreting aerial photography. (It should be noted that this is also a source of uncertainty in the mapped USC&GS shoreline position, because tidal adjustment could be effected only based on tidal variation recorded by the survey crew during the short period of time while in the area.)

The order of magnitude of this uncertainty can be estimated from the background information of Section 2, above. The diurnal tide can range from less than 0.5 ft for small declination to 3.5 ft at great declination. The fortnightly tide can contribute another 0.5 ft, and the semi-annual secular tide has a nominal range of another foot, but can be more than twice this in some years. All of these are independent contributors to the total water level variation (and we have not even addressed the additional factors of wind denivellation or flood events). A nominal composite uncertainty from tide variation alone is as large as 5 ft. From USGS topography, the detail map of Figure 8 indicates the area potentially subject to inundation due to these tidal variations only. Even a rise of 2-3 ft in water level can significantly encroach into this zone and influence the apparent shoreline position.

Key dimensions of the Cedar Bayou channel are the *throat width* and *backbay width*, as defined in the previous section (see Fig. 6 and associated text). These are least-width measures in

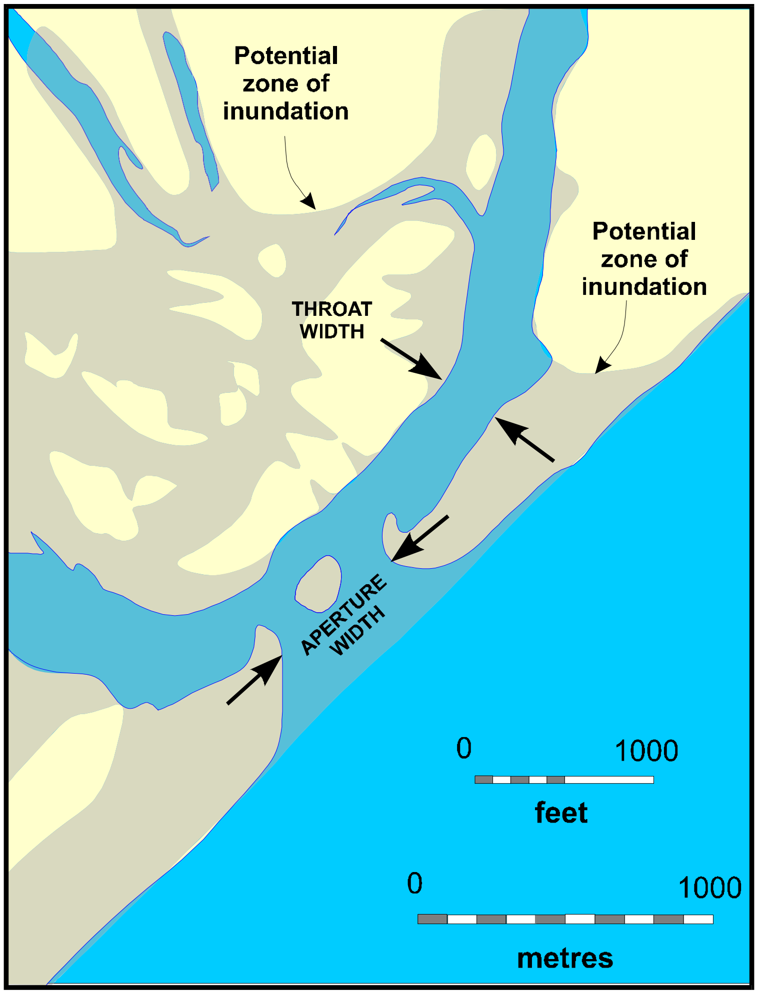

Figure 8 - Detail of Cedar Bayou entrance with 1973 shoreline, showing region subject to inundation by normal tidal and seasonal water-level variations (grey area)

specific reaches of the channel. To these we add one more, the *aperture width*, which is defined to be the least width of the segment of the channel running across the beach zone to the Gulf, generally orthogonal to the shoreline, indicated in Fig. 8. The most desirable measure of each of these is not the width or the depth, but the cross sectional area, because this is the parameter most closely related to the capacity of the channel to carry flow, to its ability to exchange water between estuary and sea, and to its effectiveness as a migratory access. Moreover, cross section area depends sensitively on both width and depth, and the smallest value in the entire Cedar

Bayou channel (usually the smaller of the throat or the aperture) is the controlling section for these physical exchange processes.

Since we are able to determine widths (without depths) from maps and photos, and occasionally find a depth reported (without width), an estimate of cross section area is at best only approximate. A simple cross-section geometry is assumed, that depth across the channel is a parabolic function of width with apex at the talweg, and the measured cross section from the 1954 survey together with the three (3) instances in the historical record in which *both* talweg depth and channel width are reported were used to establish the parameters of this relation. Details are given in Appendix D. (Any such measurements used to determine channel shape are limited only to those occasions when the channel shape represents the response to normal forces of deposition and scour. After dredging or hurricane events, this relation cannot be expected to hold, even approximately.) The resulting estimated cross section should be regarded only as a numerical *index* to the functional dependence of section area on width or depth, not as an accurate computation of cross section. Indeed, profile irregularities, multiple channels, and shelf regions will undermine the accuracy of the parabolic channel approximation. For example, for the survey of 1954, the actual channel area was overestimated by about 30%.

The measured Cedar Bayou channel widths from maps and photography, surveyed or reported depths, the associated estimated channel cross sections, and the single set of surveyed profiles from 1954 make up the core of the inlet chronology assembled in this project. These were compiled into a time series extending from 1900 through 2009 (which we define as the "present" thereby preserving the academic tradition of always being behind schedule). In addition, occasional reports of the depth over the bar (meaning the shoal directly out from the Gulf mouth of the inlet), controlling depth (without width) in the channel, and typical talweg depth, as well as controlling depth after dredging, were included in the compilation for informational purposes.

The literature is replete with qualitative reports of the status of the pass as "open" or "closed", or some equivocal partial measure such as "open at high water," "shoaled at low water," or "occasionally open." These are valid observations when reported by reliable observers, but are not readily quantifiable. The exception, of course, is the "closed" state, which is taken to mean that the aperture has zero width (and zero cross section). To include these sorts of observations in the chronology, they were translated to three categories, "open", "closed" and "marginal". The last of these, "marginal" includes all of the equivocal reports, as well as oblique photographs that display an inlet with apparently very small dimensions. Quantified cross sections (from maps and vertical aerial photographs) were incorporated into this *categorical* compilation by assuming "marginal" to apply to those with cross sections less than 100 sq ft, and anything larger to be "open". By this artifice, the time series of inlet *category* becomes the longest and best-populated chronology of an inlet feature that we can construct.

To this compilation was added (1) tropical cyclones that offer some potential for affecting the Cedar Bayou area (or were invoked in a literature report as explaining some observed behavior of Cedar Bayou), (2) human activities affecting the inlet, *viz*. dredging or closure, (3) flood events entering San Antonio Bay, (4) any other events (e.g., meteorological) that might be of use in interpreting the response of the pass, or the behavior of water quality (e.g., salinity) or biology (e.g., abundance). The complete compilation of these data is presented in Appendix A. It is intended to be organic, and to continue growing as new entries are found, validated and entered.

The data on tropical disturbances are particularly important in seeking to explicate the observed behavior of Cedar Bayou. The ultimate authority on tropical storm data is the National Hurricane Center, which continues to sort and sift through historical data on these storms to improve their track lines and characterization. For this compilation, McAdie et al. (2009) was the primary source, supplemented by additional references where warranted. Three classifications of intensity are used in McAdie et al. (2009): "tropical storm", "hurricane" and "major hurricane", in which a major hurricane is Category-3 or higher on or about landfall, on the Simpson-Safir scale. In the chronology of Appendix A, the storm name, intensity classification, date of landfall, approximate landfall location, and comments regarding the behavior of the storm or reported effects on Cedar Bayou are given. A more complete listing of storms landfalling in Texas or potentially (however remote) affecting Cedar Bayou or the neighboring coast is tabulated in Appendix B. Which storms from Appendix B were ultimately included in the chronological compilation was a matter of judgment. The effects of such storms, especially those of marginal intensity, are frequently exaggerated, not only in the press but occasionally in scientific reports: there is a tendency to connect any unusual hydrographic behavior on the coast to a tropical disturbance somewhere. The usual effect of such a storm is considered to be the opening of inlets, especially on the barrier island north of the landfall. These storms can also increase the littoral sand load by generating swell, which becomes surf in the nearshore zone, and both mobilizes sediment and forces a longshore drift.

It is sometimes stated that flood events play a rôle in maintaining Cedar Bayou or in re-opening the inlet after it has closed. This no doubt arises from the observation that Cedar Bayou is now open, or is larger than it was before, on some occasion that happens to follow, perhaps by some weeks, a flood event, especially on the Guadalupe or San Antonio rivers. Such connections can be specious. When precisely the inlet opened or enlarged is often unknown. Flood events frequently happen in association with seasonal high waters in the spring or fall, and perhaps with frontal passages, so it can be difficult to separate which hydrographic effect, if any, might have been responsible. To allow the examination of relations between the inlet and inflow, the total inflow into San Antonio Bay, based largely upon the evaluation of gauge data of the U.S. Geological Survey, and analyses and modeling of the Texas Water Development Board (see Ward, 2010), was included in the present data compilation.

Figure 9 is a graphic depiction of the chronological compilation of Cedar Bayou history starting in 1910. This is rather information-dense. For clarity, it is divided into three segments, each consisting of 40 years (the last two segments having a 10-year overlap with the previous segment at their beginning). Quantitative data on the inlet state, as measured by the estimated controlling cross section (i.e., the minimum of the throat and the aperture), are shown as prominent data points, while the categorical state (open, marginal, or closed) is indicated by the shaded zones. (The actual observations or reports used to define these zones are evident as small data points on the zone boundaries. Consultation of Appendix A will disclose the nature and source of each observation.) On this time graph are superposed the tropical disturbance events, dredge or fill events, and a time series of monthly flow into San Antonio Bay. Tropical disturbances are shown as vertical arrows at the top of the diagram, their length and pen-weight indicating the strength of the event (tropical storm, hurricane, major hurricane), along with the general area of

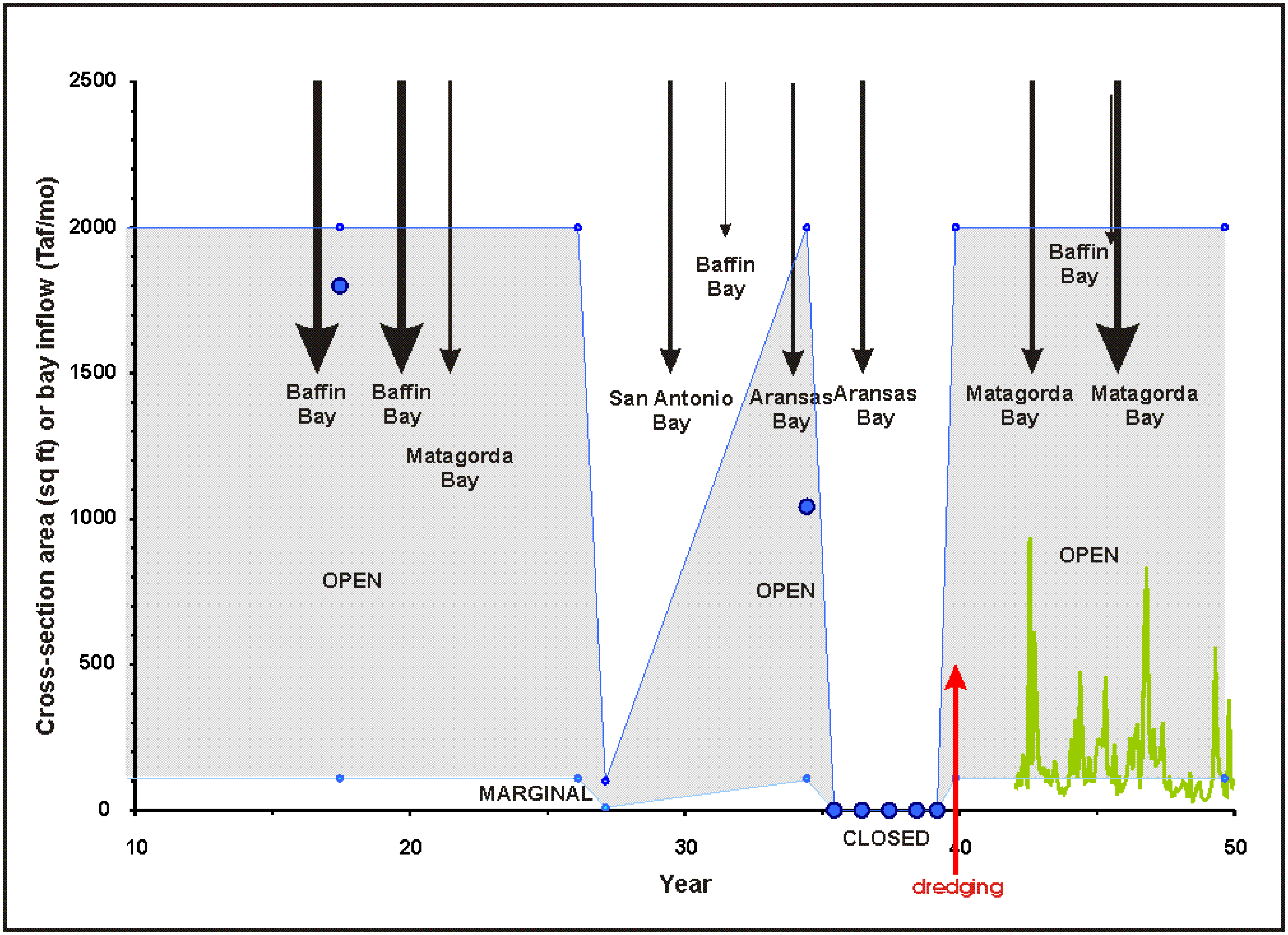

Figure 9a - Time history of Cedar Bayou, from chronological data (see text), 1910-1950.

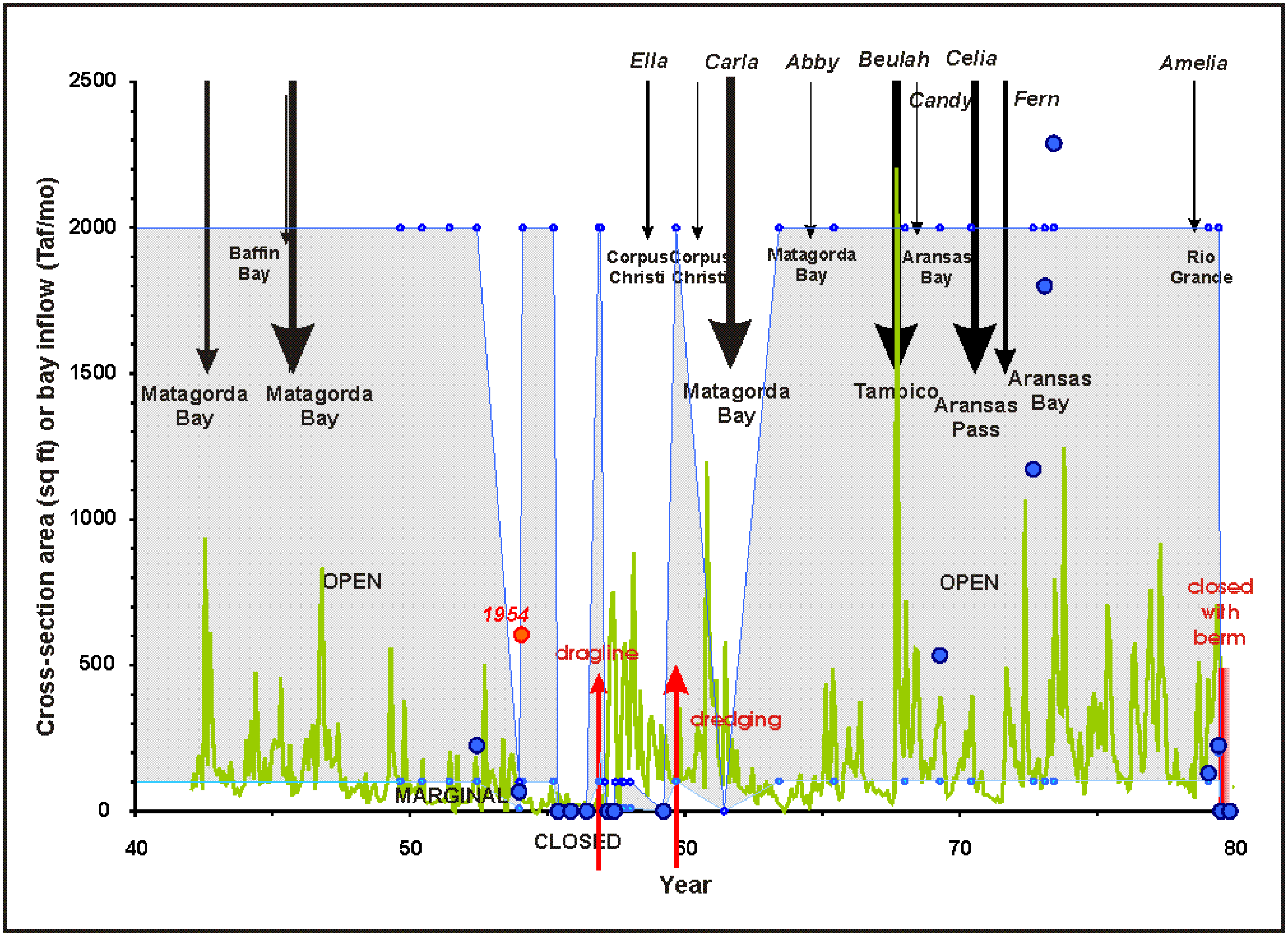

Figure 9b - Time history of Cedar Bayou, from chronological data (see text), 1940-1980.

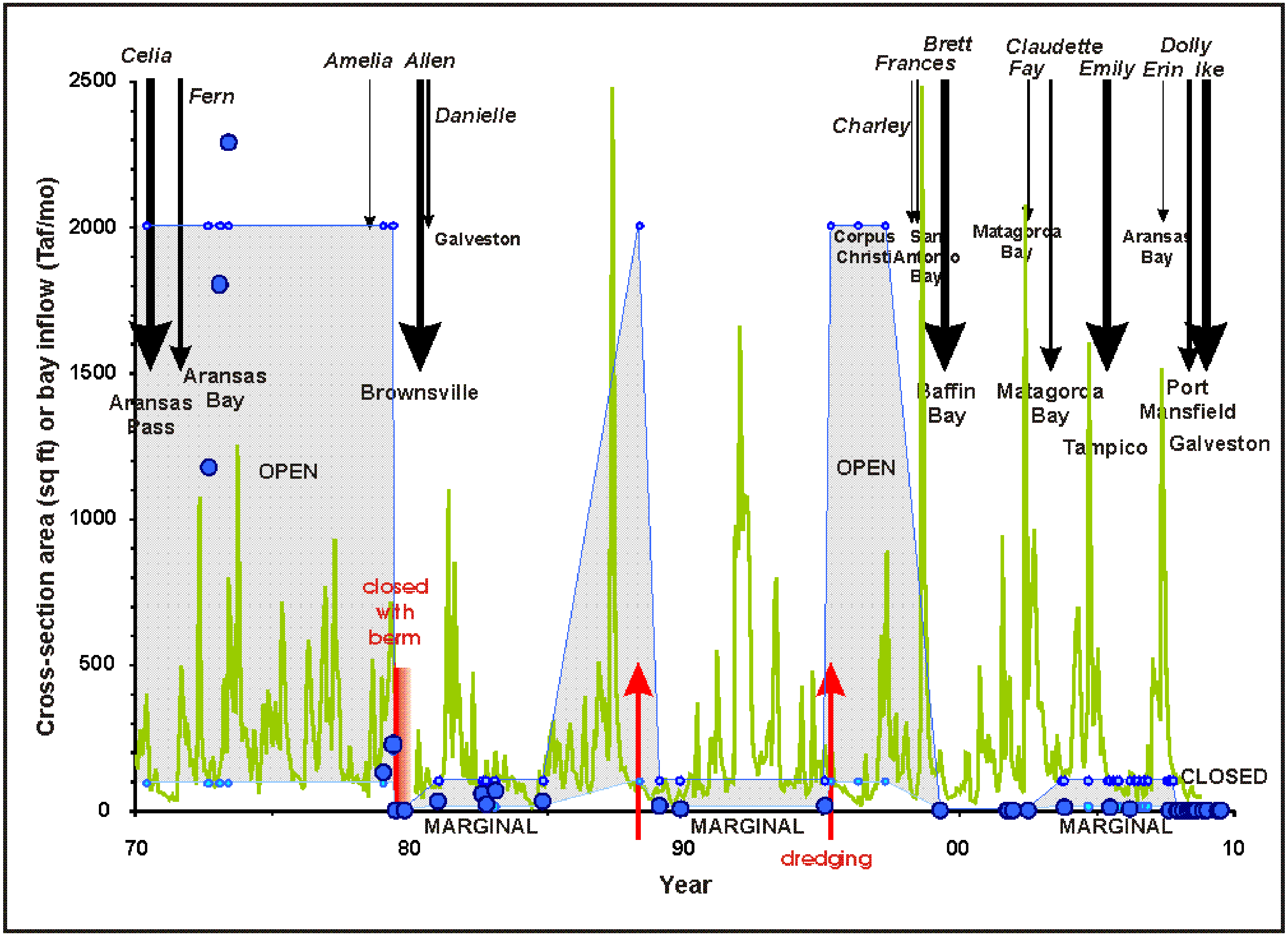

Figure 9c - Time history of Cedar Bayou, from chronological data (see text), 1970-2010.

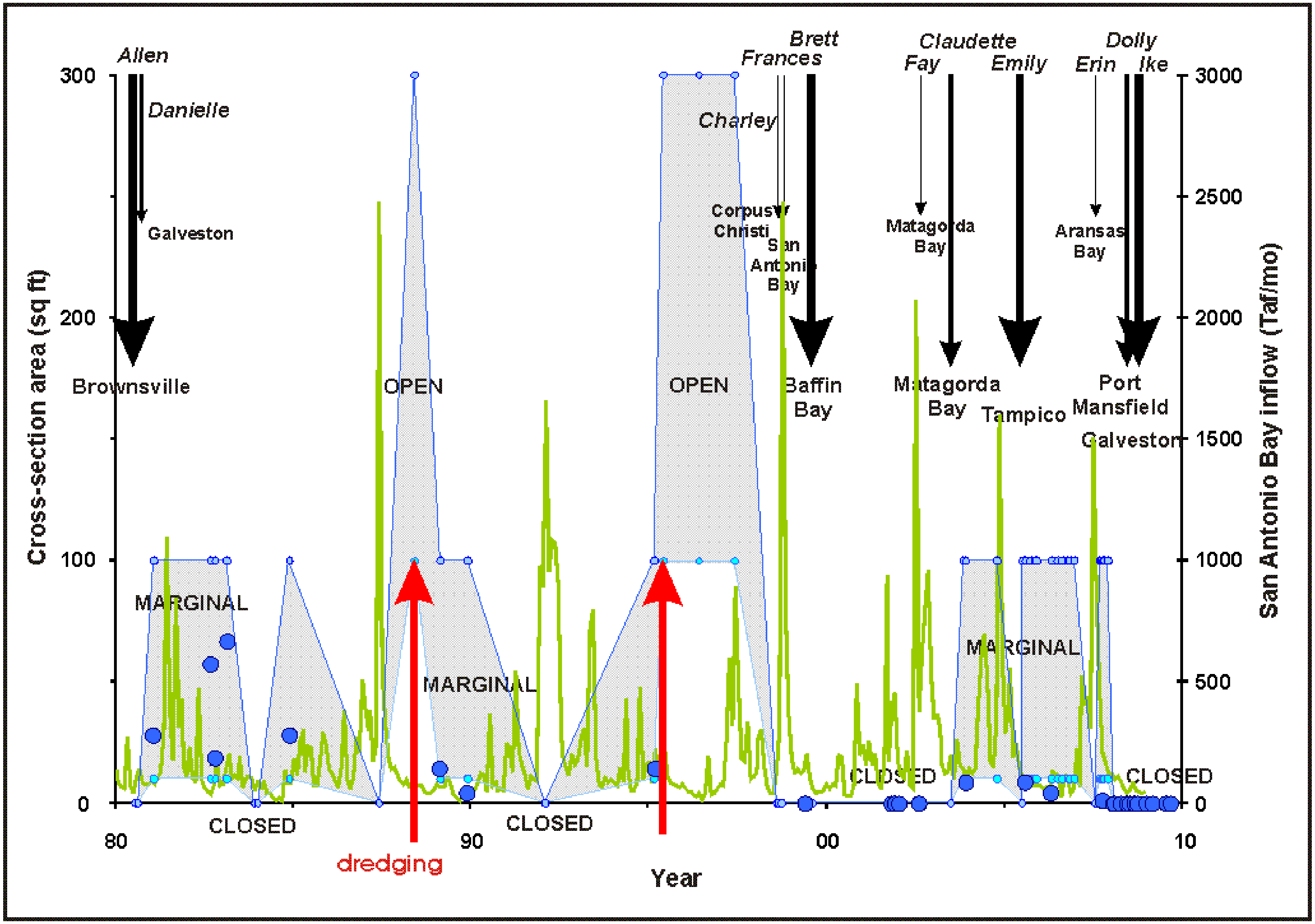

Figure 10 - Time history of Cedar Bayou, from chronological data (see text), 1980-2010, with better resolved cross-section data.

landfall. Dredge and fill events, in contrast, are depicted as vertical red arrows at the bottom of the diagram. The monthly flow into the bay is the green trace starting in 1942. The left ordinate serves as the axis for both estimated cross section (square feet) and total flow (thousands of acre-feet per month).

Generally, over the past 100 years, Cedar Bayou has declined in cross section, despite the efforts to open the inlet by dredging. Because of the recent activity in this respect and the importance of interpreting the inlet's behavior, Figure 10 shows a more resolved display of inlet cross section for the time period 1980-2010 (also somewhat better resolved in time than Fig. 9). In this period, there is no quantitative measure of inlet area that exceeds 100 sq ft (our qualitative category of "marginal"), despite two dredging projects, numerous tropical storms and record inflows to the estuary. A detailed examination of the history of the inlet offers insight into this fact.

In the first half of the Twentieth Century, the inlet was generally open, except for closing during the 1950's drought. This general statement is, however, based on four surveys in the area and qualitative reports in the literature. What is probably more significant is the size of the inlet in those years, with cross section exceeding 1000 sq ft (when open). The controlling (i.e., least) depth was found in the inlet aperture, and there was no indication of shoals in the throat area. Although there are numerous reliable later reports that the inlet was "open", the next quantifiable data does not appear until the early 1950's, when the inlet was evidently shoaling and ultimately closed. Unfortunately, there is a data gap after the 1959 dredging project of TGFC until 1969 (Fig. 9b), a crucial segment of the inlet's history. (The one report that the inlet was closed in 1961 appeared in the *U.S. Coastal Pilot* for 1962, and is of dubious authority. Apparently, after the inlet's first appearance in the 1958 *Pilot*, no new reports were received so the *Pilot* continued to post the last known status of the inlet. All later *Pilot* reports were therefore ignored in this data compilation.) The 1969 aerial (see Fig. 5) indicates a controlling cross section of 500 sq ft (during a high-water event). For the next decade, the inlet began to increase, achieving its largest recorded historical size in 1973. At the close of the decade (with a 6-year gap in coverage), the inlet has shoaled to marginal dimensions.

Figure 11 - Aerial photograph 11 Nov 79 showing Ixtoc berm in place

Figure 12 - Aerial photograph 2 Dec 81 after inlet abandoned bermed channel

Figure 13 - Aerial photograph 6 Mar 89 within months of completion of 1988 dredging

In summer 1979, to prevent contamination from the Ixtoc oil spill, Cedar Bayou was bulldozed closed, as evident in Figure 11. There is no reliable information available as to how long this berm remained, though there are anecdotal reports that the inlet was re-opened by Hurricane Allen (August 1980). Certainly by 1981, while there is a remnant of the berm, the inlet channel has shifted to the north, see Figure 12. By September 1982, the channel had re-occupied its original southernmost channel, and there was no vestige of the berm remaining. From this point in time on, as depicted in Figure 10, the inlet remained in a marginal condition apart from two or three years after the 1995 dredging project.

For the remainder of the 1980's the inlet appears much as it did prior to the berm installation of Fig. 11, i.e. extending over the entire reach of the beach zone and debouching to the sea in the southernmost channel location. Hoese (1958) and Simmons and Hoese (1959) describe the evolution of the inlet from its open state in November 1939 (after the TGFOC dredging project)

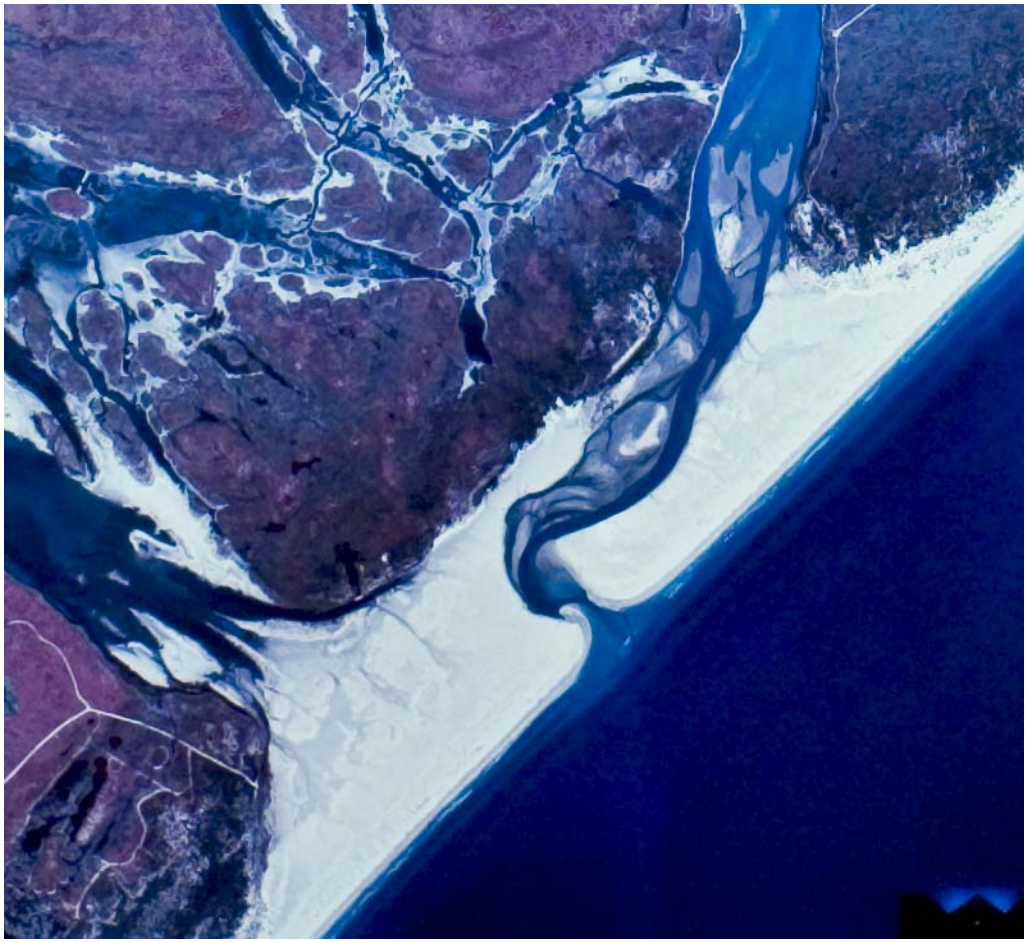

Figure 14 - Aerial photograph 18 Mar 95

to its closure in 1955 as proceeding from a channel to the sea at the northern end of the beach zone, as an extension of the main axis of the interior channel, to one positioned at the southern end, via spit accretion from Matagorda Island and erosion of the San Jose Island shoreline. This is consistent with the migration of the larger tidal passes on the coast, notably Aransas (prior to stabilization) and Cavallo, under the influence of dominant littoral drift from the northeast. The 1988 dredging project was reported to have resulted in an "open" inlet, but there are no photographs available or quantitative soundings. In any event, within the year, the inlet was marginal again (Fig. 10). Its configuration in March 1989 is shown in Figure 13. Probably the inlet was opened by again dredging to the sea in the direction of the main axis of the interior channel, i.e. opening the channel on the north end of the beach zone, but information is not available to confirm this. Following the pattern reported by Simmons and Hoese (1959), the aperture channel migrated to the south. There is a hiatus in photography and reports for the first five years of the 1990's, until just before the 1995 dredging project, Figure 14, then another hiatus for the next five years.

In considering the morphology of Cedar Bayou, one notable change is evident between its state in the mid-twentieth century and that at the close of the century, as disclosed by a close examination of Figures 2 (1969), 12 (1981), 13 (1988) and 14 (1995), namely the growth of substantial bars and shoals in the lower section of the interior channel upstream from the beach zone. This is first evident in 1981, Fig 12, by a spit prograding upstream in the center of the main channel. By 1988, bar structure has developed well into the interior reach (note the shoals upstream from the emergent island in Fig. 13), and by 1995, these shoals have become complex and occupy the majority of the channel, Fig. 14.

There is little evidence in these time series that tropical disturbances are the operative agent in keeping the inlet open anywhere near its original size. There certainly has been no shortage of such events since 1998, yet the state of the inlet seems impervious. The only apparent distinction between the storms during the 1970's compared to those more recently is that the earlier storms made landfall squarely on Aransas Bay, with three storms within a four-year period. If such storms do play a rôle in the maintenance of the inlet, it will have to be exposed by a much more careful and quantitative analysis than merely correlation in time.

In Chapter 2 above, a plausibility argument for the rôle of floods in inlet maintenance was proffered by which the operative mechanism is an elevation of water behind the barrier island that forces a flow through the inlet. It was judged that such an event would have to exceed at least 400 Taf/mo to inundate the inlet, and more would be needed to force a flow sufficient to scour the inlet. In the chronology depicted in Figures 9 and 10, there are ample events exceeding even three times this level of flow. The fact that most of these have occurred in the modern period of Figure 10, including record levels of flow and cumulative discharge, yet the pass has remained chronically closed or minimal, refutes the notion that inflow events maintain Cedar Bayou.

5. CONCLUSIONS

The assembly of data establishing a chronology for Cedar Bayou is intended to continue, because there are additional sources of data that have not yet been located for inclusion in the data base. Therefore, it is premature to represent any conclusions from this work as final. At best, this provides a data base for potentially examining whether the state of Cedar Bayou is an operative factor in the variation of abundance of species within the estuaries of San Antonio Bay, Aransas-Copano Bay and their secondary systems, which was, after all, the objective of the project. The time and resources available to this study limited the archival work to sources readily available. We expect that holdings of state agency files (notably, Texas Parks & Wildlife Department coastal laboratories), private aerial photography sources and public sources limited to hardcopy only (such as Galveston District Corps of Engineers), and the files of individual coastal researchers, will yield more information on the history of the pass.

What has emerged thus far is that Cedar Bayou has tended to diminish in size from the surveys of the early twentieth century to the aerial photography of the twenty-first century. The mechanisms that operate to scour and maintain tidal inlets, *viz*. tides, seasonal water-level variations, set-up and set-down from meteorological disturbances, surge from tropical storms, and inflow events, seem to be operating now at roughly the same intensity and frequency over this period, except perhaps for freshwater inflow, which is trending upward. There is apparent no ready hydrometeorological or hydrographic explanation for the declining trend in inlet dimensions, though this certainly warrants detailed study. It may be that the answer lies in alterations in the littoral sand budget along this area of the coast.

The data reported by King (1971) demonstrated the importance of Cedar Bayou as a migratory access route for diadromous species. In light of the chronology depicted in Figure 9, it is important to realize that the pass in the years of the King study was much larger than it has been more recently, certainly since around 1980. It is unlikely that, even when presently “open”, it will now have anything like the effect that it had in the 1960’s, though this must be tested by data analysis.

REFERENCES

Andrews, P. B., 1970: *Facies and genesis of a hurricane washover fan, St. Joseph island, Central Texas Coast*. Report of Investigations No. 67, Bureau of Economic Geology, University of Texas at Austin.

Anthes, R. A., 1982: *Tropical cyclones: their evolution, structure and effects*. Met. Monogr. Vol. 19. Boston: American Meteorological Society.

Bache, A.D., 1859: *Report of the Superintendent of the Coast Survey, showing the progress of the survey during the year 1858.* Ex. Doc. No. 14, Senate, 35th Congress, 2d Session. Washington, D.C.: William A. Harris, Printer.

Bagnold, R. A., 1963: Beach and nearshore processes, I. Mechanics of marine sedimentation. *The Sea*, *3* (M.N. Hill, Ed.), 507-528. London: Wiley Interscience.

Bengston, S., R. Blankinship, and C. Bonds, ca 2004: *Texas Parks & Wildlife Department History 1963-2003*. TPWD, Austin.

Bureau of Economic Geology, 2010: *Shoreline change atlas*. Online resource, URL: http://www.beg.utexas.edu/coastal/imsindexNew.php. (Last access, August 2010.)

Carothers, H., and H. Innis, 1960: Design of inlets for Texas coastal fisheries. *Proc. ASCE, 86* (WW3), 103-128.

Chapman, B. R., 1981: Effects of the Ixtoc I oil spill on Texas shorebird populations. *Proc. Oil Spill Conf.*, API, Washington, D.C.

Collier, A. and J. Hedgpeth, 1950: An introduction to the hydrography of tidal waters of Texas. *Publ. Inst. Mar. Sci. Univ. Texas 1* (2), 120-194.

Deal, D. E., 1973: Geologic environment of Matagorda Island. *Matagorda Island, a natural area survey*. Office of Research, Lyndon B. Johnson School of Public Affairs, University of Texas at Austin.

Elsner, J., and A. Kara, 1999: *Hurricanes of the North Atlantic*. New York: Oxford University Press.

Farrington, J. W., ca 1985: *NOAA Ship Researcher/Contract Vessel Pierce Cruise to Ixtoc-1 Oil Spill: Overview and Integrative Data Assessment and Interpretation*. NOAA Contr. NA80RAC0017, Woods Hole Oceanographic Inst.

Galtsoff, P., 1931: *Survey of oyster bottoms in Texas, Vol 1*. Inv. Rep. 6, Bureau of Fisheries.

Gilbert, S.A., 1859: Extracts from the report of Assistant S.A. Gilbert, descriptive of the coast of Texas intervening between Matagorda bay and Corpus Christi. Appendix No. 32, in: *Report of the Superintendent of the Coast Survey, showing the progress of the survey during the year 1859* (A. Bache, 1860). Ex. Doc. No. 41, Senate, 36th Congress, 1st Session, 324-328. Washington, D.C.: William A. Harris, Printer.

Harris, D. L., 1963: *Characteristics of the hurricane storm surge*. Tech. Pap. 48, Weather Bureau, U.S. Department of Commerce. Washington, D.C.: Government Printing Office.

Hill, G. 1979. Ixtoc's Oil has a Silver Lining. *Audubon 81* (6), 150-159.

Hoese, H. D., 1958: *Hydrographic and ecological studies in Mesquite Bay and Cedar Bayou, Texas*. M.S. Thesis, Dept. Zoology, TAMC, College Station.

Inman, D. and R. Bagnold, 1963: Beach and nearshore processes, II. Littoral processes. *The Sea, 3* (M.N. Hill, Ed.), 529-553. London: Wiley Interscience.

King, B. D., 1971: *Study of migratory patterns of fish and shellfish through a natural pass*. Tech. Report Proj. 2-55-R, Texas Parks and Wildlife Department, Austin.

Leary, T. R., 1959: Aerial photographic survey of Texas Gulf passes. Job E-2, Project M-R-1, Project Report, Texas Game & Fish Commission, Austin.

Lockwood & Andrews, 1954: Field surveys of fish passes at Brown Cedar Cut and Cedar Bayou. L&A, Inc., Corpus Christi.

McAdie, C., C. Landsea, C. Neumann, J. David, E. Blake and G. Hammer, 2009: *Tropical cyclones of the North Atlantic Ocean, 1851-2006*. Hist. Clim. Series 6-2 (6th Rev.), National Climatic Data Center, Asheville, NC.

More, W. R., 1969: A contribution to the biology of the blue crab (*Callinectes sapidusrathbun*) in Texas with a description of the fishery. Tech. Series. No. 1, Texas Parks and Wildlife Department, Austin.

Morton, R. A., 1977: Historical shoreline changes and their causes, Texas Gulf coast. *Trans. Gulf Coast Assn. Geol. Soc. 27*, 352-364.

Shalowitz, A. L., 1964: *Shore and sea boundaries with special reference to the interpretation of Coast and Geodetic Survey data, Vol. 2*. Publ. 10-1, U.S. Department of Commerce, Coast and Geodetic Survey. Washington, D.C.: Government Printing Office.

Shepard, F., and D. Moore, 1955: Central Texas coast sedimentation: Characteristics of sedimentary environment, recent history and diagenesis. *Bull. Am. Assoc. Petr. Geol. 39*(8), 1463-1593.

Shepard, F., F. Phleger, and T. Van Andel (Eds.), 1960: *Recent sediments, northwest Gulf of Mexico*. Tulsa: American Association of Petroleum Geologists.

Shepsis, V., and J. Carter, 2007: Cedar Bayou: inlet dynamics and engineering. *Coastal Sediments '07*, ASCE, New York.

Sikes, D., 2002: Cedar Bayou dredging remains a sticky issue. *Corpus Christi Caller*, 22 Aug 2002.

Simmons, E.and H. Hoese, 1959: Studies on the hydrography and fish migrations of Cedar Bayou, a natural tidal inlet on the central Texas coast. *Publ. Inst. Mar. Sci. 6,* 56-80.

Tunnell, J. W., Jr., B. Chapman, M. Kindinger, and Q. Dokken, 1982: Environmental impact of Ixtoc I oil spill on South Texas sandy beaches: Infauna and shorebirds. *Simposio Internacional Ixtoc I*, Mexico City. 2-5 June 1982.

U.S. Coast & Geodetic Survey, 1936: *United States Coast Pilot Gulf Coast, Key West to the Rio Grande*. Serial No. 590, Government Printing Office, Washington, D.C.

U.S. Coast & Geodetic Survey, 1958: *United States Coast Pilot: Gulf Coast, Puerto Rico and Virgin Islands, 4th Ed*. Government Printing Office, Washington, D.C.

U.S. Coast & Geodetic Survey, 1962: *United States Coast Pilot: Gulf Coast, Puerto Rico and Virgin Islands, 5th Ed.* Government Printing Office, Washington, D.C.

U.S. Corps of Engineers, 2008: *Coastal Engineering Manual*. EM 1110-2-1100, Department of the Army, Washington, D.C.

Ward, G. H., 1980: Frontal-induced hydrographic responses of the Texas bays. *Second Conference on Coastal Meteorology (Preprint Volume)*, 304-307. Boston: American Meteorological Society.

Ward, G. H., 1997: *Processes and trends of circulation within the Corpus Christi Bay National Estuary Program study area*. Report CCBNEP-21, Corpus Christi Bay National Estuary Program, Corpus Christi.

Ward, G. H., 2010: *Inflows to San Antonio Bay*. Interagency Contract No. 0900010973, Surface Water Resources Division, Texas Water Development Board.

Watson, R. L., 1971: Origin of shell beaches, Padre Island, Texas. *J. Sed. Petr. 41* (4), 1105-1111.

Watson, R. L., 2010: Aerial photos of Texas coast. Unpublished photos available on Internet, URL: http://texascoastgeology.com/passes/cedarbayou.html.

Wilkinson, B. H., 1973: *Matagorda Island – the evolution of a Gulf coast barrier complex*. Ph.D. Diss., University of Texas at Austin.

Glossary

aeolian	Windblown.
central pressure index	In a cyclone, the difference between standard atmospheric surface pressure (1013 mb) and the minimum pressure in the center of the cyclone. Also, referred to as central pressure anomaly.
controlling depth	The smallest depth along the axis of a channel. The term is nautical, referring to the depth that limits passage of a ship. The controlling section is the cross section (perpendicular to the channel axis) of minimum area, which limits the volume of flow transported in the channel.
diadromous	Refers to a species that migrates between inland watercourses and the sea at key stages of its life. The term includes anadromous species, like salmonids, that migrate from the sea as adults to breed in inland rivers, and catadromous species, like shrimp, that migrate from estuaries to the sea as subadults, to reproduce offshore.
distributary	A small channel in a delta or alluvial feature cut by water and that occasionally carries flow.
error	In science, the difference between a measured, estimated or modeled value of a variable and its true value.
frequency	With reference to a time signal that repeats, the number of repetition cycles per unit time. The reciprocal of frequency is period, the time duration of one cycle. A complex repeating time signal can be expressed as a sum of simple harmonics, or sine waves, each with a different frequency. This sum is called the Fourier decomposition, or spectrum, of the time signal.
littoral	The nearshore environment generally including the beach and extending out beyond the surfzone.
littoral transport	Movement of material, usually in reference to sediment, within the littoral zone. Littoral drift is synonymous. The component parallel to the shore, called longshore transport or longshore drift, is generally the most important.
longshore drift	See littoral transport.
oblique photography	See vertical photography.
period	See frequency.

Pleistocene	The geological epoch encompassing the most recent cycles of glaciation, from about 2.5 My to 12 Ky BP, its close marked by the retreat of the Wisconsinan glaciers in North America.
prograde	To advance in a specified direction by the accumulation of sediment. For barrier island, this direction is seaward.
talweg	The locus of maximum cross sectional depths in a channel. (The Swedish spelling “thalweg” is also used.)
texture	The grain-size characteristics of sediment, e.g. fractions of sand, silt and clay.
tidal delta	A fan-shaped deposit on either end of a tidal pass. Currents flowing through the pass are of sufficient speed to carry sediment within the pass channel. Upon emerging from the pass, current speeds slow because the flow becomes spread over a larger area, and sediments fall out, forming the delta. Also referred to as the tidal bar. The bar on the interior end of the inlet is the flood bar, on the exterior (or seaward) end, the ebb bar.
vertical photography	Aerial photography in which the plane of the photograph is perpendicular to the local vertical. In contradistinction to oblique photography, in which the perpendicular to the plane of the photograph makes an acute angle with the ground surface.
washover fan	Deposits formed by water flowing across a coastal sedimentary barrier, such as a bar, peninsula or island. As the flow issues into the water behind the barrier, it spreads and loses its ability to carry sediment, resulting in a fan-shaped deposits. Also referred to as washover delta.

APPENDIX A
Chronology of Cedar Bayou

date					BEACH REACH						BACKBAY REACH	
day	*mon*	*year*	*status*	*event*	*least depth (ft)*	*associated width (ft)*	*least depth over bar (ft)*	*aperture width (ft)*	*throat width (ft)*	*controlling cross section estimated (ft^2)*	*typical talweg depth (ft)*	*least width (ft)*
	ca	1900	open		4.5	600	1.5	600	600	1800	5.5	300
18	Aug	1916		major hurricane, landfall Baffin Bay								
	ca	1917	open		4.5	600	1.5	600	600	1800	5.5	300
14	Sep	1919		major hurricane, landfall Baffin Bay								
22	Jun	1921		hurricane, Matagorda Bay								
	Feb	1926	open									
	Feb	1927	marginal									
29	Jun	1929		hurricane, San Antonio Bay								
28	Jun	1931		tropical storm, Baffin Bay								
25	Jul	1934		hurricane, Aransas Bay								
	ca	1934	open		4	750	3	600	500	1042	5	300
		1935	closed					0		0		
27	Jun	1936		hurricane, Aransas Bay								
	ca	1936	closed					0		0		
	ca	1937	closed					0		0		
	Jun	1938	closed					0		0		
	Mar	1939	closed	dredging begun				0		0		
	Nov	1939	open	dredging complete								
29	Aug	1942		hurricane, Matagorda Bay								
21	Jul	1945		tropical storm, Baffin Bay								
27	Aug	1945		major hurricane, Matagorda Bay								
30	Aug	1949	open									
	ca	1950	open									
	ca	1951	open									
	ca	1952	open		3							
	ca	1952	open					300	350	225		300
31	Dec	1953	marginal					200	200	67		
15	Feb	1954	open		2.5	600	1.1	610	495	**600**	5	250
31	Mar	1955	open									

(continued)

date			source	citation or reference	comment
day	*mon*	*year*			
	ca	1900	navigation chart	C&GS 209	3 ft on the bar
18	Aug	1916	NCDC	McAdie et al. (2009)	
	ca	1917	navigation chart	C&GS 209	same shoreline& depths as 1900 ed.
14	Sep	1919	NCDC	McAdie et al. (2009)	considerable damage Corpus Christi & Port Aransas, passes opened on St Joseph Is (Shepard & Moore, 1955)
22	Jun	1921	NCDC	McAdie et al. (2009)	
	Feb	1926	observation	Galtsoff (1931)	12 visits to Mesquite Bay, majority in Jun-Sep 26
	Feb	1927	observation	Galtsoff (1931)	water over the Gulf bar at high tide, no measurements
29	Jun	1929	NCDC	McAdie et al. (2009)	
28	Jun	1931	NCDC	McAdie et al. (2009)	
25	Jul	1934	NCDC	McAdie et al. (2009)	
	ca	1934	navigation chart	USC&GS 1285	3 ft on the bar, same shoreline as 1917
		1935	coastal pilot	USC&GS (1936)	least depth back bay reach 2 ft
27	Jun	1936	NCDC	McAdie et al. (2009)	
	ca	1936	observation	Collier and Hedgpeth (1950)	
	ca	1937	observation	Collier and Hedgpeth (1950)	Collier's notes on his 1936-38 surveys
	Jun	1938	TGFOC annual reports	Ward (1997)	
	Mar	1939	TGFOC annual reports	Ward (1997)	TGFOC dredging operations Mar - May, Jul - Nov
	Nov	1939	TGFOC annual reports	Ward (1997)	
29	Aug	1942	NCDC	McAdie et al. (2009)	closed Murdocks Pass according to TGFOC (Ward, 1997)
21	Jul	1945	NCDC	McAdie et al. (2009)	
27	Aug	1945	NCDC	McAdie et al. (2009)	tracked along Texas coast from Baffin Bay, until making landfall
30	Aug	1949	report, aerial photograph	Simmons and Hoese (1959)	reported aerial photograph by Naval Air Station on this date
	ca	1950	observation	Simmons and Hoese (1959)	
	ca	1951	observation	Simmons and Hoese (1959)	
	ca	1952	observation	Shepard & Moore (1955)	
	ca	1952	USGS topo map	St Charles Is SE	
31	Dec	1953	report, aerial photograph	Shepsis & Carter (2007)	aerial photo, dubious
15	Feb	1954	field survey	Lockwood & Andrews (1954)	**cross-section area measured from field data** on depths across section
31	Mar	1955	report, aerial photograph	Simmons and Hoese (1959)	referenced TGFOC photo, see their Fig. 6

(continued)

APPENDIX A
(continued)

					BEACH REACH						BACKBAY REACH	
date day	date mon	date year	status	event	least depth (ft)	associated width (ft)	least depth over bar (ft)	aperture width (ft)	throat width (ft)	controlling cross section estimated (ft^2)	typical talweg depth (ft)	least width (ft)
31	May	1955	closed					0		0		
ca	Nov	1955	closed					0		0		
	ca	1956	closed					0		0		
22	Nov	1956	open	opened with dragline								
17	Dec	1956	open									
11	Feb	1957	marginal		1							
22	Mar	1957	closed					0		0		
	ca	1957	closed					0		0		
27	Jun	1957	marginal	high water, temporary opening								
18	Sep	1957	marginal	high water, temporary opening								
22	Oct	1957	marginal									
	Jan	1958	marginal	high water, temporary opening								
5	Sep	1958		tropical storm Ella, Corpus Christi								
5	Sep	1958		high water, temporary opening								
1	Apr	1959	closed	just before dredging begins				0		0		
	Sep	1959	open	dredging complete	15	200	15					
24	Jun	1960		tropical storm, Corpus Christi								
		1961	closed ?									
11	Sep	1961		major hurricane Carla, Matagorda Bay								
		1963	open									
7	Aug	1964		tropical storm Abby, Matagorda Bay								
3	Oct	1964		major hurricane Hilda, SE LA								
		1965	open									
20	Sep	1967		major hurricane Beulah, Tampico								
	Sep	1967		3rd highest inflow for San Antonio Bay								
	Jan	1968	open				9				14	290
23	Jun	1968		tropical storm Candy, Aransas Bay								
22	Apr	1969	open					1350	400	533		
	Jun	1970	open				3					

(continued)

APPENDIX A
(continued)

date			source	citation or reference	comment
day	mon	year			
31	May	1955	observation	Simmons and Hoese (1959)	
ca	Nov	1955	observation	Simmons and Hoese (1959)	
	ca	1956	observation	Simmons and Hoese (1959)	
22	Nov	1956	observation	Simmons and Hoese (1959)	local fishermen's actions
17	Dec	1956	report, aerial photograph	Simmons and Hoese (1959)	
11	Feb	1957	observation	Simmons and Hoese (1959)	channel had shifted to south and shoaled
22	Mar	1957	observation	Simmons and Hoese (1959)	completely closed, no evidence of channel
	ca	1957	coastal pilot	USC&GS (1958)	
27	Jun	1957	observation	Simmons and Hoese (1959)	Inundated 3 ft 27 Jun - 1 Jul, attributed to Hurricane Audrey
18	Sep	1957	observation	Simmons and Hoese (1959)	attributed to high river discharge
22	Oct	1957	oblique aerial photo	Leary (1959)	TGFC photo
	Jan	1958	observation	Simmons and Hoese (1959)	attributed to high river discharge
5	Sep	1958	NCDC	McAdie et al. (2009)	
5	Sep	1958	observation	Simmons and Hoese (1959)	attributed to TS Ella
1	Apr	1959	oblique aerial photo	Leary (1959)	TGFC photo
	Sep	1959	report	King (1971)	dredged by TGFC
24	Jun	1960	NCDC	McAdie et al. (2009)	Dwelled over watershed of San Antonio and Guadalupe
		1961	coastal pilot	USC&GS (1962)	Inspection cruise in 1961 of Key West to Rio Grande by USCGS *Scott*
11	Sep	1961	NCDC	McAdie et al. (2009)	
		1963	report	More (1969)	sampled semi-monthly Jan 63 - Nov 65
7	Aug	1964	NCDC	McAdie et al. (2009)	drifted W over lower watershed of San Antonio Bay
3	Oct	1964	report	Andrews (1970)	water level 2-2.5 ft above normal, extensive erosion from beach & deposition on back bay, attributed to Hilda
		1965	report	More (1969)	
20	Sep	1967	NCDC	McAdie et al. (2009)	drifted northward slowly, delivering heavy rainfalls, then tracked into Mexico
	Sep	1967			
	Jan	1968	observation	King (1971)	beginning of data collection
23	Jun	1968	NCDC	McAdie et al. (2009)	tracked N over lower watershed of San Antonio Bay
22	Apr	1969	USGS B&W vert aerial	AR1VCFI00010053	
	Jun	1970	observation	King (1971)	end of data collection

(continued)

APPENDIX A
(continued)

date			status	event	BEACH REACH least depth	associated width	least depth over bar	aperture width	throat width	controlling cross section estimated	BACKBAY REACH typical talweg depth	least width
day	mon	year			(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)	(ft)
3	Aug	1970		major hurricane Celia, Aransas Pass								
10	Sep	1971		hurricane Fern, Aransas Bay								
	Sep	1972	open					1380	520	1172		
15	Feb	1973	open					1200	600	1800		
	ca	1973	open					1500	650	2289		290
30	Jul	1978		tropical storm Amelia, Rio Grande								
1	Feb	1979	open					250	350	130		300
	Jun	1979	open					300	500	225		
ca	Jul	1979	closed	deliberate closure by sand berm				0		0		
11	Nov	1979	closed	berm still in place				0	350	0		
9	Aug	1980		major Hurricane Allen, Brownsville								
5	Sep	1980		tropical storm Danielle, Galveston								
12	Feb	1981	marginal					150	190	28		300
21	Sep	1982	marginal					200	190	57		
5	Nov	1982	marginal					130	220	18		320
6	Mar	1983	marginal					280	200	67		390
	Dec	1983		killer freeze thru early Jan								
	Jan	1984		massive kills of fish & shellfish								
7	Dec	1984	marginal					150	150	28		
	Jun	1987		2nd highest inflow for San Antonio Bay								
		1988	open	dredging complete								
2-9	Feb	1989		extreme low temperature event on coast								
6	Mar	1989	marginal					200	120	14		380
10	Dec	1989	marginal					100	80	4		300
	Feb	1992		5th highest inflow for San Antonio Bay								
18	Mar	1995	marginal					120	150	14		380
		1995	open	dredging complete								
		1996	open									
		1997	open									
22	Aug	1998		tropical storm Charley, Corpus Christi								

(continued)

APPENDIX A
(continued)

date			*source*	*citation or reference*	*comment*
day	*mon*	*year*			
3	Aug	1970	NCDC	McAdie et al. (2009)	Eroded dunes but deposited sand on beaches of Mat Is (Wilkinson, 1973)
10	Sep	1971	NCDC	McAdie et al. (2009)	3-5 ft surge, substantial deposition on Mat Is beaches (Wilkinson, 1973)
	Sep	1972	NASA/MSC CIR vert aerial	AR6216000200119	both Bayou & Vincent merged & wide open
15	Feb	1973	report, aerial photograph	Shepsis & Carter (2007)	aerial photo
	ca	1973	USGS topo map	St Charles Is SE	photorevised
30	Jul	1978	NCDC	McAdie et al. (2009)	drifted NW into San Antonio Bay wateshed
1	Feb	1979	USGS B&W vert aerial	AR1VEOC00040056	
	Jun	1979	NASA/Ames CIR vert aerial	Nov 79 aerial	widths from post-berm photograph (see below)
ca	Jul	1979	report	IXTOC websites below	to prevent pollution from Ixtoc blow-out (June 79)
11	Nov	1979	NASA/Ames CIR vert aerial	AR5790028428336	aperture measured behind berm
9	Aug	1980	NCDC	McAdie et al. (2009)	
5	Sep	1980	NCDC	McAdie et al. (2009)	drifted W over lower watershed of San Antonio Bay
12	Feb	1981	USGS NHAP CIR vert aerial	NC1NHAP810273026	Ixtoc berm gone
21	Sep	1982	NPW CIR vert aerial	ARL820510131978	
5	Nov	1982	USGS NHAP CIR vert aerial	NC1NHAP810377096	
6	Mar	1983	USGS NHAP CIR vert aerial	NC1NHAP810703176	
	Dec	1983			
	Jan	1984			
7	Dec	1984	report, aerial photograph	Shepsis & Carter (2007)	aerial photo
	Jun	1987			
		1988	report	Bengston et al. (ca 2004)	dredged by TPWD
2-9	Feb	1989			Mesquite Bay at 0 on 6 Feb
6	Mar	1989	USGS NAPP CIR vert aerial	NP0NAPP001506112	
10	Dec	1989	NASA/Ames CIR vert aerial	AR5890039814074	throat reduced due to bar structures
	Feb	1992			high flows throughout Dec 91 - Jun 92 period
18	Mar	1995	USGS NAPP CIR vert aerial	NP0NAPP008669010	throat reduced due to bar structures
		1995	report	Hagen (2003)	300,000 cu yds dredged by TPWD
		1996	oblique aerial photo	Watson (2010)	
		1997	oblique aerial photo	Watson (2010)	narrower than 1996
22	Aug	1998	NCDC	McAdie et al. (2009)	

(continued)

APPENDIX A
(continued)

date			status	event	BEACH REACH						BACKBAY REACH	
day	*mon*	*year*			*least depth (ft)*	*associated width (ft)*	*least depth over bar (ft)*	*aperture width (ft)*	*throat width (ft)*	*controlling cross section estimated (ft^2)*	*typical talweg depth (ft)*	*least width (ft)*
10	Sep	1998		tropical storm Frances, San Antonio Bay								
	Oct	1998		highest inflow for San Antonio Bay								
	ca	1999	closed					0		0		
22	Aug	1999		major hurricane Brett, Baffin Bay								
	Nov	2001	closed					0	100	0		
14	Dec	2001	closed					0				
7	Feb	2002	closed					0	220	0		380
	Jul	2002		4th highest flood for San Antonio Bay								
22	Aug	2002	closed					0		0		
6	Sep	2002		tropical storm Fay, Matagorda Bay								
15	Jul	2003		hurricane Claudette, Matagorda Bay								
	Nov	2003	marginal						50			
18	Dec	2003	marginal					200	100	8		
4	Nov	2004	marginal					110	60	2		
20	Jul	2005		major hurricane Emily, Tampico								
22	Jul	2005	marginal									
	Aug	2005	marginal					100	100	8		
9	Oct	2005	marginal					300	200	67		300
22	Nov	2005	marginal									
11	Dec	2005	marginal									
	May	2006	marginal					80	100	4		
16	May	2006	marginal									
17	Jul	2006	marginal									
31	Aug	2006	marginal									
28	Oct	2006	marginal									
17	Nov	2006	marginal									
8	Jan	2007	marginal									
16	Aug	2007		tropical storm Erin, Aransas Bay								
21	Sep	2007	marginal									
	Oct	2007	marginal					50	100	1		

(continued)

APPENDIX A
(continued)

date			source	citation or reference	comment
day	mon	year			
10	Sep	1998	NCDC	McAdie et al. (2009)	stalled offshore for several days before landfall, then tracked N into N Texas
	Oct	1998			sustained through November
	ca	1999	report	Hagen (2003)	reported shoaled
22	Aug	1999	NCDC	McAdie et al. (2009)	
	Nov	2001	report, aerial photograph	Shepsis & Carter (2007)	aerial photo
14	Dec	2001	GLO CIR vert aerial	GLO 201PT 9-04	
7	Feb	2002	USGS NAPP CIR vert aerial	NP0NAPP012817064	
	Jul	2002			
22	Aug	2002	report	Sikes (2002)	
6	Sep	2002	NCDC	McAdie et al. (2009)	drifted W into lower watershed of San Antonio Bay
15	Jul	2003	NCDC	McAdie et al. (2009)	
	Nov	2003	oblique aerial photo	Watson (2010)	narrow channel through beach & dune line, width estimated
18	Dec	2003	report, aerial photograph	Shepsis & Carter (2007)	aerial photo
4	Nov	2004	USDA-FSA-APFO CIR vert aerial		water level low, lots of exposed bars
20	Jul	2005	NCDC	McAdie et al. (2009)	tracked W into N Mexico, opened Packery Channel
22	Jul	2005	oblique aerial photo	Watson (2010)	stated to be opened by Emily
	Aug	2005	TGLO CIR vert aerial		
9	Oct	2005	USDA-FSA-APFO NC vert aerial		shoreline indistinct, looks like high water event
22	Nov	2005	oblique aerial photo	Watson (2010)	looks same as 22Jul except lower water level
11	Dec	2005	oblique aerial photo	Watson (2010)	
	May	2006	TGLO CIR vert aerial		water level low
16	May	2006	oblique aerial photo	Watson (2010)	
17	Jul	2006	oblique aerial photo	Watson (2010)	
31	Aug	2006	oblique aerial photo	Watson (2010)	
28	Oct	2006	oblique aerial photo	Watson (2010)	stated to be "nearly closed at low tide"
17	Nov	2006	oblique aerial photo	Watson (2010)	
8	Jan	2007	oblique aerial photo	Watson (2010)	
16	Aug	2007	NCDC	McAdie et al. (2009)	
21	Sep	2007	oblique aerial photo	Watson (2010)	higher water level than photos of 06 & early 07
	Oct	2007	TGLO CIR vert aerial		water levels dropping

(continued)

APPENDIX A
(continued)

date			status	event	BEACH REACH						BACKBAY REACH	
day	*mon*	*year*			*least depth (ft)*	*associated width (ft)*	*least depth over bar (ft)*	*aperture width (ft)*	*throat width (ft)*	*controlling cross section estimated (ft^2)*	*typical talweg depth (ft)*	*least width (ft)*
20	Oct	2007	marginal									
5	Nov	2007	marginal									
16	Dec	2007	marginal									
6	Feb	2008	closed					0		0		
27	Feb	2008	closed					0		0		
28	Apr	2008	closed					0	50	0		330
28	Jun	2008	closed					0		0		
23	Jul	2008		hurricane Dolly, Port Mansfield								
28	Jul	2008	closed					0		0		
12	Sep	2008		major hurricane Ike, Galveston Bay								
17	Sep	2008	closed					0		0		
18	Oct	2008	closed					0		0		
8	Jan	2009	closed					0	70	0		330
16	Mar	2009	closed					0		0		
8	Aug	2009	closed					0		0		
14	Sep	2009	closed					0		0		

(continued)

APPENDIX A
(continued)

date			source	citation or reference	comment
day	*mon*	*year*			
20	Oct	2007	oblique aerial photo	Watson (2010)	stated to be "closed at low tide"
5	Nov	2007	oblique aerial photo	Watson (2010)	
16	Dec	2007	oblique aerial photo	Watson (2010)	
6	Feb	2008	oblique aerial photo	Watson (2010)	
27	Feb	2008	oblique aerial photo	Watson (2010)	moistened channel visible
28	Apr	2008	TOP-NAIP CIR vert aerial	TNRIS l2896_58_1	drainage channels visible, after high-water event?
28	Jun	2008	oblique aerial photo	Watson (2010)	
23	Jul	2008	NCDC	McAdie et al. (2009)	
28	Jul	2008	oblique aerial photo	Watson (2010)	wave wrack on beach, including former entrance location
12	Sep	2008	NCDC	McAdie et al. (2009)	into N Texas
17	Sep	2008	oblique aerial photo	Watson (2010)	
18	Oct	2008	oblique aerial photo	Watson (2010)	moistend region in vicinity of old mouth, effect of high water?
8	Jan	2009	TOP-NAIP CIR vert aerial	TNRIS l2896_58_1	
16	Mar	2009	oblique aerial photo	Watson (2010)	
8	Aug	2009	oblique aerial photo	Watson (2010)	
14	Sep	2009	oblique aerial photo	Watson (2010)	

APPENDIX B
Chronology of tropical cyclones since 1900 making landfall in Texas or potentially affecting the Cedar Bayou region

landfall date *yr*	*mo*	*da*	*status*	*name*	*landfall*	*comment*
1901	Jul	10	tropical storm		Matagorda Bay	
1902	Jun	26	hurricane		Aransas Bay	minimal hurricane
1909	Jun	29	hurricane		Brownsville	
1909	Jul	21	major hurricane		Freeport	
1909	Aug	28	major hurricane		Tampico	
1910	Aug	30	tropical storm		Brownsville	
1910	Sep	14	hurricane		Port Mansfield	
1912	Oct	16	hurricane		Baffin Bay	Moved N into Corpus Christi area
1913	Jun	27	hurricane		Baffin Bay	
1914	Sep	19	tropical storm		Sabine Lake	Moved W into Houston area
1915	Aug	17	major hurricane		Freeport	Recurved NE into midwest and Miss-Ohio Valley
1916	Aug	5	tropical storm		Tampico	
1916	Aug	18	major hurricane		Baffin Bay	continued into Rio Grande Valley
1918	Aug	8	major hurricane		Sabine Lake	
1919	Sep	14	major hurricane		Baffin Bay	
1921	Jun	22	hurricane		Matagorda Bay	continued N into Oklahoma
1921	Sep	6	hurricane		Vera Cruz	curved N into Rio Grande Valley
1925	Sep	6	tropical storm		Brownsville	Rio Grande Valley
1929	Jun	29	hurricane		San Antonio Bay	
1931	Jun	28	tropical storm		Baffin Bay	
1932	Aug	13	major hurricane		Galveston Bay	
1933	Jul	6	hurricane		Tampico	
1933	Jul	22	tropical storm		Freeport	
1933	Sep	4	hurricane		Brownsville	
1934	Jul	25	hurricane		Rockport	
1934	Aug	26	tropical storm		Freeport	neared Freeport, curved back to SE, then landfalled at Tampico
1936	Jun	27	hurricane		Aransas Pass	
1936	Sep	13	tropical storm		Brownsville	Rio Grande Valley
1938	Oct	17	tropical storm		Freeport	minimal storm
1940	Sep	23	tropical storm		Galveston Bay	minimal storm
1941	Sep	15	tropical storm		Galveston Bay	drifted SW over San Antonio Bay watershed
1941	Sep	23	hurricane		Freeport	
1942	Aug	29	hurricane		Matagorda Bay	Closed Murdocks Pass according to TGFOC (Ward, 1997)
1943	Jul	27	hurricane		Galveston Bay	drifted into N Texas
1943	Sep	16-18	hurricane		W Louisiana	looped off coast of Texas for 16-18 Sep before drifting N to Louisiana
1945	Jul	21	tropical storm		Baffin Bay	drifted SW into Mexico
1945	Aug	27	major hurricane		Matagorda Bay	tracked along Texas coast from Baffin Bay, until making landfall
1947	Aug	1	tropical storm		Brownsville	minimal
1947	Aug	24	hurricane		Galveston Bay	

(continued)

APPENDIX B
(continued)

landfall date *yr*	*mo*	*da*	*status*	*name*	*landfall*	*comment*
1949	Oct	3	hurricane		Freeport	N trajectory
1953	Sep	26	hurricane	Florence	Pensacola	Shepard & Moore report this flooded beaches on N end of Padre Island
1954	Jun	25	tropical storm		Tampico	drifted NW up Rio Grande Valley
1957	Jun	27	major hurricane	Audrey	Sabine Lake	
1958	Sep	5	tropical storm	Ella	Corpus Christi	hurricane strength in Cuba, but weakened when it reached W Gulf
1959	Jul	25	tropical storm	Debra	Galveston Bay	
1960	Jun	24	tropical storm		Corpus Christi	Dwelled over watershed of San Antonio and Guadalupe
1961	Sep	11	major hurricane	Carla	Pass Cavallo	tracked NE into Canada
1963	Sep	17	hurricane	Cindy	Galveston Bay	after landfall drifted SW just inside coast down to Laredo
1964	Aug	7	tropical storm	Abby	Matagorda Bay	drifted W over lower watershed of San Antonio Bay
1967	Sep	20	major hurricane	Beulah	Tampico	drifted northward slowly, delivering heavy rainfalls, then tracked into Mexico
1968	Jun	23	tropical storm	Candy	Aransas Pass	tracked N over lower watershed of San Antonio Bay
1970	Aug	3	major hurricane	Celia	Corpus Christi	drifted WNW into Rio Grande Valley
1970	Sep	15	tropical storm	Felice	Galveston Bay	curved N into N Texas
1971	Sep	16	hurricane	Edith	W Louisiana	paralleled Texas coast 15-16 Sep just offshore
1971	Sep	10	hurricane	Fern	Aransas	SW track into Mexico
1973	Sep	5	tropical storm	Delia	Freeport	dwelled offshore 4-5 Sep, then SW over lower San Antonio Bay watershed
1974	Sep	7	tropical storm	Carmen	Barataria	tracked W into Texas dissipating over upper Guadalupe watershed
1977	Sep	2	major hurricane	Anita	Tampico	
1978	Jul	30	tropical storm	Amelia	Rio Grande	drifted NW into San Antonio Bay wateshed
1979	Aug	31	tropical storm	Elena	Matagorda Bay	minimal, drifted into NE Texas
1979	Sep	12	major hurricane	Frederick	Mobile Bay	extreme high tides in 2nd week of Sep, according to Chapman (1981)
1979	Sep	n/a	tropical storm	Henri		high wave action off Padre, Farrington (1985), This storm never made landfall, but drifted from Campeche into NE GOM
1980	Aug	9	major hurricane	Allen	Brownsville	WNW into N Mexico
1980	Sep	5	tropical storm	Danielle	Galveston	drifted W over lower watershed of San Antonio Bay
1983	Aug	17	major hurricane	Alicia	Galveston Bay	tracked N into Oklahoma
1983	Aug	28	hurricane	Barry	Brownsville	moved W into N Mexico
1988	Sep	16	hurricane	Gilbert	Tampico	moved N into N Mexico
1993	Jun	20	tropical storm	Arlene	Baffin Bay	minimal
1995	Jul	30	tropical storm	Dean	Freeport	minimal, moved NW into N Texas

(continued)

APPENDIX B
(continued)

landfall date yr	*mo*	*da*	*status*	*name*	*landfall*	*comment*
1998	Aug	22	tropical storm	Charley	Corpus Christi	drifted W into Rio Grande Valley
1998	Sep	10	tropical storm	Frances	San Antonio Bay	stalled offshore for several days before landfall, then tracked N into N Texas
1999	Aug	22	major hurricane	Bret	Baffin Bay	tracked W into N Mexico
2001	Jun	5	tropical storm	Allison	Freeport	reversed, moved back offshore then into Lousiana
2002	Sep	6	tropical storm	Fay	Matagorda Bay	drifted W into lower watershed of San Antonio Bay
2003	Jul	15	hurricane	Claudette	Matagorda Bay	Rio Grande Valley
2003	Aug	16	hurricane	Erika	Brownsville	N Mexico
2003	Aug	31	tropical storm	Grace	Galveston Bay	minimal
2005	Sep	23	major hurricane	Rita	Sabine Lake	
2007	Aug	16	tropical storm	Erin	Aransas Bay	
2007	Sep	12	hurricane	Humberto	Galveston Bay	tracked N
2008	Jul	23	hurricane	Dolly	Port Mansfield	W into Mexico
2008	Aug	6	tropical storm	Edouard	Galveston Bay	into N Texas
2008	Sep	12	major hurricane	Ike	Galveston Bay	into N Texas

Appendix C
Aerial photography employed in study
obtained from state or federal agencies

File ID	*EROS Entity ID*	*Acquisition Date*	*Image Type*	*Flying Height in Feet*	*Agency*	*Project*	*Roll Nbr*	*Frame Nbr*
5SGY03011_062	AR1VCFI00010053	4/22/1969	BW	15600	U.S. Geological Survey	VCFI00	1	53
7OTQ02042_121	AR6216000200119	9/0/1972	CIR	9863	NASA Johnson Space Center	216	2	119
5WWT02011_056	AR1VEOC00040056	2/1/1979	BW	40000	U.S. Geological Survey	VEOC00	4	56
5RTQ10031_474	AR5790028428336	11/11/1979	CIR	65003	NASA - Ames Research Center		2842	8336
5MRD02052_027	NC1NHAP810273026	12/2/1981	CIR	40000	USGS NHAP	NHAP81	273	26
8EWT05011_075	ARL820510131978	9/21/1982	CIR	12005	National Park Service	82051	13	1978
5MRD04041_097	NC1NHAP810377096	11/5/1982	CIR	40000	USGS NHAP	NHAP81	377	96
5MBL05032_177	NC1NHAP810703176	3/6/1983	CIR	40000	USGS NHAP	NHAP81	703	176
7DYL09032_112	NP0NAPP001506112	3/6/1989	CIR	40000	USGS NAPP	NAPP	1506	112
8PWT10041_064	AR5890039814074	12/10/1989	CIR	63700	NASA - Ames Research Center		3981	4074
1BBL04052_010	NP0NAPP008669010	3/18/1995	CIR	40000	USGS NAPP	NAPP	8669	10
GLO 201PT 9-04	n/a	12/14/2001	CIR		TGLO			
1DWT28042_064	NP0NAPP012817064	2/7/2002	CIR	40000	USGS NAPP	NAPP	12817	64
TNRIS d289658_1	n/a	11/4/2004	CIR		USDA-FSA-APFO	TOP		
TGLO 4699 229-234	n/a	8/0/2005	CIR		TGLO			
TNRIS e2896_58_1	n/a	10/9/2005	NC		USDA-FSA-APFO	TOP		
TGLO 4743 232-233	n/a	5/0/2006	CIR		TGLO			
TGLO 4812-UTM14-157	n/a	10/0/2007	CIR		TGLO			
TNRIS l2896_58_1_cir_28042008	n/a	4/28/2008	CIR & NC		NAIP	TOP		
TNRIS l2896_58_1_cir_08012009	n/a	1/8/2009	CIR & NC		NAIP	TOP		

NAPP	National Aerial Photography Program
NHAP	National High Altitude Program
TOP	Texas Orthoimagery Program
NAIP	National Agricultural Imagery Program

Appendix D
Estimation of inlet cross-section area

Assume the cross section profile of the channel to be symmetric about the central axis. We postulate a parabolic variation of bed elevation $z(y)$, measured positive upward from the low-point datum, across the lateral distance of the cross section y, with origin in the center of the channel, as sketched in Figure A-1. The equation for the bed elevation is:

$$z(y) = m\, y^2 \tag{1}$$

The coefficient *m* governs the shape of the cross section. The water level, or stage d, is then related to stream width w by:

$$d = m\, w^2 / 4 \tag{2}$$

the mean depth is:

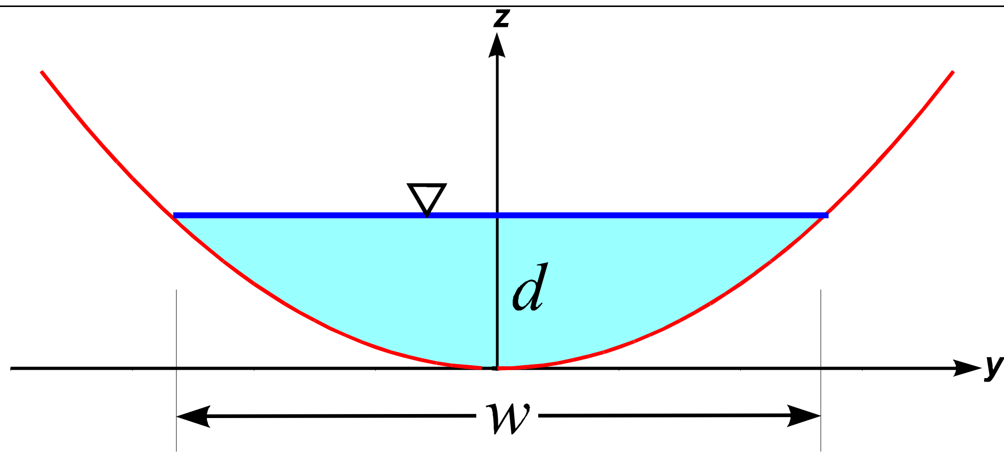

Figure A-1 - Definition sketch for mathematical depiction of channel cross section

$$D = h - \frac{1}{w}\int_{-w/2}^{w/2} z(y)dy = d - m\,w^2/12 \tag{3}$$

and cross section area is:

$$A = d\,w - m\,w^3/12 \tag{4}$$

or, as a function of width alone,

$$A(w) = m\,w^3/6 \tag{5}$$

From data on width and depth (observed simultaneously), *m* can be evaluated from:

$$m = 4\,d / w^2 \tag{6}$$

Four surveys were utilized from the historical record of Cedar Bayou (see Appendix A), namely:

date	least depth (ft)	associated width (ft)	computed *m* (1/ft)	source
1917	4.5	600	5.000E-05	navigation chart
1934	4	750	2.844E-05	navigation chart
1952	3	350	9.796E-05	observation + topo map
1954	2.5	600	2.778E-05	field survey

The average of the individual computed values of *m* is 5.11×10^{-5}. First averaging the least depths and associated widths then computing *m* from these values using (6) gives 5.10×10^{-5}. For the estimated cross section relation we adopt a value of $m = 5 \times 10^{-5}$.